Global Action to Advance Carbon Capture and Storage

A Focus on Industrial Applications

International Energy Agency

Annex to Tracking Clean Energy Progress 2013

Carbon Capture, Use and Storage (CCUS) Action Group

CLEAN ENERGY MINISTERIAL
Accelerating the Transition to Clean Energy Technologies

INTERNATIONAL ENERGY AGENCY

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- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
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Summary and recommended global actions
Where are the opportunities for progress?

Energy-intensive industries account for a significant part of global carbon dioxide (CO_2) emissions. Industrial sectors such as cement, iron and steel, chemicals and refining represent one-fifth of total global CO_2 emissions, and the amount of CO_2 they produce is likely to grow over the coming decades. Carbon capture and storage (CCS) in industrial applications refers to the prevention of CO_2 emissions through the capture, transport and storage or use of CO_2 from these sectors. Analysis by the International Energy Agency shows that CCS in industrial applications could represent around half of the emission reductions achieved through CCS by 2050.

CCS is the only option to decarbonise many industrial sectors. CCS is currently the only large-scale mitigation option available to cut the emissions intensity of production by over 50% in these sectors. Further energy efficiency improvements, while urgently needed, have limited potential to reduce CO_2 emissions, partly due to the non-energy related emissions from many industrial processes. As a result, it may not be possible to decarbonise industrial sectors without CCS. Failure to make the case for CCS in industrial applications and to undertake the actions needed for deployment poses a significant threat to the world's capacity to tackle climate change. In addition, economies where CCS is available may be better placed to host and benefit from industrial production in the future. Developing and deploying CCS in energy-intensive industries is of critical importance.

CCS in industrial applications requires more attention from policy makers. Deploying a pollution control method such as CCS requires policy action; it is not something that a market will deliver if left alone. The third Clean Energy Ministerial meeting (CEM 3), held in London in 2012, identified CCS in industrial applications as a crucial area for action. This document complements and expands upon the more general analysis of the status of CCS provided in the main text of the International Energy Agency (IEA) Tracking Clean Energy Progress report for CEM 4. Three important impediments to deployment are identified: remaining knowledge gaps regarding costs and technical performance; potential impacts of CCS on competitiveness; and, limited engagement of industrial sectors in tackling common CCS challenges, such as developing public understanding of CO_2 transport and storage.

Demonstration of CCS in industrial applications is not happening fast enough. CCS is already proven in some industrial sectors, such as natural gas processing, which offer low-cost opportunities for early deployment of CCS. Yet, the commercial-scale demonstration stage in key sectors such as iron and steel, cement or some processes in the refining sector has not yet been reached. All these sectors require further experience with CCS technologies. However, the policy drivers for gaining this experience are lacking. Coalitions of willing governments and companies can valuably drive the development of these crucial technologies now to make them available for the coming decades.

Policies must consider the global competitiveness of industrial sectors. The majority of the industrial sectors are active in global markets and exposed to global trade. The competitiveness of their products is highly sensitive to production costs. This issue significantly influences how policy architectures might be constructed. CCS increases production costs – by less than 10% for methanol production or refinery products, but up to 100% for cement – and could therefore distort existing competitiveness patterns if it is implemented on a regional basis only.

In 2011, the IEA and the United Nations Industrial Development Organisation (UNIDO) produced a Technology Roadmap for CCS in Industrial Applications, with key actions to advance CCS towards the levels of deployment considered necessary (IEA, 2011). These key recommended actions are listed in Annex I. None of the near-term actions for 2015 or 2020 appear to be much closer to realisation, but all remain valid. A more focused suite of six inter-linked recommendations is provided below to help policy makers to grasp this opportunity despite ongoing challenges in financing projects.

Recommendations

Develop, demonstrate and deploy

1. ***Commit public funds to around ten pilot and demonstration-scale projects that show the technical and economic feasibility of large-scale CO_2 capture in sectors such as iron and steel and cement.***

   Such projects are of the utmost importance in the near term and should receive the greatest attention from both government and industry. Today's political and financial environment has been unsuccessful in driving sufficient private investment in research and development (R&D) for CCS systems in these sectors, yet the technologies need to be available in the next decade in order to achieve deep reductions in greenhouse gas (GHG) emissions. Overall expenditure would be minimised by supporting regional and international consortiums of industrial partners that can jointly lead technology development programmes. Funds could come from CO_2 certificate revenues or sectoral production levies, in addition to R&D budgets.

