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Attitudes and Barriers to Deployment of CCS from Industrial Sources in the UK

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Executive Summary

Globally, there has been less focus on Carbon Capture and Storage (CCS) applied to industrial sources of CO_2 (i.e. from heavy industries except gas processing) than on applications of CCS in power generation. This is despite the fact that the energy-intensive industrial sector comprising large point sources (LPS) presents high potential for emissions mitigation through CCS. This report analyses and presents the main factors affecting the progress of CCS in industry and examines the question, "what policy environment and concomitant conditions would be required for the feasible deployment and operation of CCS from industrial sources in the UK (both including and excluding power production)?"

The findings are informed by a review of the relevant academic literature on industrial CCS, undertaken with reference to three of the UK's most highly emitting industries making up 57% of projected total industrial emissions by 2050: high purity emission sources such as ammonia production (i.e. >30% CO_2 by volume); cement production; and iron and steel manufacturing.

Based on this review, we conducted a survey of international industrial experts. This allowed us to analyse and evaluate the consistency of expert views across industrial sectors, sub-sectors and geographical regions with regard to a number of factors, including: perceptions on the UK's energy policies and incentives applicable to the industry; barriers of implementing industrial CCS; and future efforts needed to promote its implementation. Figure 1 provides an overview of the survey methodology and analysis. A full definition of these terms is given in Box 1.1; note that 'industrial CCS' excludes natural gas processing. Almost 100 responses to the survey were received, with a relatively good spread across the different sectors and sub-sector divisions. Box 1.2 presents a summary of the responses from the survey.

It is important to note that this was a preliminary study on the research topic and is the first of its kind. Although a good response rate was achieved, the sub-sectors were relatively small, giving rise to indicative rather than conclusive findings. Where results are statistically significant, they have been highlighted. The insight obtained from this preliminary study indicates that a larger follow-up study would be a worthwhile endeavour to attain a more complete picture of the complex issues surrounding the implementation of industrial CCS.

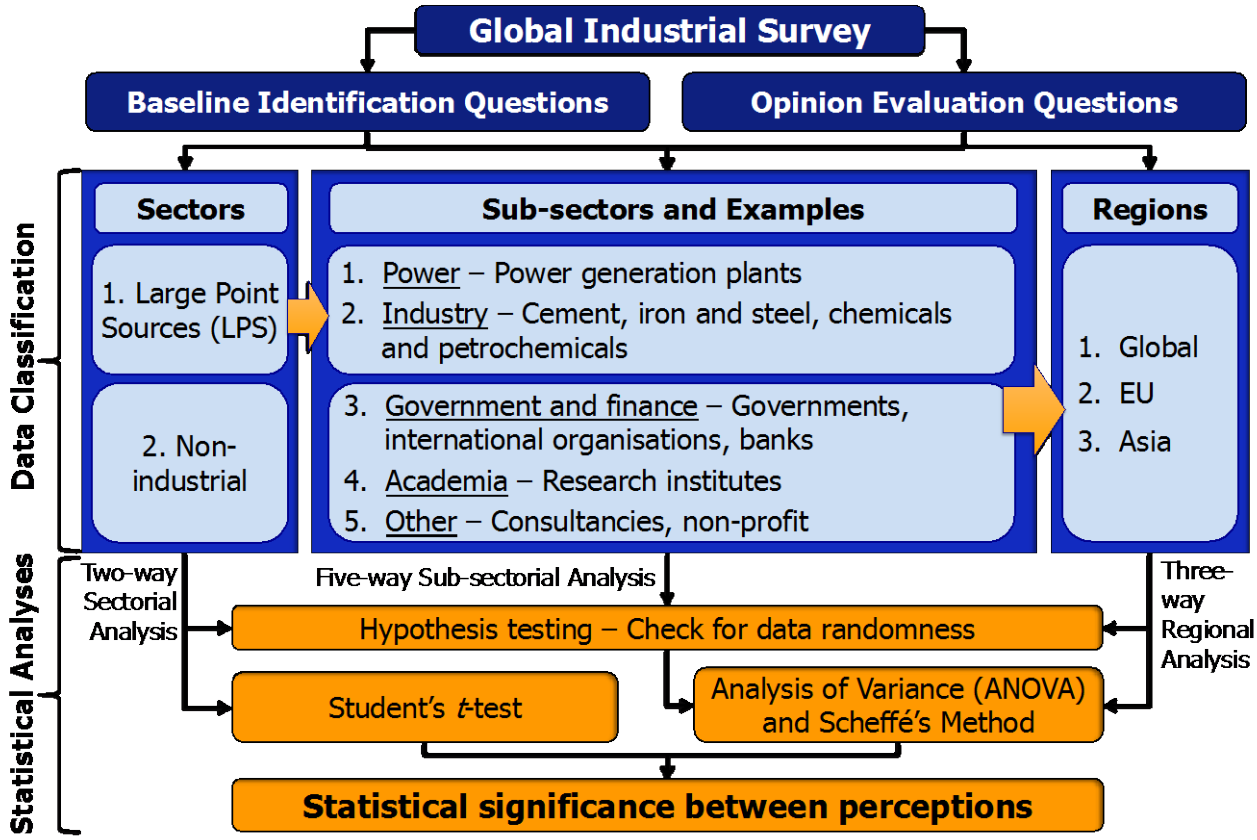

Figure 1: Graphical representation of the survey and analysis methodology

Box 1.1: Key definitions of different groupings

Industrial CCS: CCS applied to non-power large point sources of CO_2

Level 1: Two-way sectoral split

- **Large point sources (LPS):** Power and Industry sub-sectors
- **Non-industrial sector:** Government & Finance, Academia, and Other sub-sectors

Level 2: Five-way sub-sectoral split

- **Power sub-sector:** All power generation and distribution organisations
- **Industry sub-sector:** Industrial organisations which manufacture goods rather than electricity, excluding natural gas processing
- **Government and Finance sub-sector:** All government entities and financial institutions
- **Academia sub-sector:** Organisations whose primary output is research, but are not privately owned
- **Other sub-sector:** Not-for-profit organisations and consultancies.

Level 3: Geographical split

- **World:** Everywhere except the EU and Asia

Analyses

- **Two-way analysis:** Comparing LPS and Non-industrial sectors
- **Three-way analysis:** Comparing EU, Asia, and Global operations
- **Five-way analysis:** Comparing Power, Industry, Government and Finance, Academia and Other sub-sectors

Box 1.2: Responses to the survey

The quantitative analysis was done on a 10-point Likert scale, i.e. 1 to 10, with 1 being “strongly disagree” and 10 being “strongly agree”.

98 people completed the survey, a 65% response rate, and the final response count after removing incomplete responses was 87.

Primary Sector	Secondary Sub-sector
LPS (34)	Power generation (16)
	Industry (18)
Non-industrial (53)	Academia (25)
	Government and finance (18)
	Other (10)

Results and Findings

Table 1: Summary of key findings from the statistical analysis of survey responses

Analyses	Baseline Identification	Opinion Evaluation		
	Effectiveness of Policies, Incentives and Knowledge Sharing Platforms	**Greatest Barriers of Implementing Industrial CCS**	**Greatest Perceived Risks**	**Future Efforts Most Essential in Promoting Industrial CCS**
Two-way (Sectoral) *t-test*	**Current government policies and incentives are barely adequate** LPS considered government funding as severely inadequate	**Economics of CCS greatest impact on LPS** Barriers relatively higher for LPS than non-industrial	**Uncertainty in payback** Stakeholder acceptance Loss in throughput	**Monetary incentives and capital funding** **Improvements to regulatory frameworks** (especially for LPS)
Five-way (Sub-sectoral) *ANOVA*	Current policies are inadequate Incentives significantly less adequate for consultancies than industry	**Barriers have greater impact on industry**	**Uncertainty in payback**	**Financial mechanisms** Policy changes e.g. doubling carbon price less favoured by industry
Three-way (Regional) *ANOVA*	EU finds policies more effective than other regions do	**EU finds barriers lower than other regions do**	**Throughput loss (EU and Asia)**	**Monetary incentives and increase in capital funding (EU)** Consultancies most confident about effectiveness of policy changes

Having assessed the baseline of present CCS deployment status and existing perceptions through the survey, and evaluated opinions on industrial CCS issues, we conclude that the perceived challenges of implementing CCS in industry primarily arise from:

- **The economic barriers of deployment;**
- **The absence of long-term policies and frameworks** guiding future development of industrial CCS;
- Infrastructural constraints such as the **lack of nearby storage sites** and **connectivity to transport and storage infrastructure**.

The key points are summarised in Table 1.

Key Lessons from Survey

Lesson 1: Organisations are looking to implement CCS in the medium- to long-term, and are already engaged in carbon dioxide emissions reduction

Most organisations researching CCS expect to implement it in over five years' time, with only about one-quarter looking to implement it before then.

Lesson 2: Three primary barriers to deployment of industrial CCS have been observed from the survey, aligned to findings from literature review.

Economics of CCS[1] was perceived to be the most significant barrier, more so perceived by the LPS than non-industrial sector at 5% significance. The *absence of long-term policies* was rated as the next highest scoring barrier. The *lack of nearby storage sites* was perceived to be the third barrier of concern, in tandem with the relatively high *necessity of transport and storage networks*. In general at the sub-sectoral level industry perceives the barriers to successful implementation of CCS to be significantly higher than remaining sub-sectors do, to 1% significance (i.e. there is 99% confidence that the results are valid).

Lesson 3: Technology issues are considered to be more important by the industry than power producers

Whilst LPS as a whole perceived greater *technological awareness* as being less important for the promotion of CCS than non-industrial groups, the industry sub-sector felt it knew less about CCS than the power sub-sector, although more data would be needed to determine statistical

[1] "Economics of CCS" refers to the barriers and drivers of the uptake of CCS which are related to capital and operating expenditure, the costs of financing construction and operation, and the effect of CCS on revenue streams.

significance in this result. *Technology lock-in*, i.e. being locked with an obsolete technology in the long run, was also found to be a significant issue especially with the industry sub-sector.

Lesson 4: Most believe *present incentives and knowledge sharing platforms* might not be adequate in promoting the uptake of CCS, although the industry sub-sector had different views from all others.

Ratings across sectors were relatively low, and the LPS sector as a whole gave lower ratings for current government funding and knowledge-sharing platforms than the non-industrial sector. While *present government funding for CCS deployment* was perceived by the power, academic and government and finance sub-sectors to be mildly adequate in promoting CCS uptake, the industry sub-sector tended to consider it insufficient.

Existing platforms for knowledge sharing across the industry were perceived to be mildly adequate amongst the power, industry, academic, and government and finance sub-sectors, with the industry sub-sector being most positive about them. The 'other' sub-sector regarded *existing knowledge-sharing platforms* as being insufficient.

Methods to Accelerate Adoption of Industrial CCS

After considering the barriers to industrial CCS, and having validated the effectiveness of policies and initiatives in facilitating its implementation, potential solutions in the short, medium and long-term were proposed and outlined below. These could assist policymakers in establishing effective mechanisms to promote industrial CCS development in the UK.

- **Enhance Regulatory Frameworks.**
  To achieve the emissions targets set out in the UK carbon budgets, clarity and stability of the regulatory framework governing CCS should be enhanced, particularly with regards to industrial CCS, to alleviate existing implementation challenges and reduce uncertainties by providing guidance on future CCS development plans.
- **Support Development of Financial Incentives.**
  Financial incentives, such as loan liquidity and tax relief, could reduce the barrier of high upfront costs of a CCS system. Compensation schemes for the potential loss of competitiveness and mechanisms adjusting the cost of carbon at UK's borders could mitigate the risks of carbon leakage.
- **Accelerate CO_2 Utilisation.**
  Enhanced Oil Recovery (EOR) is the most mature form of CO_2 utilisation, and is common in North America. By ensuring that a regulatory framework that allows or promotes EOR is developed and implemented, its potential for reducing the net cost of capturing CO_2 can be

harnessed, especially in the first stages of CCS roll-out. Promoting other uses of CO_2 may raise the market price of CO_2 further. However, the climate benefits of CCS + EOR are less clear than those where CO_2 is stored in e.g. a saline aquifer.

- **Develop Transport and Storage Infrastructure.**
  Government support for transport and storage infrastructure would significantly improve industry confidence in the success of CCS. Well-planned placement of pipelines will maximise the potential for industrial clusters, especially at the beginning of CCS rollout. Publishing guidelines on best practices for the design and operation of equipment such as compressors, CO_2 'polishing' plant for impurity removal, as well as solvents and sorbents will promote more efficient systems.
- **Promote Inclusion of Industry in Consultations and Discussions about CCS.**
  Since the industry sub-sector perceived the barriers to CCS deployment to be much higher than other remaining sub-sectors did, their greater inclusion in discussions and consultations about all aspects and forms of CCS may help alleviate their uncertainties. Furthermore, it may facilitate identification of more barriers for CCS amongst the industry sub-sector, which may be different from those facing the power sub-sector, and initiate potential mitigations.
- **Continue to Develop the UK's Leadership Role in Industrial CCS.**
  The UK is well-positioned to take on a leading role in CCS, including within the industry. Skills from the oil and gas industry, as well as mature and efficient industrial and financial sub-sectors, provide the UK with advantages over other countries. The reputation of being a first-mover in a field as important to global emissions reduction as industrial CCS may improve British influence in trade and climate change negotiations.

Introduction

Worldwide, primary energy supply reached 12 730 million tonnes of oil equivalent (533 EJ) in 2010 and corresponding carbon dioxide (CO_2) emissions amounted to 31.7 gigatonnes (Gt), with approximately a third being attributed to industrial activities and fuel transformation (World Energy Outlook, 2012).