2. ***Scale up step-by-step. Support projects according to their contribution to knowledge, not their short-term impact on emissions reduction.***

   Different sectors are at different levels of development and their CCS cost estimates vary. This means that funding programmes need to be tailored to the various stages of technical maturity. Demonstration projects provide a considerable return on investment globally in terms of reducing policy makers' uncertainty about technologies. Rather than emphasising immediate CO_2 emission reductions, current demonstration programmes should ensure that they maximise learning and knowledge sharing in areas where there are gaps, in order to increase confidence in the technology.

Create a policy environment to support deployment

3. ***Governments should incorporate CCS into forward-looking industrial strategies.***

   Experience indicates that for CCS in industrial applications, investments will flow where the sector has a confident outlook and is a governmental priority in the region. Investor confidence is crucial when considering the location of demonstration projects that require a production plant to remain competitive for a decade after the start of project planning. Governments need to be aware of the ways in which technologies and sectoral dynamics could change in the next twenty years. Longer-term confidence that climate policy will support industrial production will stimulate industry to actively develop CCS solutions.

4. ***Start to address competitiveness concerns in relation to energy and climate policies.***

   Companies that compete internationally see fragmented regional climate policies as a risk to competitiveness, while governments see them as a risk to jobs and carbon leakage. After the demonstration phase and as a complement to CO_2 pricing, international or national sectoral policy instruments – such as quantity measures, consumption-based accounting, emissions standards or "feebate" schemes – could provide greater security for investors to plan for a low-carbon future that includes CCS as a competitive advantage.

Engage all sectors in strategic CCS activities, including CO_2 transport and storage needs

5. ***Exploit synergies between sectors, including the power sector.***

   There are many opportunities to reduce costs through cooperation on challenges and infrastructure, including with the power sector. Examples include: open-access pilot facilities for optimising the various CO_2 capture technologies on different flue gases; sharing CO_2 transport and storage infrastructure of first-mover (*e.g.* power sector) projects with next phase projects (*e.g.* iron and steel sector) through co-location; effort-sharing for cluster development and public communication. The construction and operation of a third-party commercial CO_2 transport and storage network is a common and crucial need among all sectors.

6. ***Involve all relevant stakeholders.***

   All relevant industrial sectors should be included in actions to advance CCS. This will raise the level of knowledge among all companies that will need to use CCS and will recognise that the local endorsement of CCS will be crucial to the future of industrial sectors in the region. This should include national and regional actions to reduce risks and uncertainties through: public engagement; knowledge sharing; CO_2 storage capacity mapping; exploration and operation; and, R&D across the CCS value chain.

We believe that implementing the full suite of recommendations in a co-ordinated manner would be the most effective approach to addressing the identified obstacles. Policies will vary across countries, however, as the impacts on competitiveness and the levels of awareness of CCS will be different in each jurisdiction.

This report sets out the need for CCS in industrial applications and the main obstacles that it faces. In general, these obstacles are found to be common across the sectors studied, but individual sectors present specific costs, challenges and levels of readiness for CCS. The resulting policy recommendations take into account these differences. They aim to provide carbon capture, use and storage (CCUS) Action Group governments with the tools to prepare the ground for CCS to make a significant contribution in the timeframe of agreed climate targets, starting next decade.

Timing is crucial. Analysis has indicated that no more than one-third of proven reserves of fossil fuels can be consumed prior to 2050 if the world is to achieve the goal of limiting warming to 2°C, unless CCS technology is widely deployed (IEA, 2012a). If it is widely deployed, CCS could contribute one-sixth of cumulative emissions reductions between now and 2050, with half of this contribution coming from industrial applications (IEA, 2012b). To have a significant impact, commercial deployment of CCS will be required from 2030 in most CO_2-intensive sectors. Yet it can take five years to pilot a technology, and 10 to 15 years before sufficient demonstration is complete. Reaching the 2030 target for wide deployment in all sectors requires the development process to start in earnest today, otherwise the risk of further locking-in emissions in long-lived infrastructure will increase.

The scarcity of policies to reward the switch from unabated use of fossil fuels to CCS has no doubt contributed to the slow rates of CCS project development and hesitation by private actors. This paper explains why it is not just because we anticipate a continued – and in many regions, growing – role for fossil fuels that we need CCS, but also because we expect the economy to continue to rely heavily on materials whose production cannot be decoupled from high CO_2 emissions without CCS.

Government actions that assert the importance of CCS will help unlock the necessary actions in the private sector and establish confidence in the ability of industrial sectors to limit their emissions.

Section 1
Why is CCS in industrial applications of critical importance?

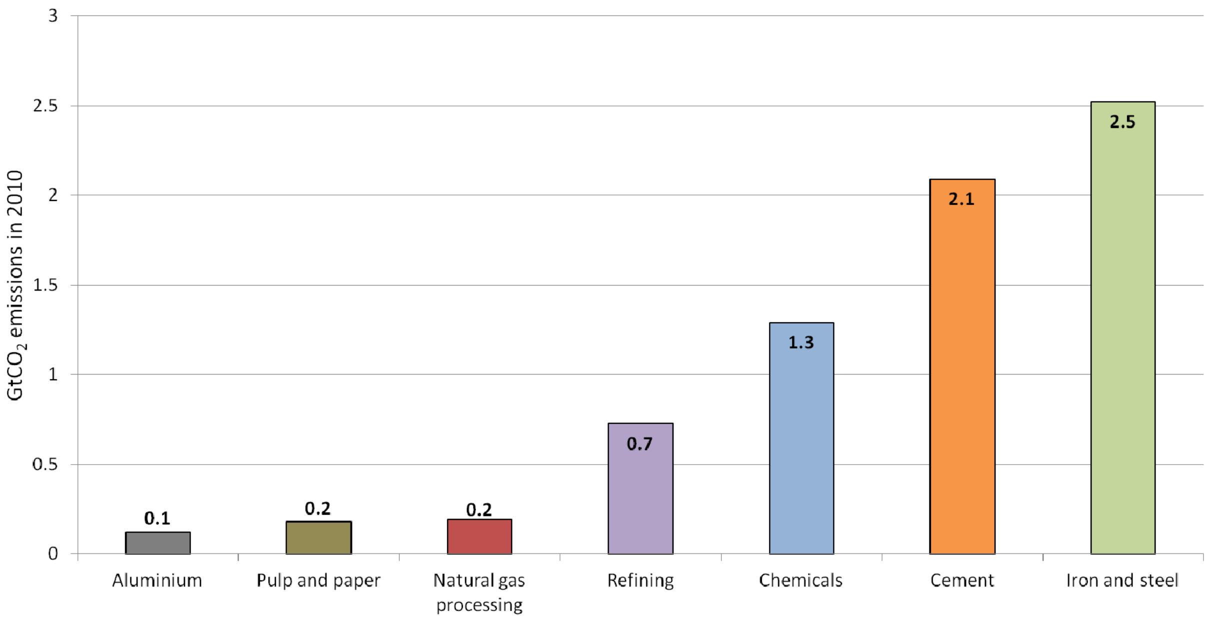
- ***Accounting for nearly one-quarter of global CO_2 emissions, industrial sectors require CCS if they are to successfully make deep cuts in the CO_2 intensity of their production processes.***

Industrial sectors such as cement, iron and steel, chemicals and refining account for one-fifth of total global CO_2 emissions (see Figure 1). Furthermore, as shown in Figure 2, emissions from each of these sectors are expected to grow until at least 2050 under current policies. This is primarily because of increasing demand for consumer products and infrastructure in growing economies, but also due to changes in product specifications, such as standards for lower sulphur diesel fuels; this requires additional processing to meet fuel demand from a variety of crude oils.