With similar proportions of industrial carbon emissions in the UK, meeting its strict long-term targets of 80% emission reduction by 2050 as compared to 1990 levels requires a crucial contribution from the industrial sector (UK Government, 2008). While energy efficiency measures in the short term could significantly help the UK work towards its target, reducing energy intensity by up to 40% by 2050, carbon capture and storage (CCS) would have to be deployed to allow deeper cuts in emissions, so as to reduce pressure on existing emission reduction alternatives and low carbon technologies (Committee on Climate Change, 2011). As the IEA concluded in 2012, with rapid implementation, CCS alone could help mitigate up to 20% of total global CO_2 produced by 2050, with the power generation sub-sector contributing about 55% and the remaining 45% from other emission-intensive industrial sub-sectors.

The deployment of CCS in industry appears to be an essential emissions reduction technology in the UK, both in the medium (2030) and long-term (2050 and beyond). It is the only means of enabling energy intensive industries – cement, iron and steel, and refineries – to meet UK's strict emission reduction targets (IEA, 2012). However, this is an uphill task as most efforts in developing CCS have been focused on power generation (Mott MacDonald, 2010). While technologies for carbon capture are commercially available and deployable throughout various industries presently, the main difficulty arises from integration with commercial-scale projects, as these technologies require high capital investments, contrary to some low-carbon options such as some solar photovoltaic technologies (IEA, 2012).

Implementation of CCS has also been challenging in the UK. Historically, the priorities of UK's energy policy revolve around four key pillars – mitigating climate change, ensuring supply security and reliability, addressing fuel poverty, as well as driving competitive markets as a means to achieve these primary objectives (Department of Trade and Industry (DTI), 2007). This long-term commitment towards ensuring competitive energy markets, which might seem to contradict the deployment of CCS (Scrase & Watson, 2009). A number of additional barriers exist, preventing extensive deployment of CCS in industry, e.g. poor infrastructural support, high upfront cost, absence of clear market mechanisms and regulatory regimes for managing initiatives, and general public reluctance (Blunt, 2010). Gas processing is currently the most successful sector with regards to CCS deployment. Therefore it is assumed that the attitudes and barriers within this industry are different from those in other large industrial facilities, and gas processing is not

included in the “Industry” category.

Objectives of Research

Recognising the significance of industrial CCS towards the UK’s 2050 emissions reduction target, the research aimed to examine the policy environment and concomitant conditions required for feasible operation of CCS within the industrial sub-sector, and to identify the extent to which policies and other factors could aid or inhibit industrial CCS implementation.

This was done by establishing the current status of industrial CCS adoption and analysing the perceptions of CCS applied to industrial sources through a global survey, where the insights of experts across various sub-sectors of large point sources and non-industrial sectors were analysed and the results methodologically evaluated. This enabled validation of consistency of views across the sub-sectors, thereby determining potential disparities in perceptions and gaps in existing policies.

Report Structure

Beginning with an overview of industrial CCS, the report will present its current status, global efforts, and fundamental implementation challenges. Thereafter, the methodology applied will be discussed, and the results and findings from the survey will be presented, analysed and discussed. Finally, a number of potential solutions in overcoming key barriers will be discussed.

Current Situation of Industrial CCS

Overview of the Global Industrial Sub-sector

The industrial sub-sector is highly energy intensive, accounting for 40% of total energy utilisation (Worrell, 2008) and emitted over 8 Gt CO_2 in 2010 (IEA, 2012a). Within the industrial sub-sector, the emission-intensive industries such as iron and steel generated up to 31% of emissions, cement production 27%, petroleum refining 10% and high-purity sources (such as ammonia manufacture) 7%. Other sub-sectors produced the remaining 25% of total industry and fuel transformation emissions (IEA; UNIDO, 2011).

In the UK, the industrial sub-sector alone was responsible for 186 million tonnes of CO_2 equivalent ($MtCO_2e$) out of 549 $MtCO_2e$ total emissions in 2011, contributing to approximately a third of total greenhouse gas (GHG) emissions. Of this, CO_2 makes up about 80%, comprising both direct and indirect sources (Committee on Climate Change (CCC), 2012). Direct sources from the combustion of fossil fuels and chemical processes gave rise to 71% of these emissions, with the remaining 29% contributed by indirect, i.e. electricity-related sources, as shown in Figure 0 (Committee on Climate Change (CCC), 2012).

Energy intensive industries such as cement, iron and steel, chemicals, paper, and ceramics production are responsible for 45% of direct carbon emissions from the UK's industrial sub-sector (Houses of Parliament, 2012).

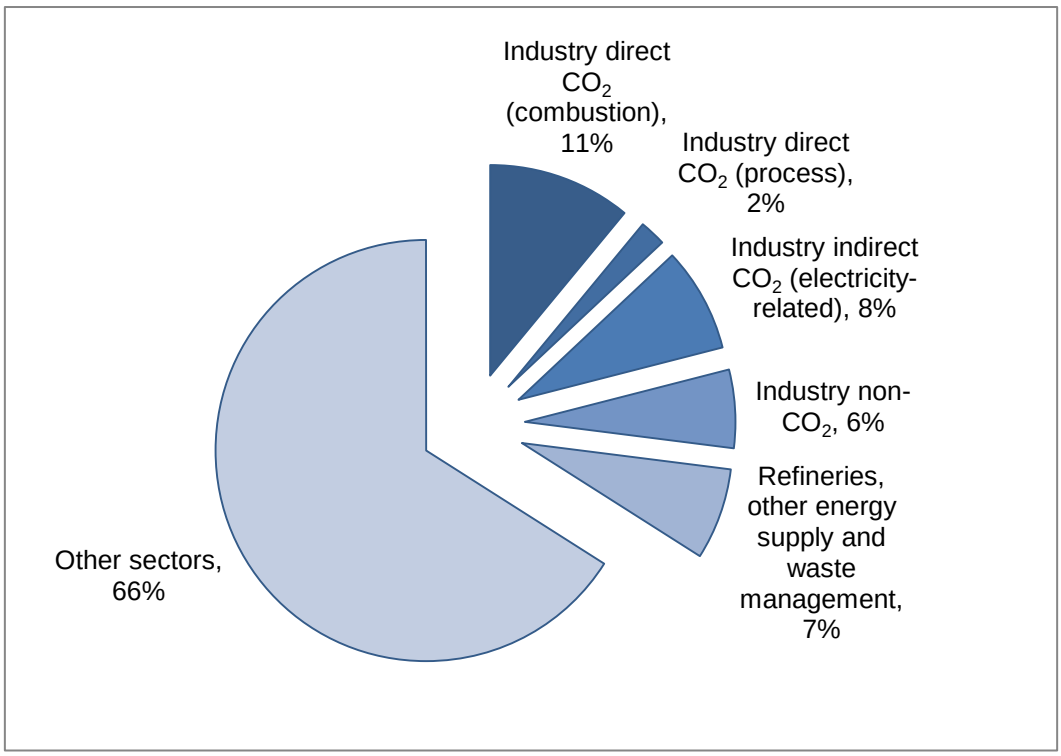

Figure 2: Breakdown of the industrial sub-sector's contribution to UK's total GHG emissions. Total emissions: 549 Mt CO_2e (Committee on Climate Change (CCC), 2012)

Mitigating emissions from the industrial sub-sector is thus of paramount importance, serving as a potential enabler for the UK to meet its target of reducing emissions by 20% in 2020 and 80% in 2050 (Dagoumas & Barker, 2010).

Overview of CCS in the Global Context

Globally, a number of initiatives have been started to accelerate global deployment of CCS. The Asia-Pacific Partnership on Clean Development and Climate (APP) has paved the way for knowledge-support schemes, and Canada is collaborating with the US in developing a similar framework. The Global CCS Institute's main objective is to promote the success of CCS through knowledge-sharing activities across national boundaries (Global CCS Institute, 2013b). The European Commission (EC) has initiated a Project Network to enable sharing of information acquired from CCS demonstrations from Member States in the European Union. With regard to legislation, the EC has also put in place the Directive on Geological Storage of Carbon Dioxide[2] (also commonly known as the CCS Directive), with the goal of ensuring safe carbon capture and storage practices in the EU, in line with the EU's emission reduction goals and climate change mitigation beyond 2020 (Lipponen, Burnard, Beck, Gale, & Pegler, 2011). As of November 2013, the Directive has been transposed in all but six Member States (European Commission, 2013a).

However, there has been limited progress with regards to actual CCS deployment, especially within Europe. According to the Global CCS Institute there are only twelve projects in operation worldwide capturing over 25 million tonnes of CO_2 per year. Three of these twelve are CCS projects, while the remaining nine are Enhanced Oil Recovery (EOR) initiatives without full monitoring systems to assess long-term carbon storage feasibility, see Figure 3. Two of these are in Norway and the others are outside Europe. There are eight projects currently in the 'execute' phase (i.e. detailed design, construction or commissioning), of which none are in Europe. Of the sixteen projects in the 'define' stage (i.e. sufficient detail is being developed to allow a final investment decision), five are in Europe, including one in the UK (Global CCS Institute, 2013). For comparison with other countries, see Table 2.

[2] Directive 2009/31/EC.

Table 2: The state of global CCS projects

Country	Projects in:		
	'Operate' phase	'Execute' phase	'Define' phase
Europe *(of which UK)*	2 *(0)*	0 *(0)*	5 *(1)*
USA	7	2	6
Canada	1	4	1
Australia	0	1	0
China	0	0	3
Other	2	1	1
Total	**12**	**8**	**16**

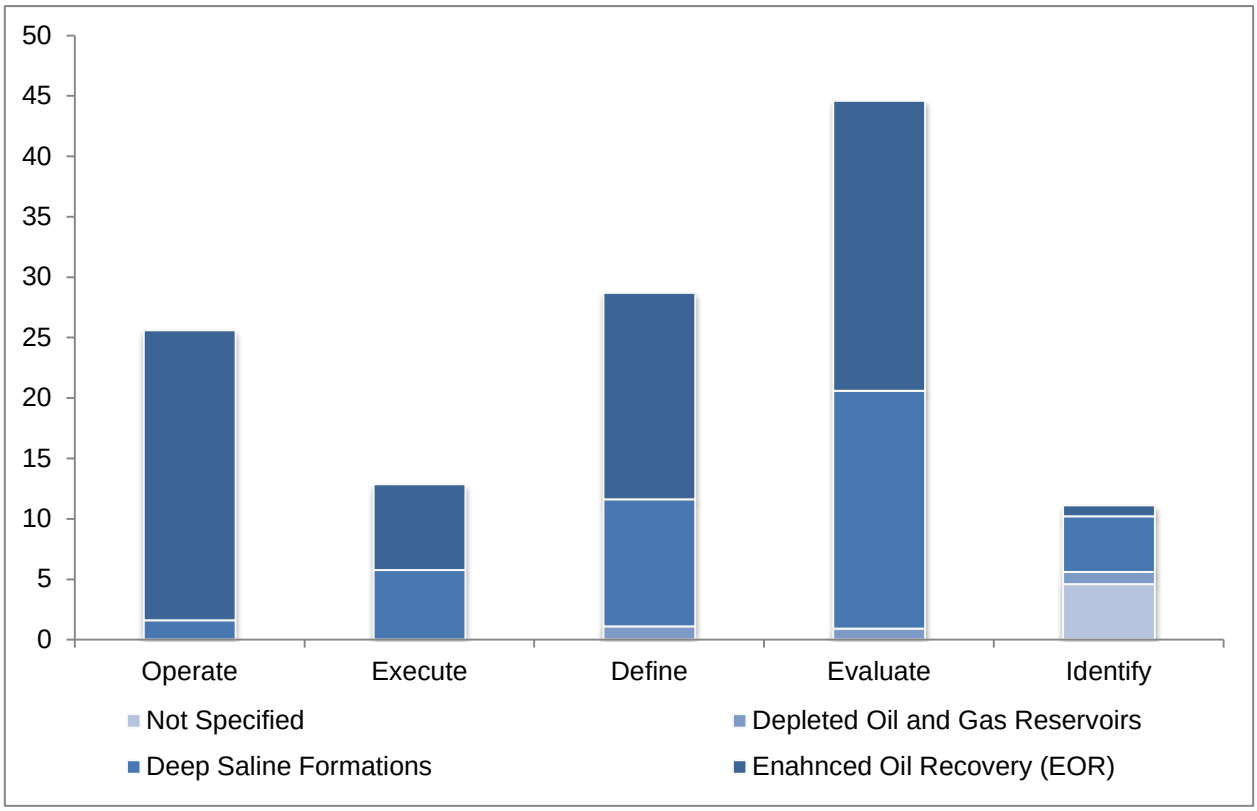

Figure 3: CO_2 capture and storage capacity by capture project lifecycle stage (Global CCS Institute, 2013)

There have been several cancellations of projects recently. At the time of going to press, the latest cancellation was that of full-scale carbon capture at the Mongstad refinery's power plant in Norway. Projects in Germany, Italy and Poland have also been cancelled (European Commission, 2013b). Between the publications of the GCCSI lists in 2012 and 2013, thirteen projects were removed (not including Mongstad) and only three were added. This is all in contrast to G8 countries' commitment to launch twenty CCS demonstration projects by 2010 with extensive deployment by 2020 (MOFA, 2010). In 2009 over $30bn of funding for CCS was available across various governments, but in 2013 this amount had dropped to $12.4bn, of which $7bn has already been allocated (Global CCS

Institute, 2013), see Figure 4. The IEA reports different amounts, with about $14bn of public money spent or committed on CCS R&D, construction and operation (IEA, 2013a).