Industrial applications could comprise half of the emission reductions achieved through CCS globally by 2050 (IEA, 2012b). However, this could be even greater if CCS deployment in the power sector does not reach foreseen levels, for example if energy efficiency measures or other low-carbon technologies contribute more to than their expected shares of electricity generation.

In contrast to the power sector, several of the world's most carbon-intensive industries have no alternatives to CCS for deep emissions reduction because much of the CO_2 is unavoidably generated by their production processes, and not from fuel use. CCS will thus be essential for these sectors and this is where attention needs to be focused.

Figure 1. Global emissions from the seven most CO_2-intense industrial sectors in the IEA *Energy Technology Perspectives* (*ETP*) analysis



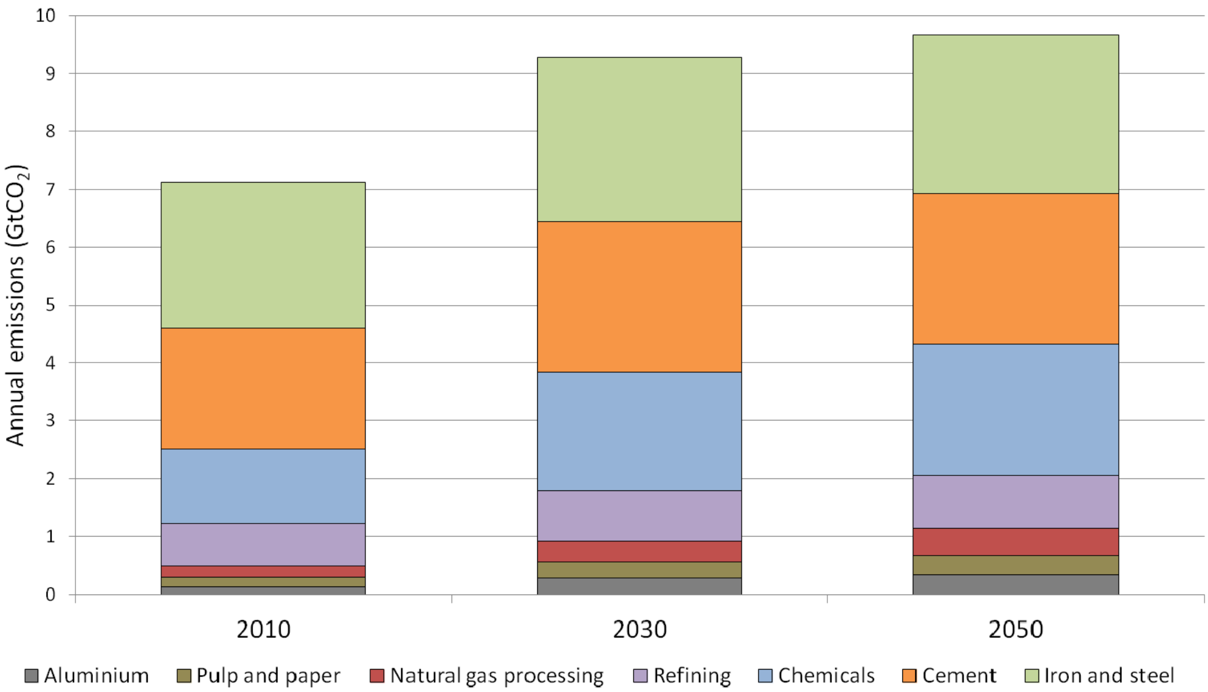
Notes: based on the 4°C Scenario (4DS), which takes into account pledges made by countries up to 2012 to limit emissions. The food and drink and biofuels sectors are not included here due to their low contribution. Emissions from biofuels are considered as net zero emissions in GHG accounting principles, but biofuels can in some cases provide low-cost opportunities for emissions reduction through CCS. The chemicals sector includes petrochemicals.

Source: IEA (2012b).

Crucially, CCS in industrial applications could break the link between economic growth and CO_2 emissions in CCUS Action Group countries.[1] This is because of the importance of commodities such as steel, cement, liquid fuels and chemicals for the growth of modern economies. In addition, materials like steel, carbon fibres and concrete are fundamental to the supply chains of other low-carbon technologies – *e.g.* wind and nuclear power – that seek sustainable lifecycle performance. Put simply, without CCS, there are no alternative methods on the horizon in the near term for the production or substitution of these commodities in a way that avoids generating CO_2.