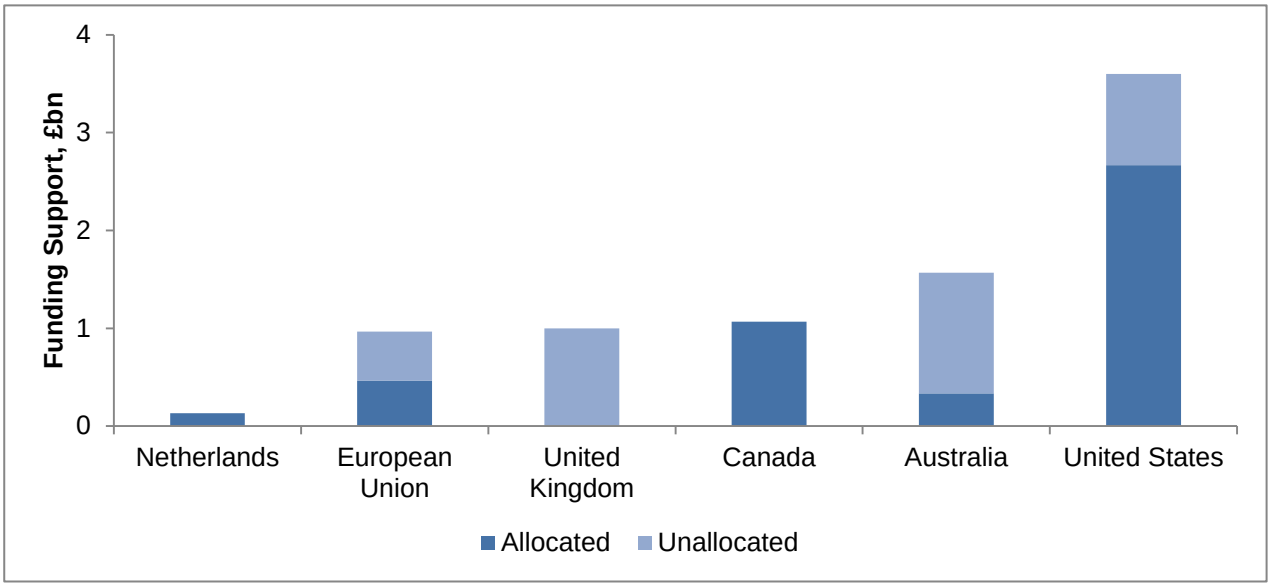

Figure 4: Public funding for CCS projects (Global CCS Institute, 2013)

About 45% of captured CO_2 is expected to come from industry in 2050 (IEA 2012a), but a disproportionately greater amount of research is centred on CCS for power generation (30 identified projects) compared with industry (13 projects). It was recognised at the Clean Energy Ministerial meeting in Abu Dhabi in April 2011 that this disparity would have to be corrected (IEA; UNIDO, 2011).

Current Global Efforts

UK

Energy Policies and Incentives Applicable to Industry

Presently, several policies applicable to the industry have been put in place in the UK. These initiatives will have a direct and indirect impact on industrial CCS, and will be examined in this section.

1. Climate Change Levy (CCL) and Climate Change Agreements (CCAs)

The CCL is a tax imposed on the commercial sector, including the industry, for taxable energy commodities i.e. electricity, gas and fuels, used to generate power, heating, and lighting. It serves to promote the use of renewable energy and reduce the energy consumed commercially (UK Government, 2013a).

To protect energy intensive industries from prohibitively high costs, which could result in a loss of competitiveness, they are subjected to reduced CCL through CCAs, enabling claims of up to 65% of CCL if emissions mitigation or energy efficiency targets were met (DECC, 2013a).

2. Renewable Heat Incentives (RHI)

Launched in November 2011, the RHI is the first long-term incentive promoting use of heat from renewable sources, by providing payments to subscribed industrial consumers using renewable energy (e.g. biomass, geothermal, heat pumps and solar thermal) instead of fossil fuels to produce heat. This contributes to emission reduction targets by reducing CO_2 emissions arising from the burning of fossil fuels (DECC, 2013b).

3. EU Emissions Trading System (EU ETS)

Implemented in 2005, the EU ETS is a mandatory carbon trading system covering 45% of total emissions from all EU Member States which aims to mitigate emissions through “cap-and-trade”. A limit on the total permissible emissions is set, and allowances to emit are either allocated to, or purchased by, organisations in sub-sectors covered by the cap. These allowances are then traded, creating a carbon price, which incentivises low carbon production (Parliamentary Office of Science and Technology, 2010).

Presently, commercial power generation and emission intensive industries with large point source stationary emitters, such as cement production and iron and steel works, are included in the scheme. These emitters have to measure and report their emissions, and surrender an equivalent number of allowances at the end of each trading year (Houses of Parliament, 2012).

In Phase 1, the limits set by EU MS have exceeded their verified emissions in the first phase of EU ETS, with a significant majority of emission permits being given for free, leading to a collapse in the carbon price. Even though limits have been tightened in the second phase, the carbon price has remained low, due to reduced emission arising from the onset of global recession in 2008. This has reduced its effectiveness in promoting adoption of emission reduction technologies (Parliamentary Office of Science and Technology, 2010). In an attempt to deal with structural problems within the ETS, the Commission has postponed the auctioning of some allowances and has also put forward a legislative proposal to establish a market stability reserve at the beginning of the next trading period in 2021 (European Commission 2014).

4. Carbon Price Floor (CPF)

The CPF was imposed from 1 Apr 2013 through a tax levied on fossil fuels used for electricity generation, as they have mostly been exempted from the CCL to date (HM Treasury, 2011). It aims to incentivise investments in lower carbon electricity generation by providing greater carbon

price certainty. Launched at around £16/tonne CO_2 equivalent, the CPF is designed to attract low carbon investment into the UK by increasing the cost of pollution and enhancing the rewards of reducing emissions (Sandbag, 2013). Through the CPF, the UK Government will remove these exemptions and tax fossil fuels at rates based upon average carbon contents (DECC, 2012a).

5. Contracts for Difference (CfD)

As a part of the UK's Electricity Market Reform (EMR), CfD was introduced as a mechanism to enhance investment security and certainty, delivering a secure low-carbon electricity system. CfD applies mainly to power generation CCS, and is an official long-term, private agreement paying the generator the difference between the estimated electricity market price ('reference price') and the projected long-term price essential for facilitating investment in a particular technology ('strike price') (DECC, 2013c).

With CfD, low-carbon generators will continue to participate actively in the sale of electricity to the wholesale market, with reduced long-term exposure to risks in electricity price fluctuations. This considerably eases projects' business-related risks, promoting investments in low-carbon generation while ensuring minimal cost to consumers (DECC, 2012a).

Current Efforts Supporting CCS in the UK

Economically, the UK Government has been supportive towards CCS development. In December 2010, a £1 billion CCS Commercialisation Competition supporting the first commercial scale CCS demonstration project was re-launched by the Department of Energy and Climate Change (DECC). It is intended to promote innovation in the design and operation of large-scale plants, driving down the costs of implementing CCS and encouraging industry to develop suitable CCS business models. Proposals were accepted between April and July 2012, and projects will be implemented after 2014 with the target of being operational between 2016 and 2020 (DECC, 2010).

Apart from the competition, government funding has been provided to support CCS RD&D as well as the £20 million three-year Cleaner Fossil Fuels programme. The UK Government is continuing to collaborate with industry to make CCS cost-competitive by the 2020s, supporting CCS innovation and RD&D through a co-ordinated £125 million four-year programme from 2011 to 2015. Funded by DECC, the Energy Technologies Institute (ETI), the Technology Strategy Board (TSB), and Research Councils, about a hundred projects have been supported through this programme (DECC, 2012b).

Other Countries

Current Efforts and Initiatives

A number of projects supporting CCS are currently underway in the US and Canada, most of which involve EOR. Of the eight operating carbon capture facilities in North America, all send their CO_2 for EOR. Three of these are industrial plants: Enid Fertilizer CO_2-EOR Project (0.7 $MtCO_2$/y), Air Products Steam Methane Reformer EOR Project (1 $MtCO_2$/y) and Coffeyville Gasification Plant (1 $MtCO_2$/y). These are smaller than typical natural gas processing capture capacities. Four North American industry CCS projects are being built at the moment. Two of these are expected to use the CO_2 for EOR and two will store the CO_2 in onshore deep saline formations.

In Canada, the Alberta provincial government has invested approximately $1.3 billion in CCS development over 15 years to fund two large-scale CCS projects – the Alberta Carbon Trunk Line and Shell Quest (Alberta Energy, 2013). The Alberta Carbon Trunk Line is a 240km pipeline transporting CO_2 from a fertilizer plant and an oil sands bitumen refinery in Alberta's industrial heartland to oil fields in central Alberta. The Shell-led Quest project is the first commercial-scale fully-integrated CCS project capturing, transporting, injecting and storing CO_2, to tackle emissions from oil sands extraction. It aims to capture and store up to 1.2 million tonnes of CO_2 per year.

In other parts of the world, two of the most established CCS facilities are Sleipner, off the West Coast of Norway, and In Salah, in Algeria. Both projects inject CO_2 into a saline aquifer in a rock formation. The Sleipner project was developed in response to a sovereign tax placed upon offshore emissions of CO_2. While the In Salah project was intended as a 'learning-by-doing' project, where the companies involved gain experience in CO_2 injection into saline aquifers, operation had been suspended in November 2012, pending a business decision on whether to continue with commercial operation of the storage program. Norway has operated another capture and storage plant at Snøhvit, in the Barents Sea, since 2008. Brazil completed an EOR project in the Lula oil field in the Santos Basin in 2013, capturing and injecting 0.7Mt CO_2/y.

There are no industrial CCS projects outside North America in the construction phase, with only two natural gas processing projects, Uthmaniyah CO_2-EOR Demonstration Project in Saudi Arabia (0.8 $MtCO_2$/y) and the Gorgon Carbon Dioxide Injection Project (3.4-4.1 $MtCO_2$/y) in Australia, currently being built. However two industrial CCS projects are expected to come online in 2015: the ESI CCS Project in Abu Dhabi, UAE capturing 0.8 $MtCO_2$/y from a Direct Reduced Iron plant, and the Sinopec Shengli Dongying CCS Project in Shandong, China capturing 0.5 $MtCO_2$/y from a chemical plant (Global CCS Institute, 2013).

Challenges of Implementing Industrial CCS

Fundamental implementation challenges suggested by the literature included technological issues, market frameworks, carbon leakage and competitiveness, discussed as follows.

Technological Issues of Integrating CCS with Industry

Due to uncertainties in future regulatory frameworks, carbon prices, and development of CCS technologies, there is a lack of clarity of when widespread adoption of industrial CCS will be viable (Markusson & Haszeldine, 2008) (Boot-Handford, M. E. et al, 2014). Being a relatively nascent technology, there is potential for significant technological improvements to be made to CCS in the near future, and should the technology take off rapidly in the industry, there might be risks of 'locking-in' of existing technologies in plants. For example, an integrated steel mill built with current Best Available Technology could not be easily converted to a low-CO_2 production process, such as the Hisarna process (Ulcos, 2013). While power plants could ensure capture readiness – i.e. ensuring that plants initially not having CCS capability can subsequently be retrofitted with CCS technologies at minimal cost – if they are only capture ready for a single existing system, plants might also be locked-in to an obsolete technology in the long run, making their investments much less valuable (IEA Greenhouse Gas R&D Programme (IEA GHG), 2007). Furthermore, industrial supply and value chains can be more complex than power systems, and are therefore less amenable to a simple classification of "capture readiness".

Hence, as Florin and Fennell (2010) noted, comprehensive CCS demonstration and deployment for commercial scale testing and ironing out of issues prior to projected global rollout post-2020 is essential to mitigate the risks of potential lock-in to earlier CCS systems which might be superseded, especially considering CCS' high capital intensity.

Incentives and Market Frameworks Promoting Cost Effective CCS Deployment

Presently, the EU ETS carbon price is too low to incentivise investment in CCS (IEA, 2013a) (IEA, 2013b), and no other effective EU-wide long-term incentives rewarding carbon storage or penalising emissions are in place across much of the EU.

Overall, as suggested by Lipponen et al. (2011), it is essential to strengthen short-term regulatory frameworks and comprehensive schemes to promote CCS demonstration and commercial-scale deployment respectively. A carbon price rising to 35-40 $€_{2010}$/t CO_2 by 2030 should sufficiently incentivise CCS deployment within the power sector, as long as demonstration projects are up and running before 2020. However, this is not expected to be enough on its own to produce demonstration plants (ZEP, 2013). The same can be said of industrial sectors, where the cost of CCS may be even higher and relocation of economic activity is possible (IEA 2013b).

Carbon Leakage and Competitiveness of Industry

As a result of increased costs (either perceived or actual) brought about by countries' emissions policies, industries may choose to relocate to other countries without such frameworks in order to avoid additional costs of operation, resulting in a rise in carbon emissions in other parts of the world, a phenomenon known as carbon leakage (Parliamentary Office of Science and Technology, 2010).

Globally, carbon leakage arising from the relocation of industries to foreign jurisdictions to avoid penalties for carbon emissions is a key impediment to countries' low-carbon transition, where efforts in carbon mitigation in a country are counterbalanced by increases in others (Reinaud, 2009). By implementing CCS in industry, the increase in cost would alter the competition dynamics between emission-intensive sub-sectors incorporating CCS and their non-constrained competitors in other parts of the world. The higher cost of operation arising from constraints of stringent emission targets would also drive relocation of these industries, especially for the emission-intensive and internationally trade-exposed operations (i.e. that have a high trade intensity) producing fungible products – aluminium, cement, pulp and paper, iron and steel, chemicals and refineries. This has imposed a barrier in adopting industrial CCS.

The challenge of producing competitive products from facilities with CCS is different for each industry; the cost of capturing CO_2 can be 2-100% of the market price of the product. Furthermore, industries are faced with different reasons for lack of competitiveness. This will require different regulatory approaches and incentives for each industry, especially early on. A carbon price is seen as sufficient for the uptake of CCS in less trade-exposed industries, but other policies such as border carbon adjustments can reduce or remove the threat of carbon leakage from industries with high international trade intensity (IEA, 2013b) (Cosbey et al, 2012).

Methodology

A global survey was designed, outlined in Figure 5. Participants from a wide range of backgrounds were identified. The target participants were representatives from both the LPS and non-industrial sectors, summarised by the five sub-sectors of power generation, industry, academia, government and financing, and other non-industrial organisations ('other' sub-sector).