A policy change is required that can reduce and then reverse the growth in emissions from the most CO_2-intensive sectors globally, while enabling continued production of key commodities that underpin economic development, competitiveness and, consequently, employment. The four sectors with the highest emissions levels all have long-lived infrastructure that changes only incrementally at a global level. For these sectors, 2050 is only one investment cycle away and thus reliable low-carbon production routes, including CCS, would need to be available to investors in new production capacity as early as 2025, to have a major impact. This emphasises the vital need for early action.

Figure 2. Global emissions trends by industrial sector in the IEA *ETP* scenario that accounts for recent emissions reduction pledges by governments



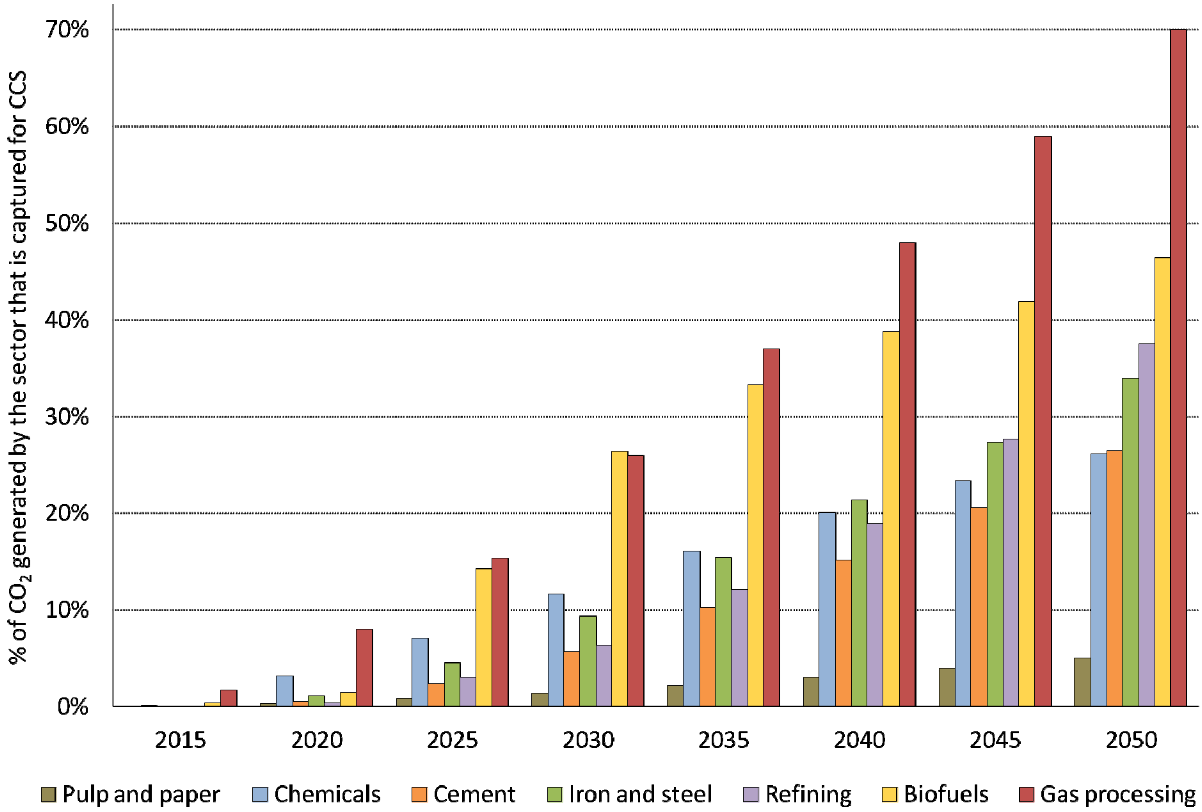
Notes: the 4DS takes into account pledges made by countries by 2012 to limit emissions. The food and drink and biofuels sectors are not included here due to their low contribution.

Source: IEA (2012b).

The *ETP* 2°C Scenario (2DS) charts the lowest cost pathway to achieving the goal of limiting global temperature rise to not more than 2°C. Figure 3 shows that high proportions of the production volumes in these CO_2-intense sectors should be equipped with CCS, starting from the 2020s. One-third of all steel production would involve CCS, and one-quarter of all the CO_2 from cement production would be captured and stored by CCS by 2050. These figures mean that at least one-third of all new and refurbished plants would have CCS from 2030 worldwide. Continued industrial expansion in developing countries would mean that they would host the majority of CCS activity.

[1] These are listed in Annex V.

Figure 3. Proportion of CO_2 generated globally that is captured and stored through CCS in the sectors analysed in the 2DS



Source: IEA (2012b).

Starting from today, the early focus for deployment is on sectors such as gas processing. Natural gas from some fields is extracted with a CO_2 content that is too high for the natural gas pipeline infrastructure and the CO_2 must be stripped out before selling the gas. This CO_2-removal process is very common today but the highly pure CO_2 that is separated is usually vented to the atmosphere. However, the commercial application of CCS has already started in Norway, and could be applied to two-thirds of all such activities by 2050. The CO_2 from ethanol production for biofuels is also very pure but is vented today; this is why it too is seen as an early opportunity for emissions reductions via CCS in Figure 3. Up to 2030, the proportions of gas processing and chemicals (ammonia and methanol) facilities that would be storing their CO_2 would exceed that of coal-fired power plants.

CCS in industrial applications is important because it would reduce the costs of tackling climate change. If CCS were not available to the power sector alone, the investment needs for electricity generation would increase by 40% to reach the same emission target in 2050 (IEA, 2012b). However, it is suggested that if CCS were not available for deployment in either power or industry, the global mitigation costs across the economy could rise by 50%, including fuel costs (Kober *et al.*, 2013). Any reduced production of steel and cement as a consequence would negatively impact economic growth.

From the perspective of achieving lowest cost emissions reductions in the global economy, CCS in certain industrial applications presents significant potential. Looking at the CO_2 capture and usage projects that are already in operation – the large-scale projects are all in industrial applications (GCCSI, 2012). Many of these projects are commercially viable because the CO_2 is purchased for enhanced oil recovery (EOR). The choices made by EOR operators regarding their CO_2 providers therefore reveal the lowest cost CO_2 sources.

These industrial applications provide relatively cheap CO_2 primarily due to the inevitable production of relatively pure CO_2 which does not require significant clean-up as part of the manufacturing processes. Hydrogen production in the chemicals sector is another good example of a process where some of the generated CO_2 is already captured and used; in this case as a feedstock for the production of urea fertiliser from ammonia or for methanol. Although the volumes of CO_2 that can be used this way are limited[2] and these uses do not prevent the CO_2 from re-entering the atmosphere, the message is clear: CO_2 is captured commercially today from several sectors at an acceptable cost. New chemical uses of CO_2 could potentially assist the economics of CCS, especially in the chemicals sector, but are unlikely to reduce significantly the need for geological storage.

The processes with the lowest CO_2 capture costs will generally also have the lowest climate mitigation costs associated with CCS. This is because CO_2 transport and storage costs for a given volume will be broadly the same regardless of the CO_2 source and are a relatively small proportion of the overall CCS costs.

A number of energy-intensive sectors have already recognised the need to reduce emissions intensity by at least 50% in the coming decades;[3] with the relative contributions of different sectors depending on marginal abatement costs. Reductions in CO_2 emissions can be, and are, achieved through continual efficiency improvements to production technologies, often driven by a desire to reduce energy costs. Further reductions will be possible by using renewable heat and electricity to provide the energy used in these sectors. But, crucially, the extent to which efficiency, renewables and imported electricity can lower fossil energy demand is technically limited. Without CCS, emissions that are inseparably associated with the production processes cannot be avoided.[4]

In conclusion, CCS in industrial applications is of critical importance because almost a quarter of the world's CO_2 emissions are from industrial sectors that will have no other way to cut the CO_2 intensity of their production processes by more than 50% in the next 40 years. Furthermore, it offers many of the cheapest opportunities for CCS and for climate mitigation more generally.