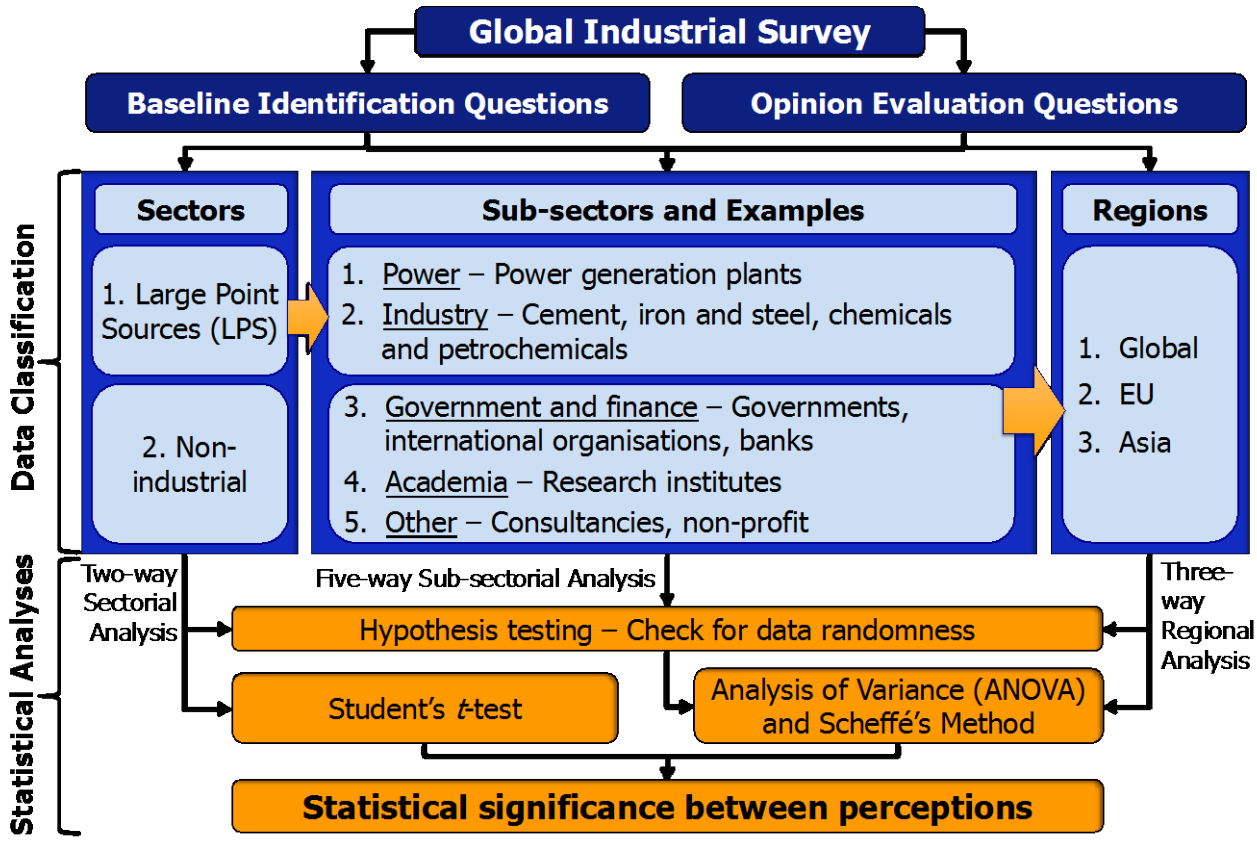

Figure 5: Global industrial survey methodology

Survey Methodology

Questionnaire Design

The questionnaire was designed to enable quantitative and qualitative analysis of responses. This allowed comparison of sub-sectors' perceptions through statistical analysis, while allowing qualitative expression of additional views on areas of concern, analysed separately. Respondents rated options on a Likert scale of 1-10, 1 being strongly disagree and 10 being strongly agree, coupled with open-ended questions allowing participants to elaborate on their choices.

The survey questions were designed to identify baselines and evaluate opinions. Baseline identification questions provided insight on current status and existing perceptions, allowing for comparison of various sub-sectors' responses. These included questions identifying the sectoral

classification of participants, their awareness of climate change and issues, as well as existing carbon reduction efforts and status of CCS adoption in their organisations. Views on present efforts in policies, incentives and knowledge sharing platforms facilitating industrial CCS adoption were also established.

Thereafter, questions enabling evaluation of participants' opinions on a broad range of issues pertaining to CCS were also included. Questions elicited views on respondents' perceived barriers and risks of implementing CCS across their respective sub-sectors, as well as potential enhancements of policies and future efforts needed to promote CCS uptake in the industry.

Targeted Sectors and Sub-sectors for Data Collection

Within the industrial sub-sector, participants included representatives from the iron and steel industry, cement manufacturing, chemicals, refineries, industrial equipment manufacturing and supply chain industry. Academic participants comprised primarily of researchers either in institutes of higher learning (IHLs), or national research entities, and other non-industrial organisations surveyed ('other' sub-sector) consisted of consultancies in the energy field as well as non-profit organisations.

As CCS for power generation faces similar issues as that on industrial processes, the power generation and industry sub-sectors have been grouped together under the LPS sector, for two-way analysis between LPS and non-industrial respondents. As the project also aimed to identify the challenges and opportunities on a global scale, participants included representatives from operations spanning different regions, such as the EU, UK, Asia, US and Africa, to ensure that the research conducted was representative of global views.

Based on these considerations, 150 participants were shortlisted as prospective respondents for the survey, and a total of 98 responses were obtained, rendering a response rate of 65%. From the 98 responses received, incomplete entries were removed, giving an overall response count of 87. The classification and number of responses in each category is summarised in Table 3 as follows.

Table 3: Classification of respondents with the number of respondents in each classification shown in parentheses

Research Platform	Primary Sector	Secondary Sub-sector	Description
Survey	LPS (34)	Power generation (16)	Representatives from the global power generation sub-sector
		Industry (18)	Representatives from iron and steel, cement, chemicals, refineries, industrial equipment manufacturing and supply chain industries
	Non-industrial (53)	Other (10)	Energy consultancies and non-profit organisations
		Academia (25)	Researchers in institutes of higher learning (IHLs), or national research entities
		Government and finance (18)	Government and financial sub-sector representatives from different countries
Structured Interviews	LPS (2)	Power generation (1)	Senior management level power sub-sector representative
		Industry (1)	Senior management level chemical industry representative
	Non-industrial (2)	Academia (1)	Management level representative from national research entity
		Government and finance (1)	Senior management level financial sub-sector representative

Structured interviews through industrial engagement

Structured interviews were conducted on participants of the 7th Trondheim CCS (TCCS) Conference and present implementers of CCS initiatives. These interviews followed a similar line of questioning to that in the questionnaire, although options (such as *uncertainty in payback, loss or deviation in throughput arising from implementing CCS* and *stakeholder acceptance* with reference to question 15) were not provided, allowing the incorporation of a wider range of topics and the identification of any issues or growing trends yet to be observed.

Statistical Analysis of Questionnaire Results

The data was rigorously processed through a three-step analysis, summarised in Table 4. Firstly, hypothesis testing was carried out to validate statistical significance of differences to the expected value. It was assumed that random data has a mean of 5.5 and a normal distribution. Thereafter, the data was split into two sub-groups – LPS and non-industrial sector, and Student *t*-tests were conducted between the sub-groups to determine if there were significant differences in perceptions between the groups. The data was also split by three regions – global, Asia and Europe, and five industrial sub-sectors – power generation, industry, academia, government and financing, and

other non-industrial types ('other' sub-sector), and processed through the Analysis of Variance (ANOVA) using Scheffé's Method to determine statistical significance in perceptions.

Table 4: Summary of data processing methodology

Step	Test	Data Processed	Purpose of Test	Null Hypothesis
1	Hypothesis testing	All data	Check for randomness	H_0 = The data is random
2	*t*-test	Two-way split (i.e. LPS and non-industrial sector)	Determine statistical significance in perceptions between both groups	H_0 = The distributions of the two groups are the same
3	ANOVA and Scheffé's Method	Three-way regional split Five-way sub-sector split	Determine statistical significance in perceptions across all groups	H_0 = The distributions of the groups are the same

Summary of survey results

Key Observations

The main observations of results obtained from the survey are presented and discussed in this section. Of the randomness tests undertaken, 59% were found not to be normally distributed with a mean of 5.5, to 1% significance, 74% to 5% significance, 81% to 10% significance and 86% to 20% significance. Note that while not all results were found to be significant, this did not imply that respondents entered random numbers for the insignificant response sets; instead, it could indicate that a sample of answers had a normal distribution around a mean of 5.5. The fact that a high proportion of answers were not random at 1% and 5% significance levels suggested that the respondents did not enter random values, and it would be relatively safe to assume that this was true for all questions.

Current State of CCS Deployment

All of the organisations surveyed considered themselves to be moderately active in reducing their carbon dioxide emissions, and the LPS and non-industrial sector alike were relatively familiar with the concepts of climate change, renewable energy technologies, and CCS, indicating scores higher than the "random" average of 5.5. All sub-sectors were similarly very familiar with these concepts, and most sub-sectors were also considering implementing CCS to some extent. Organisations based in the EU were actively engaged in reducing their carbon dioxide emissions, in line with current trends in the global landscape of CCS deployment. **EU and global operations were significantly more familiar with CCS than their Asian counterparts, at 5% significance.**

Effectiveness of Current Policies in Facilitating Adoption of Industrial CCS

To examine baseline perceptions on the adequacy of current government policies in incentivising industrial CCS uptake, a number of policies were surveyed, including: the Climate Change Levy (CCL), Climate Change Agreements (CCA), Carbon Price Floor (CPF), Renewable Heat Incentive (RHI), EU Emissions Trading System (ETS), and Contracts for Difference (CfD). Responses based on the three data groups are summarised in Table 7 in the Appendix.

Both the LPS and non-industrial sectors considered that current government policies such as CCL, CCA, CPF, RHI, EU ETS, and CfD were inadequate in incentivising industrial CCS uptake. As expected, the non-industrial sector rated CfD as less adequate compared to the rating given by the LPS by 1.28 points at 10% significance, since CfD applied mainly to the power sub-sector, within the LPS. Similarly, across the five sub-sectors, policies were mostly given below-average scores, ranging from 3.29 to 5.56 at 5% significance.

However, the CCL was viewed as more effective by EU-based organisations than those in other regions, by 1.80 points at 5% significance.

The scores for all parts of question 7 were amalgamated to provide a clearer insight of the impressions of the different groups towards low-carbon policy in general. The LPS was slightly more positive about these policies than non-industrial sector (0.37 points, 20% significance), and the most significant differences were observed between geographical regions. **EU-based operations were more positive about the policies than those based in other regions (0.93 points, 1% significance). Organisations with global operations were less positive about the policies than those elsewhere (0.72 points, 1% significance).** Perceptions of Asian-based entities fell in between, though more similar to the global organisations' views than the EU ones'. Academia was more positive than government and finance (0.84 points, 20% significance).

Adequacy of Present Incentives and Knowledge Sharing Platforms in Promoting Uptake of CCS

To summarise, both the LPS and non-industrial groups perceived present incentives and knowledge sharing platforms to be barely adequate, and it was evident that the LPS regarded *government funding for CCS deployment* to be inadequate, as summarised in Table 8. Further analysis through ANOVA showed that **the 'other' sub-sector** (comprising primarily of representatives from energy consultancies and non-profit organisations) **found *government funding* for CCS deployment to be 2.62 points less adequate than all remaining sub-sectors, at 2.50 and 20% significance,** and rated it 1.95 points below the industry sub-sector did, although more data is needed to determine statistical significance. The industry sub-sector regarded current *knowledge sharing platforms* to be more adequate than the remaining sub-sectors did.

Barriers of Implementing CCS

Potential barriers listed in the questionnaire included *complex industrial processes*, *high capital cost of installing CCS*, *high operating cost of CCS*, *technology lock-in*, *stakeholder perception*, *profit reduction*, *economics of CCS*, *absence of long-term policy frameworks*, *and lack of nearby storage sites*. Overall, these barriers were rated higher than the theoretical average score of 5.5, suggesting that they were generally of concern to the various surveyed sectors.

The LPS sector gave higher-than-average ratings to these barriers, as summarised in Table 9. Although the ratings generally appeared to be higher than those given by the non-industrial sector, they were subsequently verified using *t*-tests to determine statistical significance, and only ***economics of CCS* was perceived by the LPS to be significantly greater a barrier than the non-industrial sector, by 0.9 points at 5% significance. Academia considered *economics of CCS* to be less of a barrier than the remaining sub-sectors, by 1.19 points at 5%**

significance.

Amongst all 5 sub-groups, the industry sub-sector gave the highest ratings of any sub-sector in 7 out of 9 cases, and was ranked 2nd in the remaining 2 instances. More responses would be necessary to indicate whether each individual response was significant. However, overall, this indicated that the industry sub-sector considered implementation to be more of a difficult challenge than the power and government sub-sectors did.

Between regions, global operations and organisations based in Asia generally gave higher ratings to the barriers than their counterparts in the EU, as shown in Table 9. ***Complex industrial processes*** **and** ***technology lock-in*** **were perceived to be more of a barrier by respondents from Asian operations than EU ones at 5% significance, at 1.94 and 1.43 points respectively.**

Amalgamation of all scores for question 12 provided clarity on each group's perception of how large the barriers to CCS implementation were. **The LPS perceived barriers as slightly more inhibitive than the non-industrial sector did, by 0.39 points at 5% significance,** although the greatest disparity was observed between the industry and all remaining sub-sectors.

The industry sub-sector regarded the barriers to CCS implementation as being 0.91 points higher than remaining sub-sectors did, at 8.09 points and 1% significance, rating on average 0.93, 0.90 and 1.00 points above the power, academia and government and finance sub-sectors (all at 5% significance).

The EU generally regarded the barriers as being less inhibitive, rating an average score 0.57 points below other regions (at 6.99 points, 1% significance). Asia perceived them as being higher than all other regions, by 0.42 points (5%), and rated 0.60 points above the EU (5%).

An alternative measure of the barrier to CCS uptake that economics played was analysed, incorporating the answers for question 12b, c, f, g and 15a. This found several similar correlations to those for question 12g alone (the original economic barrier question). The industry sub-sector rated 0.81 points above academia (20%), compared to 1.51 points above (20%) for the original question. Other similarities included the fact that LPS rated *economics of CCS* higher than the non-industrial sector did (by 0.27 at 20% in the new measure, compared to 0.90 at 5% in 12g alone). This suggested that whilst the amalgam showed similar trends, the contrasts were not as certain or as large.

The means of each data group are summarised in Table 9 in the appendix, where each barrier is discussed further.

Perceived Risks of Implementing CCS in the Industry

With regards to perceived risks of implementing CCS, *uncertainty in payback* was perceived to be the greatest surveyed risk. Across all sub-sectors and regions, it was given the highest rating among the three potential risks listed in the survey.

The *risk of stakeholder acceptance* was rated second highest across the sectors, sub-sectors and regions, and the *risk of throughput loss* arising from CCS implementation was rated lowest amongst the risks.

Interestingly, the LPS was significantly less concerned about the loss of throughput arising from implementing CCS than the non-industrial sector, as shown in Table 10. This could indicate that the LPS had potentially greater confidence than the non-industrial sector did, with regards to CCS having a minimal impact on unexpected downtime or losses when installed on a plant.

However, within the regions, it was observed that **organisations with a global presence gave a significantly lower rating to the *risk of loss in throughput arising from CCS* – 5.83 compared to 7.38 and 7.20 for the EU and Asia, respectively. This was significant at 5%.**

Future Efforts Needed to Promote Industrial CCS Uptake

The future efforts needed to promote industrial CCS uptake were examined from two aspects: potential policies and mechanisms promoting the adoption of CCS, and broader efforts including tangible aspects such as infrastructural improvements and intangible aspects of improving skills and best practices.

1. Policies and Mechanisms Promoting Adoption of CCS

Perhaps unsurprisingly, economics-related initiatives such as *monetary incentives*, *increase in capital funding*, and *technology cost reduction*, were rated as the top three most effective mechanisms by both the LPS and non-industrial sectors. In general, economics-related mechanisms were highly rated across all the five sub-sectors, with most scores greater than 7.20, as shown in Table 11.

When asked if ***doubling of the CPF*** (i.e. from £16/tonne to £32/tonne) would significantly promote adoption of CCS, **respondents from the non-industrial sector rated this to be significantly more effective than the LPS did, by 1.8 points at 5%** (refer to Table 11) Analysis at sub-sectoral level highlighted that the viewpoint was strongly shared by the industry sub-sector, which rated it 2.10 points lower than remaining sub-sectors did at 10% significance.

Organisations operating in the EU region also regarded *monetary incentives* as the most effective means of promoting CCS adoption, followed by the *increase in capital funding for CCS installations*. However, care was taken in the interpretation of these questions, cognisant of the

potential for respondents to answer with the measures that they would prefer, rather than those most likely to improve deployment of CCS in reality.

The industry sub-sector found increased carbon pricing, through the CPF or EU ETS, to be less effective than the power sub-sector did. However, they were more confident than the power sub-sector that exempting organisations with CCS from CCLs would improve uptake of CCS.

The government and finance sub-sector's perception of the amount of *improvement in regulatory framework* required was 1.24 points lower than that of remaining sub-sectors (20% significance).

Asian organisations' perceptions of the amount of *improvement in regulatory framework* required were 0.89 points below that of the other regions' (20% significance).

EU-based organisations more strongly perceived that *exemption from the CCL* would promote industrial CCS than companies with global operations did, by 1.79 points at 5% significance.

Examining potential government policies amendments as a whole, by bringing together the scores for each part of the question together, highlighted several differences in opinion. **The 'other' sub-sector** (comprising mainly consultancies and non-profit organisations) **was 1.88 points more positive about these changes than remaining participants, at 1% significance. The government and finance and power sub-sectors were both 2.23 points below 'other' at 1% significance.** This suggested that the other sub-sector had a greater belief in the effect of policy on the uptake of CCS, especially when compared to the power generation, and government and finance sub-sectors.

Furthermore, **EU organisations rated 1.46 points above global organisations, and 0.81 points above all participants, at 1% significance. Global organisations rated 1.23 points below all participants, also at 1% significance.** This suggested that EU organisations had greater confidence that policy changes would positively affect CCS uptake. Asian operations' opinions on policy changes were more similar to EU than global organisations.

Amalgamating question 10b, c and f gave an indication of the effect of directly reducing the cost of CCS to the company. In this case, **Asian-based organisations scored 0.76 points below global operations (5%) and 0.83 points below EU (5%).**

2. Other Efforts Required to Promote Future CCS Uptake

With regards to the broader efforts of promoting CCS uptake, outlined in Table 12, *improvements in regulatory frameworks*, followed by the *development of transport and storage infrastructure* and *additional synergies in utilising captured carbon dioxide to improve CCS economics* were generally

the top rated choices across the sectors, sub-sectors and regions. The industry sub-sector generally perceived efforts required to be greater than the power sub-sector did, particularly regarding *improving skills and supply chain* and a*dditional synergies for utilising captured CO_2 to improve economics*. **The government and finance sub-sector rated *additional synergies for utilising captured CO_2 to improve economics* as 1.32 points less important than the remaining sub-sectors did, at 20% significance.** This may reflect greater realism amongst the government and finance sub-sector than any other sub-sectors.

Key Lessons from Survey Findings

In this section, key themes arising from results will be presented and discussed.

Lesson 1: Organisations are looking to implement CCS in the medium- to long-term, and are already engaged in carbon dioxide emissions reduction

By comparing the results for questions 4 and 6 (active involvement in R&D programmes for CCS and projected timescales for implementing CCS) it can be seen that most organisations researching the technology expect to implement it in over five years' time, as shown in Table 5.

Table 5: Correlation of organisations' involvement in CCS R&D with projected timescale of implementing CCS

Q4. Is your company actively involved in any R&D programmes for CCS?		Q6. On what timescale is your organisation considering implementing CCS?	
Yes	39	Short-term, i.e. 1-5 years (%)	26.7
		Medium-term, i.e. 6-10 years (%)	40.0
		Long-term, i.e. >10 years (%)	33.3
No	13		
N/A	3		

While 69% of these organisations, which includes chemicals, refineries, power generation, research and consultancies, are presently involved in CCS R&D, out of these efforts, only 26.7% are looking at implementing CCS in the short term, i.e. within 1-5 years' time.

Lesson 2: There are three primary barriers of industrial CCS, similar to those shown in existing literature

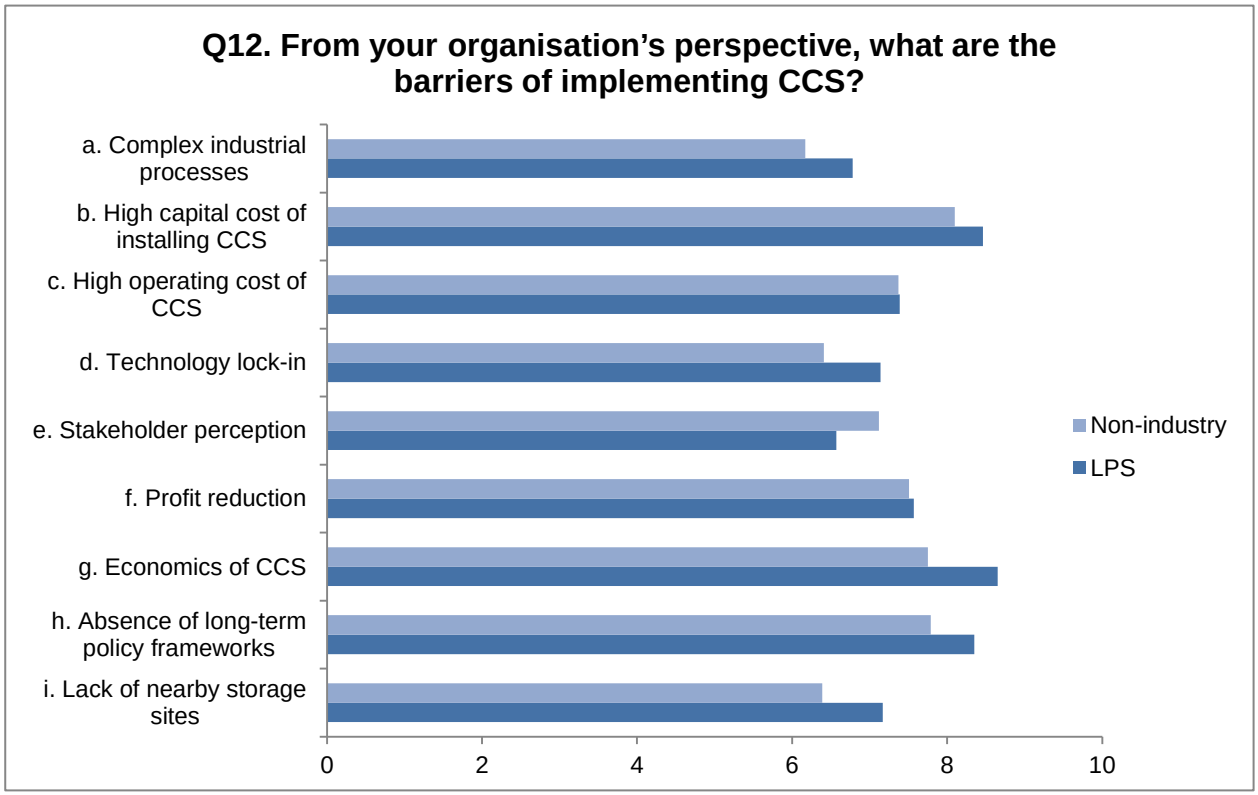

Figure 6: Barriers of implementing industrial CCS

The top-rated barriers of implementing CCS in industry were the *economics of implementing CCS*, *high capital cost of installation* and *absence of long-term policy frameworks*, in line with findings from the literature review. In contrast, technical-related barriers such as *complex industrial processes* were given lower ratings compared to other potential factors, as shown in Figure 6.

On the whole, the industry sub-sector found these barriers to be much higher than all other sub-sectors did (0.91 points at 1% significance), perhaps suggesting its more pessimistic outlook on the chances of CCS becoming a success than all remaining sub-sectors.

Economics of CCS was perceived to be the most significant barrier, more so by the LPS than non-industrial sector at 5% significance

As outlined in Section 0 and summarised in Table 11, *economics of implementing CCS* was perceived by the LPS as a whole to be a greater barrier against CCS adoption than by the non-industrial sector at 5% significance, with average ratings of 8.65 and 7.75 given by the LPS and non-industrial groups respectively. The difference in perceptions towards the issue of economics may highlight potential gaps in existing mechanisms supporting industrial CCS.

Not surprisingly, industrial organisations rated most ways of improving the economics of CCS

implementation highly, such as *increasing capital funding supporting CCS installation* (see Table 11). This was in line with the perception that *economics of implementing CCS* is one of the greatest barriers against its deployment with its high upfront capital cost deterring potential investments.

As the *economics of CCS* was a significant issue, a composite score comprising questions 12b, c, f, g and 15a was created to examine if these economics-based questions in totality reflected perceptions arising from question 12g alone. It was found that several of the significant contrasts were similar, albeit of less confidence and smaller magnitude, supporting the findings above.

Absence of long-term policies was rated as the second-highest scoring barrier

Absence of long-term policy frameworks boosting industrial confidence in capital-intensive CCS projects was also highly rated by the LPS and non-industrial sectors alike, second to economic-related barriers of implementing CCS, averaging 8.35 and 7.79 respectively, as summarised in Table 8.4. The 'global' group scored this barrier 0.98 points higher than 'EU' did at 8.46, indicating that the EU's existing policies were slightly helpful in alleviating the magnitude of this barrier.

The extent of this barrier was also substantiated through structured interviews with the government and finance sub-sector, which indicated that government support through *long-term policies* and regulatory frameworks were essential in driving the uptake of CCS. Being at an early stage of development, banks and project financiers are mostly new to CCS and are presently uncertain about the technology of CCS as well as its future outlook and development, generally perceiving CCS projects to be risky. Having *long-term policies* in place would reduce the uncertainties and risks perceived by the financing sub-sector, and provide guidance for future development pathways for CCS.

In general, through composite scoring of questions 10ai–iv, the EU was more positive than all other regions about whether changes to the policies could increase the uptake in CCS (0.81, 1%). The 'other' sub-sector was also more positive than its counterparts, especially the power and government and finance sub-sectors (by 2.23 points and 1% in both cases). Global organisations were more pessimistic about the potential effects of policy changes compared to those in other regions (i.e. Asia and EU), by 1.29 points (1%). This suggested that policy changes in the EU have a greater chance of succeeding than those in other parts of the world. Furthermore, it suggested that the government and finance sub-sector itself is relatively unconvinced about the potential uptake of CCS that could come from policy changes.

Lack of nearby storage sites was perceived to be the third barrier of concern, as well as the relatively high necessity of transport and storage networks

As shown in Table 9, the *lack of nearby storage sites* was of relatively high concern amongst the

industry sub-sector in inhibiting CCS adoption, rated 7.50. Both LPS and non-industrial sectors also gave the second highest ratings to the *development of transport and storage infrastructure*, indicating the importance of this factor (see Table 12). This may reflect concern over the lack of access to pipeline infrastructure.

The government and finance sub-sector perceived the necessity of *transport and storage infrastructure* to be relatively less important than the industry sub-sector did, rating it 6.85 out of a total score of 10, as compared to 7.85 and 8.11 for both the power and industry sub-sectors respectively, as shown in Table 12. This apparent disparity in rating could reflect the industry's concern that accessibility to transport and storage networks might not be as highly prioritised by the government as it should be. However, more data is needed to validate statistical significance.