[2] For example, the process of producing ammonia generates more CO_2 than is needed to convert all the ammonia to urea.

[3] For example, WorldSteel's CO_2 Breakthrough Programme looks at technologies that could revolutionise the way steel is made, citing CCS as the identified route for exceeding 50% CO_2 reductions. The World Business Council for Sustainable Development has collaborated with the IEA to consider a transition path for the cement sector to move towards the year 2050 with half of its current CO_2 emissions (IEA, 2009).

[4] Process emissions are CO_2 emissions that are not related to combustion of fuels, but rather are the product of chemical reactions in the production process. For example, the CO_2 that is released from limestone when making cement, or results from the removal of CO_2 from the product stream, such as from natural gas that is highly contaminated by CO_2.

Section 2
What is the status of CCS in industrial sectors, and what obstacles do policies need to address?

- ***Among certain sectors, such as steel and cement, there have not been enough projects to allow learning and reduce cost, yet companies that invest in low-carbon production still suffer competitively. Policies that address this deadlock are required.***

CEM 3 rightly identified CCS in industrial applications as a crucial area for action. They offer some exciting opportunities for early deployment of CCS, but their impact on global competitiveness and the scales of the opportunities present particular challenges for policymaking and coordination.

Externalities associated with CO_2 pollution are not routinely factored into the costs of production from energy-intensive sectors today. This market failure has in theory been addressed by carbon pricing in some regions. The logic of this approach is that a rising cost penalty for emissions will guide firms to increase efficiency, adopt low-carbon energy sources and, ultimately, implement CCS. Within a regulated CO_2 emissions limit, firms that take these steps will have lower production costs than firms that do not.

This simple outlook fails to recognise the industrial dynamics of sectors exposed to global trade. It also risks underestimating the multi-stakeholder, long-term challenge of developing the necessary suite of CCS technologies in a timely manner so that deployment can proceed smoothly, once carbon prices and other policy constraints reach sufficient levels. This section discusses how technically ready CCS is today, and why an approach based purely on carbon pricing may not lead to the availability of CCS to deliver the necessary emissions reductions.