Lesson 3: Technology issues are secondary to the power sub-sector but much more important to the industry sub-sector.

The LPS as a whole perceived *technological awareness* to be slightly less important for the promotion of CCS than the non-industrial sector did (6.23 vs. 6.89, as shown in Table 11), although more data would be needed to determine statistical significance.

While the observed divergence of views with regards to *technology awareness* between the five sub-groups was not significant at 5%, representatives from the industry, academia and government and finance sub-sectors seemed to have placed similarly high emphasis on *technology awareness*, rating it at 7.10 on average, as compared to the power sub-sector which tended to place less emphasis on its importance, rating it 5.50 (observed in Table 11). This could suggest that the power sub-sector was largely aware of existing CCS technologies, as shared through the interviews. Also, as the industry sub-sector rated this 1.60 points higher than the power sub-sector did, at 7.10, it could also indicate that the industry perceived it knew much less about CCS than the power sub-sector perceived it did, although more data is needed to conclude statistical significance.

However, the industry was also concerned with *technology lock-in* being a barrier for implementing CCS, rating it 7.70 as seen in Table 9, i.e. that current investments and technologies did not easily allow retrofitting or addition of CCS facilities. This may also reflect the lack of research specifically addressing capture readiness for industrial processes as opposed to power generation.

Lesson 4: Most respondents believed present incentives and knowledge sharing platforms might not be adequate in promoting the uptake of CCS, and the industry had contrarian views to all other sub-sectors

Ratings across all sectors were relatively low, averaging 5 out of maximum score of 10, evident from Table 8, where the LPS as a whole gave lower ratings for *current government funding* and *knowledge sharing platforms* than the non-industrial sector.

While present *government funding for CCS deployment* were perceived by the power, academia and government and finance sub-sectors to be mildly adequate in promoting CCS uptake, the industry sub-sector tended not to have found it sufficient, rating it 4.45 out of 10 (refer to Table 8).

Existing platforms for knowledge sharing across the industry were perceived to be mildly adequate by all but the 'other' sub-sector. The industry sub-sector rated these platforms the most adequate, with a score of 6.00. No statistically significant differences between the sub-sectors were found. In reality, industry is aware that intellectual property (IP) rights and proprietary information will limit the extent of knowledge openly shared across organisations through these platforms, but process industries' experience in dialogue through trade associations may have contributed to their more positive view of such platforms.

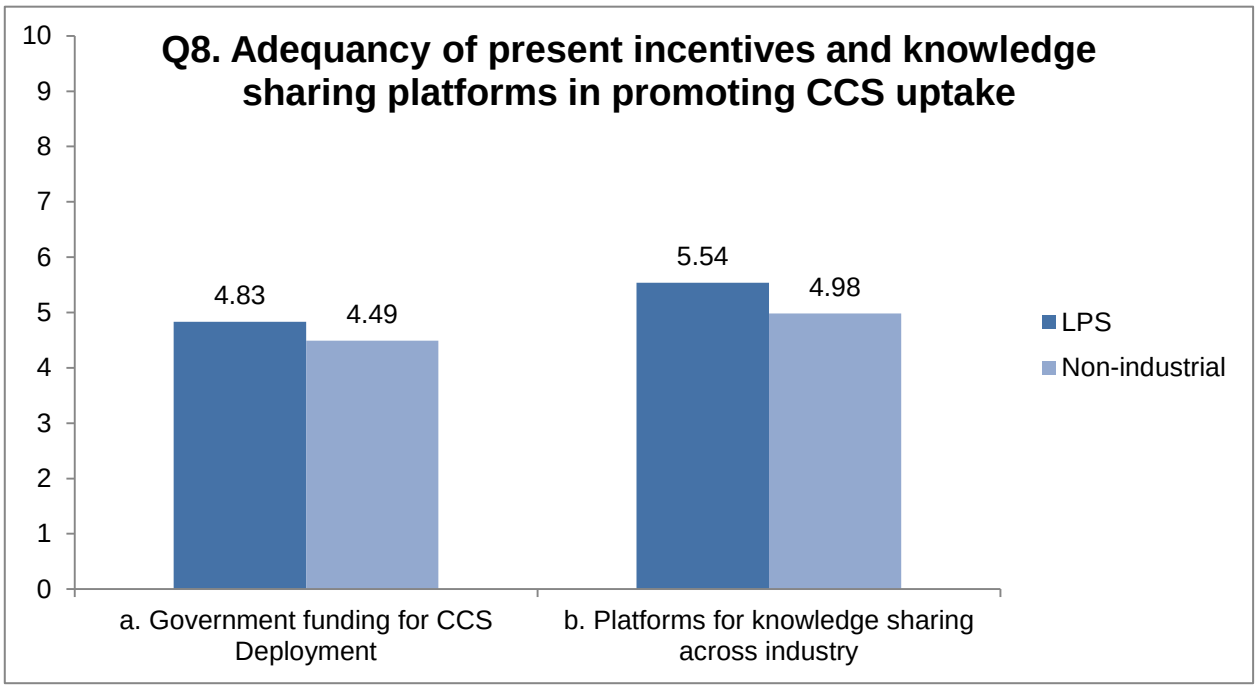

Figure 7: Adequacy of present incentives and knowledge sharing platforms in promoting CCS uptake

Summary of Discussion Points

- Organisations are looking to implement CCS in the medium- to long-term, and are already engaged in carbon dioxide emissions reduction.
- Three of the most significant barriers include *economics of CCS*, the *absence of long-term policies*, and *lack of nearby storage sites*. The last of these does not seem to be as high on the government and finance's priority list than the other sub-sectors'.
- Only the industry sub-sector and Asian organisations found *complex industrial processes* to be an important issue, highlighting evidence of both sub-sectoral and geographical variation.
- The industry sub-sector regarded the barriers of CCS implementation to be significantly higher than all other sub-sectors did.
- The findings from industrial engagement were similar to trends observed through the survey, with the *necessity of transport and storage networks* highlighted as an area requiring greater effort.

Conclusions

Through the review of existing literature on CCS, analysis of inputs from the global industrial survey, and engagement with the industry through participation in the TCCS Conference and interviewing implementers of CCS projects, the research approach undertaken has enabled identification of the factors and conditions necessary for feasible operation of industrial CCS.

Barriers to the uptake of industrial CCS have also been studied. In general, the industry sub-sector perceived that barriers to CCS implementation were higher than that perceived by any sub-sector. The most significant perceived barrier faced by organisations wishing to implement CCS from industrial sources is *economics of implementation*, which includes *high capital cost*, as perceived by the LPS as well as its power generation and industry sub-sectors, as shown in Table 9.

The *absence of long-term frameworks* was also perceived as a key barrier, second only to the *economics of implementing CCS*, and followed by the *lack of nearby storage sites*. If these opinions were an accurate reflection of the broader industrial sector as well as key CCS stakeholders such as the government and finance and research sub-sectors, the challenges would have to be addressed before an increase in industrial CCS deployment could take place in the near-term, ultimately contributing towards attainment of the UK's long-term targets of 80% carbon emission reduction by 2050.

Methods to Accelerate Deployment of Industrial CCS

Enhance Regulatory Frameworks

Globally, if CCS were absent from the technology mix, the investment required to stabilise CO_2 concentration at 450 parts per million (ppm) could increase by up to 40% (IEA, 2012). Comparatively in the UK's context, its carbon budgets will require significant decarbonisation of industry, largely achievable through CCS. Evident from the survey where the *absence of long-term policies* was rated as the second-highest scoring barrier (see Section 6 on Key Lessons from Survey Findings), the enhancement of regulatory frameworks governing CCS would alleviate existing implementation challenges, potentially reducing the uncertainties perceived by the financiers by providing guidance on future development plans for CCS.

Support Development of Financial Incentives

The perceptions on financial challenges highlighted through this survey suggested that sufficient governmental intervention is essential to stimulate the growth and development of industrial CCS. This will be helpful in driving CCS implementation in industries such as cement and steel manufacturing, as well as its continual deployment in the power sub-sector. Financial incentives, such as loan liquidity and tax relief schemes, should also be explored, which would reduce the high upfront costs of deploying a CCS system. At the same time, to ensure economic competitiveness of the industrial sector and tackle risks of carbon leakage, compensation schemes for the potential loss of competitiveness could be put in place or, as part of an internationally agreed approach, mechanisms adjusting the cost of carbon at UK's borders could be implemented.

Promote Synergies in Using Captured CO_2

Synergies in utilising captured CO_2 are also important in enhancing the *economics of CCS*, especially as perceived by the industry sub-sector. Learning can be gained from countries such as USA and Canada, which have substantial projects involving EOR. Being relatively new to the UK, financial aid for full-scale demonstration might be needed to promote utilisation of carbon dioxide, with potential government support for projects through to the commissioning stage, rather than just front-end engineering design phases. Presently, the disparity in extent of concern between the government and finance sub-sector's and the remaining sub-sectors' from the study would have to be recognised, with the former placing this further down its priorities.

Develop CO_2 Transport and Storage Infrastructure

Increasing support for the development of CO_2 transport and storage infrastructure, and

connections to industry thereof, would increase accessibility and improve the viability of industrial CCS, as highlighted through the survey and structured interviews with the industry. Early consideration and planning should be given to the placement of pipelines to ensure that they maximise the potential for future industrial clusters.

Guidelines on equipment used in CCS should also be put in place, such as implementing best practices for compressors, air separation processes, as well as solvents and sorbents used, where energy penalty benefits may be granted to technologies based on their extent of emission reductions. Improvements in construction logistics could also be adopted, and carbon capture processes optimised for various technology routes such that design margins could be reduced, thus saving costs.

Promote Inclusion of Industry in Consultations and Discussions About CCS

From the study, the industry sub-sector appeared to be more pessimistic about the success of CCS in their respective industries than any other sub-sector did. Ensuring that the industry remains included in consultations and discussions on CCS would improve perceptions on the chances of success for CCS in their fields. Furthermore, greater inclusion may lead to identification of other barriers for industrial CCS, which may differ from those identified by the power sub-sector.

Continue to Develop the UK's Leadership Role in Industrial CCS

The UK remains well positioned in leading the global development of CCS technology and infrastructure, as it possesses a number of key advantages over other countries. Structurally, extensive sedimentary basins and established oil and gas infrastructure are in place, rendering the UK capable of substantial CO_2 storage deep within the seabed of the North Sea. This is coupled with its offshore oil and gas capability, which is transferrable across CCS, and excellence in CCS research. In addition, its clusters of power and industrial plants are significant sources of emissions, giving rise to the feasibility of constructing shared CCS networks and lowered overall costs (DECC, 2012a).

Economically, UK-based industries in the CCS supply chain may benefit from the first mover advantage by becoming net exporters of CCS technologies globally. At the same time, the UK can also serve as an advisor for the global network of energy industry, sharing knowledge and applying its expertise to shape CCS development in other countries. Diplomatically, the UK's leadership in CCS could also serve to influence major polluting economies, encouraging uptake of CCS to reduce global emissions (House of Commons Science and Technology Committee, 2006). Hence, the UK government could build on its existing capabilities and work towards consolidating its leadership in CCS.

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Appendix: Detailed Analysis of Survey Results

Current State of CCS Deployment

Sectoral trend: As summarised in Table 6, all of the organisations were moderately active in *reducing their carbon dioxide emissions*, with the LPS rating 7.53 and non-industrial sectors rating 4.58. The LPS and non-industrial sectors alike were relatively familiar with *climate change*, *renewable energy technologies*, and *CCS*, indicating scores higher than the average of 5.5.

Sub-sectoral trend: Across the five sub-sectors, it was evident that representatives from the power and industry sub-sectors rated their current state of CCS deployment higher than the theoretical average score of 5.5. All sub-sectors were very familiar with the concepts of *climate change*, *renewable energy technologies* and *CCS*, rating them more than 7.5 on average, out of a total score of 10. Most sub-sectors were also *considering implementing CCS* to some extent, rating it more than 5.8 on average.

Regional trend: Organisations based in the EU are actively engaged in *reducing their carbon dioxide emissions* with ratings averaging 7.13 as shown in Table 6, higher than the average score of 5.5. This is in line with current trends in the global landscape of CCS deployment. ANOVA assessment and Scheffé's method showed at 5% significance that within the regions, EU organisations are *considering implementing CCS* to a greater extent than their Asian counterparts. Also, EU and global operations are significantly more familiar with CCS than their Asian ones, at 5% significance.

Table 6: Average ratings for the current state of CCS deployment based on respondents' survey inputs (statistically significant values for randomness are marked: $^{+}$ significant at 20%; * significant at 10%; ** significant at 5%; * significant at 1%)**

Data Groups		Current State of CCS Deployment				
		1. My organisation actively engages in reducing its carbon dioxide emissions	2. How familiar are you with:			3. Is your organisation considering implementing CCS?
			a. Climate change	b. Renewable energy technologies	c. CCS	
Primary – Sector Split						
1	LPS	7.53***	8.94***	8.59***	8.18***	6.26^{+}
	Non-industrial	4.58*	8.64***	8.40***	8.09***	5.58
	t-test	t = 4.77**	t = 0.899	t = 0.661	t = 0.155	t = 1.013
Secondary – Sub-Sector Split						
2	Power	7.94***	9.00***	8.69***	8.50***	6.38
	Industry	7.17**	8.89***	8.50***	7.89***	6.17
	Other	5.33	8.80***	8.40***	7.60*	4.11
	Academia	6.37^{+}	8.64***	8.48***	8.32***	5.81
	Government and Finance	5.69	8.56***	8.28***	8.06***	6.45
	ANOVA	F = 2.37	F = 0.246	F = 0.186	F = 0.310	F = 1.19
Tertiary – Regional Split						
3	Global	6.50	9.07***	8.53***	8.53***	5.92
	EU	7.13***	8.52***	8.12***	8.60***	6.70*
	Asia	5.53	8.05***	8.45***	6.90**	4.38^{+}
	ANOVA	F = 1.67	F = 1.60	F = 0.430	F = 3.43**	F = 3.45**

Effectiveness of Current Policies in Facilitating Adoption of Industrial CCS

Sectoral trend: Both LPS and non-industrial sectors perceived inadequacy of *current government policies* such as *CCL, CCA, CPF, RHI, EU ETS*, and *CfD* in incentivising industrial CCS uptake at mostly more than 20% significance, having rated them below-average scores of 3.74 to 5.45 (refer to **Table 7**).

Sub-sectoral trend: Similarly, across the five sub-sectors, policies were mostly given below-average scores ranging 3.29 to 5.56 at varying levels of significance. However, more data would be needed to determine if there were significant differences between sub-sectors' perceptions.

Regional trend: Analysing the ratings of all listed policies given by organisations operating in the EU, the *CCL* appeared to be the most highly rated, at 5.16, which could indicate to some extent that it was perceived to be more effective than other policies. However, more responses would have to be incorporated to determine statistical significance.

Table 7: Average ratings of effectiveness of current policies in facilitating industrial CCS as perceived by the sectors, sub-sectors and regions (statistically significant values for randomness are marked: $^{+}$ significant at 20%; * significant at 10%; ** significant at 5%; * significant at 1%)**

	Data Groups	7. In your opinion, are current government policies adequate in incentivising uptake of CCS applied to industrial sources of carbon dioxide?					
		a. Climate Change Levy (CCL)	b. Climate Change Agreements (CCA)	c. Carbon Price Floor (CPF)	d. Renewable Heat Incentive (RHI)	e. EU Emissions Trading System (EU ETS)	f. Contracts for Difference (CfD)
Primary – Sector Split							
1	LPS	4.00***	4.67^{+}	4.04***	4.48*	4.54*	5.45
	Non-industrial	4.33***	4.47**	4.21***	3.74***	3.93***	4.18***
	t-test	t = 0.584	t = 0.301	t = 0.287	t = 1.256	t = 1.045	t = 1.841
Secondary – Sub-Sector Split							
2	Power	3.92**	4.23*	4.00**	4.25**	4.15**	5.38
	Industry	4.09*	5.18	4.09^{+}	4.73	5.00	5.56
	Other	3.33*	3.67^{+}	3.33*	3.33*	3.67*	3.17^{+}
	Academia	4.83^{+}	4.96	4.64*	4.00***	4.41**	4.57*
	Government and Finance	3.93***	4.00**	3.93**	3.46***	3.29***	4.00**
	ANOVA	F=0.817	F=0.689	F=0.783	F=0.852	F=1.14	F=1.25
Tertiary – Regional Split							
3	Global	2.54***	4.31^{+}	3.17***	3.15***	4.17*	4.30
	EU	5.16	4.72^{+}	4.40**	4.50***	4.12***	4.75^{+}
	Asia	3.90***	4.25**	3.75***	3.85***	3.75***	3.65***
	ANOVA	F=7.98**	F=0.226	F=1.52	F=2.09	F=0.228	F=1.10

Adequacy of Present Incentives and Knowledge Sharing Platforms in Promoting Uptake of CCS

Sectoral trend: Both the LPS and non-industrial sectors perceived present *incentives* and *knowledge sharing platforms* to be barely adequate, rating it below the average score of 5.5. It is evident that the LPS regarded *government funding for CCS deployment* to be inadequate, rating it 4.83 out of a total score of 10, as shown in Table 8. However, there was insufficient evidence from Student's *t*-tests to determine if the LPS and non-industrial sectors had significantly different perceptions.

Sub-sectoral trend: There is potential variation in perceptions of different groups on the adequacy of incentives and knowledge sharing platforms in promoting uptake of CCS, with 'other' sub-sector rating 2.50 for both *government funding* and *knowledge sharing platforms*.

Regional trend: It was apparent that organisations in Asia also regarded *government funding* to be lower than average, at 5% level of significance, rating it 4.21 out of a total score of 10. This is aligned with existing levels of support for CCS around the world, with Asia having the lowest levels of funding and support presently at approximately US$1.1 billion, as compared to other regions such as the EU or US, having up to $4.6 billion and $7.5 billion worth of public funds committed to CCS respectively (SBC Energy Institute, 2013).

Table 8: Average ratings of adequacy of incentives and knowledge sharing platforms in promoting uptake of CCS as perceived by the sectors, sub-sectors and regions (statistically significant values for randomness are marked: $^{+}$ significant at 20%; * significant at 10%; ** significant at 5%; * significant at 1%)**

	Data Groups	8. From your knowledge, are present incentives and knowledge sharing platforms adequate in promoting uptake of CCS?	
		a. Government funding for CCS deployment	b. Platforms for knowledge sharing across industry
Primary – Sector Split			
1	LPS	4.83	5.54
	Non-industrial	4.90^{+}	4.98^{+}
	t-test	t = 0.106	t = 0.850
Secondary – Sub-Sector Split			
2	Power	5.15	5.15
	Industry	4.45^{+}	6.00
	Other	2.50***	2.50***
	Academia	5.50	5.32
	Government and Finance	5.00	5.50
	ANOVA	F = 1.81	F = 2.13*
Tertiary – Regional Split			
3	Global	4.50^{+}	5.07
	EU	5.60	5.48
	Asia	4.21**	5.16
	ANOVA	F = 1.70	F = 0.141

Barriers of Implementing CCS

Table 9: Barriers of implementing CCS rated by the sectors, sub-sectors and regions (statistically significant values for randomness are marked: $^{+}$ significant at 20%; * significant at 10%; ** significant at 5%; * significant at 1%)**

Data Groups		12. From your organisation's perspective, what are the barriers of implementing CCS?								
		a. Complex industrial processes	b. High capital cost of installing CCS	c. High operating cost of CCS	d. Technology lock-in	e. Stakeholder perception	f. Profit reduction	g. Economics of CCS	h. Absence of long-term policy frameworks	i. Lack of nearby storage sites
Primary – Sector Split										
1	LPS	6.78**	8.46***	7.39***	7.14***	6.57**	7.57***	8.65***	8.35***	7.17***
	Non-industrial	6.17*	8.10***	7.37***	6.41***	7.12***	7.51***	7.75***	7.79***	6.39**
	t-test	t=1.02	t=0.917	t=0.056	t=1.56^{+}	t=1.04	t=0.089	t=2.33**	t=1.26	t=1.30^{+}
Secondary – Sub-Sector Split										
2	Power	6.17	7.92***	6.77**	6.67**	5.92	7.31**	8.54***	8.08***	6.92**
	Industry	7.45***	9.09***	8.20***	7.70***	7.40**	7.90***	8.80***	8.70***	7.50**
	Other	6.40	7.80*	7.80**	6.80	7.60**	8.00**	8.40**	7.57**	6.40
	Academia	6.27^{+}	8.23***	7.59***	6.32*	7.00***	7.32***	7.29***	7.68***	6.95**
	Government and Finance	5.93	8.00***	6.86**	6.43**	7.14***	7.64***	8.21***	8.07***	5.50
	ANOVA	F=0.724	F=1.10	F=1.34	F=1.03	F=1.41	F=0.229	F=2.23	F=0.684	F=1.22
Tertiary – Regional Split										
3	Global	6.31	8.29***	7.69***	6.62*	6.69*	8.00***	8.69***	8.46***	6.77^{+}
	EU	5.76	8.40***	7.08***	6.08*	6.80***	7.40***	7.96***	7.48***	6.00
	Asia	7.60***	8.25***	7.85***	7.45***	7.50***	6.85**	7.50***	7.70***	7.60***
	ANOVA	F=4.15**	F=0.060	F=1.12	F=3.20**	F=1.15	F=1.20	F=2.21	F=1.78	F=2.39

a. Complex Industrial Processes

Sectoral trend: *Complex industrial processes* requiring extensive modifications was rated as one of the lowest-scoring barriers by the LPS at an average rating of 6.78 out of a total score of 10 at 5% level of significance, and was rated as the lowest-scoring barrier by the non-industrial sector at 6.17, at 10% level of significance, as shown in Table 9.

Sub-sectoral trend: Across the five sub-sectors, *complex industrial processes* were similarly rated

as one of the lowest-scoring barrier by all sub-sectors. Although the industry sub-sector seemed to have given it a higher rating than other sub-sectors, at 7.45 out of a total score of 10 (at 1% significance), there was ultimately insufficient evidence through ANOVA to indicate statistical significance of the comparatively higer rating.

Regional trend: Globally, while *complex industrial processes* was rated as the lowest-scoring by organisations with global operations and operations in the EU, organisations operating in Asia rated this barrier significantly higher than those based in the EU at 7.60 points, at 5% level of significance, validated through ANOVA and subsequently Scheffé's method.

b. High Capital Cost of Installing CCS

Sectoral trend: *High capital cost of installing CCS* was rated as the second-highest scoring barrier by the LPS at 8.46, indicating that this was perceived to be amongst the most significant barriers of implementing CCS in industry.

Sub-sectoral trend: Further analysing the means of different sub-groups for various barriers, it was evident that with an average rating of 9.09 out of 10 as shown in Table 9, the industry sub-sector regarded *high capital cost of installing CCS* as the most significant barrier among other barriers at 1% significance. While the rating appeared to be higher than the power sub-sector as well as government and finance sub-sectors, which rated it at 7.92 and 8.00 respectively, there was insufficient evidence to indicate significant difference in views between sub-sectors through subsequent ANOVA verification.

Regional trend: Between different regions, this barrier has similarly been rated as the highest-scoring barrier by organisations operating in Asia and EU at 8.25 and 8.40 respectively at 1% significance, although more data is needed to determine statistical significance between different regions through ANOVA.

c. High Operating Cost of Maintaining CCS Operations

Sectoral trend: *High operating cost of CCS* was rated similarly by the LPS and non-industrial sectors, at 7.39 and 7.37 out of a total score of 10, at the 1% level of significance.

Sub-sectoral trend: At an average rating of 8.20 as summarised in Table 9, the industry sub-sector seemed to have regarded *high operating cost of maintaining CCS operations* to be a relatively greater barrier as compared to its power generation counterpart, which gave an average rating of 6.77. This could potentially have been attributed to the fact that industrial CCS facilities would tend to be of smaller scales than power generation plants, leading to proportionately larger cost of maintaining CCS operations should it be implemented within their facilities, resulting in the observed disparity. For instance, applying CCS to a plant increases levelised costs of production, by up to 12% and 45%, for cement and steel manufacturing plant respectively (SBC Energy

Institute, 2013). However, subsequent ANOVA validation did not yield sufficient evidence to indicate statistical significance in perceptions between the industry and power sub-sectors, and more data would be required to enable further evaluation.

Regional trend: Operations in Asia rated high operating cost of CCS as its second-highest scoring barrier of implementing CCS in industry – 7.85 out of a total score of 10 – after *high capital cost of CCS*. While organisations operating in Asia seemed to have rated this barrier more highly than organisations with operations in EU or globally, more data is needed to determine statistical significance between the regions through ANOVA validation.

d. Technology Lock-in

Sectoral trend: *Technology lock-in* was considered as a less substantial barrier in CCS implementation by the LPS and non-industrial sectors, both of which rated it as the third lowest-scoring barrier at 7.14 and 6.41 respectively, at 1% significance.

Sub-sectoral trend: With an average ranking of 6.70 across the five sub-sectors of respondents, *technology lock-in* seemed to have posed a relatively greater barrier to the industry sub-sector, which gave it the highest average ranking of 7.70 across the five sub-sectors, as shown in Table 9. However, more data is needed to determine statistical significance between the regions.

Regional trend: Comparing between different regions, *technology lock-in* was the most highly rated by operations in Asia at 1% significance, at 7.45 out of a total score of 10, even though Asian operations rated this as their second-lowest scoring barrier amongst other potential barriers. Further analysis through ANOVA confirmed statistical significance at the 5% level, that operations based in Asia rated *technology lock-in* as a greater barrier, i.e. 1.37 points higher than operations based in the EU region, which rated it 6.08 out of 10 points.

e. Stakeholder Perception

Rated 5.92 to 7.60 by the five sub-sectors in the LPS and non-industrial sectors in Table 9, and 6.69 to 7.50 across the different regions of operation, *stakeholder perception* was generally rated as one of the lowest-scoring barriers across the industries and regions, with no significant differences observed between different comparison groups.

f. Profit Reduction

Sectoral trend: The LPS and non-industrial sectors similarly rated *profit reduction* at 7.57 and 7.51 respectively with scores validated at 1% significance.

Sub-sectoral trend: Within the five sub-sectors, the industry and ‘other’ sub-sector comprising consultancies and non-profit organisations generally rated this barrier slightly higher than the power, academic and government and finance sub-sectors, at 7.90 and 8.00 respectively.

However, more data is needed to determine statistical significance between the regions.

g. Economics of Implementing CCS

From Table 9*, economics of implementing CCS was* observed to be the most highly rated barrier of CCS implementation by the LPS at 8.65, and the third most highly rated barrier by the non-industrial sector at 7.75, both at 1% significance.

Sectoral trend: Further analysis through Student's *t*-test has returned a p-value of 0.016, indicating at the 5% level of significance, i.e. with 95% confidence, that the LPS perceived economics of CCS implementation to be a greater barrier than perceived by the non-industrial sector, as shown in Table 9.

Sub-sectoral trend: Overall, it was recognised that the *economics of implementing CCS* was the most significant barrier, with all sub-sectors except the academic sub-sector rating it above 8.00, as shown in Table 9. Although the power and industry sub-sectors seemed to have regarded this to be a greater barrier than the academic sub-sector, rating it at 8.54 and 8.80 respectively, more data is needed to determine statistical significance in observed differences between the sub-sectors through ANOVA.

Regional trend: Organisations with global operations also rated *economics of implementing CCS* as the greatest barrier in implementing industrial CCS, as shown in Table 9, at 8.69 out of a total score of 10. While the score seemed higher than that rated by organisations with operations in EU and Asia, at 7.96 and 7.50 respectively, there was insufficient evidence through ANOVA analysis to indicate significant differences in perceptions between organisations with global operations, operations in EU as well as those in Asia.

h. Absence of Long-term Policy Frameworks

Sectoral trend: Second to economic-related barriers of implementing CCS, *absence of long-term policy frameworks* boosting industrial confidence in capital-intensive CCS projects was also highly rated by the LPS and non-industrial sectors alike, averaging 8.35 and 7.79 respectively at 1% significance, as summarised in Table 9.

Sub-sectoral trend: Comparing between the five sub-sectors, the industry sub-sector similarly gave the highest rating at 8.70. However, through further examination with ANOVA, there was insufficient evidence to determine statistical significance in ratings between the sub-sectors.

Regional trend: Examining globally, the *absence of long-term frameworks* was rated relatively high with above-average scores across the regions. Organisations having worldwide operations rated it 8.46 on average, those in EU rated 7.48 and those based in Asia rated 7.70. Between regions, more data is needed to determine statistical significance in ratings.

i. Lack of Nearby Storage Sites

Sectoral trend: Finally, the *lack of nearby storage sites* was a barrier of relatively lesser concern among the LPS and non-industrial sectors, rated 7.17 and 6.39 respectively, as outlined in Table 9.

Sub-sectoral trend: Similarly, comparing between the five sub-sectors, industry appeared to have rated it most highly compared to the other four sub-sectors at 7.50, although through further ANOVA analysis, there was insufficient evidence to conclude if the industry sub-sector had significantly differing views.

Regional trend: Regionally, organisations based in Asia rated the *lack of nearby storage sites* as a relatively important barrier at 7.60 at 1% significance, as compared to those based in the EU or having global operations, which rated 6.00 and 6.77 respectively. This could be a factor arising from innate geographical condition of the regions, with Asia having much less storage capacity than South America or Europe, in terms of the years of storage available. For instance, Hendriks et al. reported that South East Asia only had about 3% of the world's storage capacity with regards to aquifers, as compared to 10% in South America, although estimates may vary between different sources (Hendriks & Graus, 2004). However, there was insufficient evidence from ANOVA to determine if there were significant differences in perceptions on the *lack of storage sites* posing as a barrier in industrial CCS implementation across the regions.

Perceived Risks of Implementing CCS in the Industry

Table 10: Average ratings of risks of implementing CCS as perceived by the sectors, sub-sectors and regions (statistically significant values for randomness are marked: + significant at 20%; * significant at 10%; ** significant at 5%; * significant at 1%)**

	Data Groups	15. From your organisation's perspective, what would be the perceived risks of implementing CCS?		
		a. Uncertainty in payback	b. Loss or deviation in throughput arising from implementing CCS	c. Stakeholder acceptance
Primary – Sector Split				
1	LPS	8.00***	6.27*	6.73**
	Non-industrial	8.00***	7.15***	7.36***
	t-test	t=0.000	t=1.698*	t=1.080
Secondary – Sub-Sector Split				
2	Power	7.92***	6.00	6.58+
	Industry	8.10***	6.60*	6.90+
	Other	8.80***	6.40	7.40*
	Academia	7.67***	7.33***	7.48***
	Government and Finance	8.23***	7.15***	7.15***
	ANOVA	F=0.476	F=1.08	F=0.442
Tertiary – Regional Split				
3	Global	7.69***	5.83	6.67*
	EU	8.04***	7.38***	7.13***
	Asia	7.85***	7.20***	7.70***
	ANOVA	F=0.167	F=3.51**	F=1.30

Future Efforts Needed to Promote Industrial CCS Uptake

1. Policies and Mechanisms Promoting Adoption of CCS

Sectoral analysis: As summarised in Table 11 below, with regards to policies and mechanisms potentially promoting uptake of CCS in industry, economics-related initiatives such as *monetary incentives*, *increase in capital funding*, and *technology cost reduction*, were perceived to be the top three most effective mechanisms by both the LPS and non-industrial sectors. *Monetary incentives* were rated 8.00 and 7.77 respectively by the LPS and non-industrial sectors, indicating similarity in

perceptions at 1% significance. Across the five sub-sectors, it was also observed that economics-related mechanisms were highly rated, mostly greater than 7.20.

Sub-sectoral analysis: With regards to the proposed policy change on *doubling of CPF*, statistical significance was observed in the ratings between sub-sectors at 5% (i.e. 95% confidence), through ANOVA evaluation and subsequently applying the Scheffé's method. The industry sub-sector rated *doubling of CPF* significantly lower than the academia, at 4.80 and 7.00 respectively.

Interestingly, all sub-sectors gave significantly lower ratings than the 'other' sub-sector (i.e. consultancies and non-profit organisations). From Table 11, the power sub-sector rated 6.00, industry 4.80, academia 7.00, government and finance 6.50, as compared to the high rating of 9.33 given by the 'other' sub-sector. This could be an indication that organisations such as consultancies might be over-emphasising the importance of *doubling of CPF*, whereas in reality the effect of *doubling CPF* might not be perceived by the power and industry sub-sectors to be as effective as the more economic-enhancing mechanisms like *monetary incentives*.

Regional analysis: Across the world, organisations operating in the EU region also regarded *monetary incentives* as the most effective means of promoting CCS adoption, rating it 8.29, followed by the *increase in capital funding for CCS installations*, rating it 8.04, at 1% significance.

Table 11: Average ratings of potential mechanisms promoting CCS adoption, as perceived by the sectors, sub-sectors and regions (statistically significant values for randomness are marked: $^{+}$ significant at 20%; * significant at 10%; ** significant at 5%; * significant at 1%)**

	Data Groups	10. From your organisation's perspective, which of the following would significantly promote the adoption of CCS?										
		a. Policy changes, such as:				b. Increase in capital funding supporting CCS installation	c. Monetary incentives (Taxes or incentives)	d. Implement CCS clusters connecting industries to network pipelines	e. Increase carbon prices	f. Technology cost reduction	g. Technology awareness	h. Border tax adjustments
		(i) Exempt organisations with CCS from Climate Change Levy (CCL)	(ii) Offer Renewable Heat Incentive (RHI) to organisations with CCS	(iii) Double Carbon Price Floor (CPF)	(iv) Reduce available allowances in EU ETS							
Primary – Sector Split												
1	LPS	6.77***	6.55**	5.45	5.91	7.52***	8.00***	7.57***	6.22	7.74***	6.23^{+}	5.65
	Non-industrial	6.85***	6.23**	7.26***	6.55***	7.80***	7.77***	6.93***	7.38***	7.80***	6.89***	6.46***
	t-test	t = 0.134	t = 0.582	t = 2.742**	t = 1.086	t = 0.571	t = 0.494	t = 1.203	t = 1.809*	t = 0.120	t = 1.127	t = 1.505^{+}
Secondary – Sub-Sector Split												
2	Power	6.25	6.00	6.00	5.75	7.46***	7.92***	6.92*	6.77^{+}	7.15**	5.50	5.46
	Industry	7.40***	7.20**	4.80	6.10	7.60***	8.10***	8.40***	5.50	8.50***	7.10**	5.90
	Other	7.60*	7.80*	9.33***	8.00***	8.00**	7.33^{+}	6.33	8.17***	7.67*	5.00	5.50
	Academia	6.95***	6.30*	7.00***	6.85**	8.35***	7.89***	7.20***	7.55***	7.60***	7.10**	6.60**
	Government and Finance	6.43^{+}	5.57	6.50^{+}	5.50	6.93**	7.79***	6.79**	6.79**	8.14***	7.14***	6.21
	ANOVA	F = 0.727	F = 1.75	F = 4.22**	F = 1.91	F = 1.41	F = 0.186	F = 1.48	F = 1.94	F = 0.980	F = 1.89	F = 0.655
Tertiary – Regional Split												
3	Global	5.50	5.50	5.17	5.58	7.92***	7.69***	7.54***	6.62*	8.08***	6.45	5.62

EU	7.29***	6.71***	7.04***	6.54**	8.04***	8.29***	7.00***	7.13***	7.96***	6.71**	6.63***
Asia	7.00***	6.17^{+}	6.58*	6.26^{+}	7.05***	7.22***	7.00***	7.11***	7.53***	6.89***	5.79
ANOVA	F = 3.56**	F = 1.50	F = 2.56	F = 0.810	F = 1.88	F = 2.03	F = 0.393	F = 0.258	F = 0.478	F = 0.138	F = 1.40

2. Other Efforts Required to Promote Future CCS Uptake

With regards to the broader efforts of promoting CCS uptake, summarised in Table 12, *improvements in regulatory frameworks*, followed by the *development of transport and storage infrastructure*, as well as *additional synergies in utilising captured carbon dioxide* to improve CCS economics were generally the top rated choices across the sectors, sub-sectors and regions.

Table 12: Average ratings of proposed future efforts promoting CCS uptake, as perceived by the sectors, sub-sectors and regions (statistically significant values for randomness are marked: $^{+}$ significant at 20%; * significant at 10%; ** significant at 5%; * significant at 1%)**

	Data Groups	17. In your opinion, what further efforts are required to promote future uptake of CCS?					
		a. Improvement in regulatory framework	b. Develop transport and storage infrastructure	c. Improve skills and supply chain	d. Establish and publicise best practices to facilitate technology adoption	e. Define 'CCS readiness' for industrial plants	f. Additional synergies in utilising captured CO_2 to improve economics
Primary – Sector Split							
1	LPS	8.23***	7.95***	7.09***	7.36***	6.82**	7.73***
	Non-industrial	7.73***	7.65***	7.15***	7.44***	7.03***	7.63***
	t-test	t = 1.33^{+}	t = 0.671	t = 0.118	t = 0.148	t = 0.336	t = 0.219
Secondary – Sub-Sector Split							
2	Power	8.38***	7.85***	6.69*	6.92**	6.46^{+}	7.15***
	Industry	8.00***	8.11***	7.67**	8.00***	7.33*	8.56***
	Other	8.60**	8.40**	7.60**	7.60*	7.20^{+}	9.00***
	Academia	8.00***	7.95***	7.55***	7.77***	7.14***	7.91***
	Government and Finance	6.92***	6.85***	6.31*	7.00**	6.77**	6.62*
	ANOVA	F = 2.11*	F = 1.43	F = 1.63	F = 0.818	F = 0.284	F = 2.86**
Tertiary – Regional Split							
3	Global	8.23***	7.77***	7.15**	7.38**	6.62	8.00***
	EU	8.17***	7.83***	7.29***	7.71***	6.75**	7.38***
	Asia	7.30***	7.40***	6.75***	7.20***	7.60***	7.85***
	ANOVA	F = 2.28	F = 0.399	F = 0.526	F = 0.419	F = 1.11	F = 0.642

Improvement in Regulatory Frameworks

Sectoral analysis: Student's *t*-test between the LPS and non-industrial sectors highlighted statistical significance at 20%, that LPS placed greater emphasis than non-industrial sector on *improvements to regulatory frameworks* in promoting future CCS uptake, rating it 8.23 and 7.73 respectively as stated in Table 12.

Sub-sectoral analysis: Further examining the five sub-sectors through ANOVA and Scheffé's method, it was observed that the power sub-sector perceived *improvements in regulatory frameworks* relatively more strongly than the government and finance sub-sector at 10% level of significance, rating it 8.38, i.e. 1.46 points higher than the latter at 6.92.

Additional Synergies in Utilising Captured Carbon Dioxide to Improve CCS Economics

Industrial analysis: Between the LPS and non-industrial sectors, *additional synergies in utilising captured carbon dioxide* was given similar ratings of 7.73 and 7.63 respectively, as shown in Table 12, with no significant difference in perceptions observed through Student's *t*-test.

Sub-sectoral analysis: Further analysing the five sub-sectors through ANOVA and Scheffé's method, it was observed that the industry sub-sector perceived the importance of *additional synergies in utilising captured carbon dioxide* in improving economics of CCS to be relatively greater than that perceived by the government and finance sub-sector, rating it a score of 1.94 points higher than the latter at 5% significance, averaging 8.56 and 6.62 points respectively as stated in Table 12. This might either be due to the fact that organisations classified in the industry sub-sector were likely more experienced in chemical processing than the power sub-sector – hence being relatively more aware of the potential for utilising the captured carbon dioxide. Alternatively, they might be further behind in the learning curve, not having realised that there is presently lack of sufficient market for the CO_2 produced.

At the same time, through ANOVA and Scheffé's method, the 'other' sub-sector (which comprised consultancies and non-profit organisations) was also found to have rated 2.38 points higher than the government and finance at 5% significance, averaging 9.00 points.

About the authors

This report is the product of Kun Shan Sum's MSc studies in which she was supervised by Drs Fennell and Napp, with additional input from Mr Thomas Hills.

Dr Paul Fennell heads the Energy Engineering group at Imperial Chemical Engineering and has published widely on the subject of calcium looping technology and in the wider field of chemical engineering. He sits on the Institution of Chemical Engineers Energy Conversion subject panel, the International Energy Authority High-Temperature Solid Looping Cycles Network Executive, and has written reports for the UK Department for Energy and Climate Change (DECC) on future technologies for Carbon Capture and Storage (CCS) and carbon capture readiness. He is also a deputy director of Imperial's Centre for Carbon Capture and Storage. He has published more than 40 papers since 2005.

Kun Shan Sum is a Senior Analyst with the Singapore Government at the Energy Market Authority, a statutory board under the Ministry of Trade and Industry. She has successfully implemented Singapore's first clean energy rural electrification test-bed, before commencing on the MSc in Sustainable Energy Futures with the Energy Futures Lab at Imperial College in 2012. As a recipient of the UK Government's Chevening Scholarship for her studies, Kun Shan is passionate about driving a low-carbon energy future through industrial partnerships, and collaborated with Alstom and Capture Power Limited, one of the two preferred bidders of the UK CCS Commercialisation Competition developing the White Rose CCS Project, to expand her research on the deployment of CCS from industrial sources in the UK.

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