We do not yet have experience capturing CO_2 from some key industries

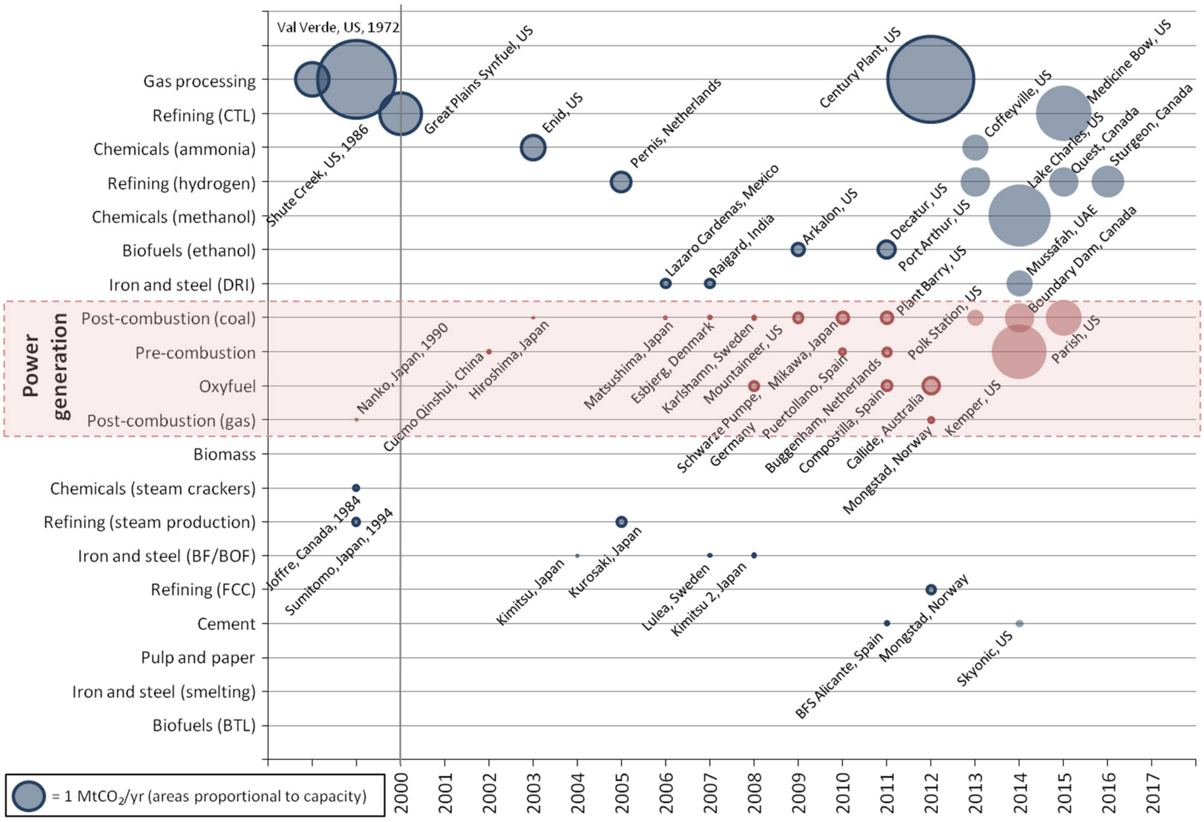
The sectors that will need to apply CCS, and their technologies for doing so, are not homogeneous. CCS is already proven at scales of one million tonnes of CO_2 per year ($MtCO_2$/yr) in the gas processing sector, and CO_2 capture is also commercially understood for large-scale hydrogen and ethanol production (in the refining, biofuels and chemicals sectors). They are used to supply the beverage industry or EOR.

In contrast, other technologies for capturing CO_2 from industrial applications are insufficiently understood and demonstrated, and costs are highly uncertain. These technologies do not yet offer a commercially viable investment proposition with an acceptable level of risk. CO_2 capture in some industrial applications (bottom of Figure 4) is not as advanced as the power sector in terms of scale of executed and planned projects. This is because they pose specific technical challenges for capturing CO_2, unlike the "high purity" CO_2 sources (top of Figure 4). If they did not, they would have already been developed for supplying EOR projects even in the absence of climate-related incentives. Their future development depends on creating sufficient urgency for deep CO_2 emissions reductions.

A variety of CO_2 sources exist within some sectors and CO_2 capture has been tested on these sources to varying degrees (Figure 4). In addition, different capture approaches will be appropriate in different circumstances. For large-scale deployment in the 2020s, it is particularly important that the different CCS technology options are tested at progressively larger scales.

Technologies move from pilot to demonstration-scale projects in sequence. Leading each technology through commercially operated and regulated demonstrations of 0.1 $MtCO_2$ to 1 $MtCO_2$/yr over the next decade will be essential. The learning from large demonstration projects continues even after they are operational. To prove the technology for commercial investment, projects may need to operate for five to ten years to generate the necessary knowledge, cost confidence and cost reductions.

Figure 4. Operational start year of the next largest CO_2 capture projects on various processes



Notes: start years beyond 2012 are taken from GCCSI (2012). Only projects defined as having reached the Define stage in accordance with the Global CCS Institute's Asset Lifecycle Model are included. Blue circles represent individual projects in industrial applications; red circles represent individual projects in the power sector; the circles without borders are not yet operational but are planned to come online in the indicated years. CTL = coal-to-liquids; DRI = direct reduced iron; BF = blast furnace; BOF = basic oxygen furnace; FCC = fluid catalytic cracker; BTL = biomass-to-liquids.

Source: unless otherwise noted, all table and figures in this paper derive from IEA data and analysis.

The lower cost options that are already operating at scale today are beyond the stage of demonstrating CO_2 capture technologies and can be considered commercially proven. These applications can make their most significant contributions by testing and developing the full CCS chain, including CO_2 transport and storage.

Although CO_2 transport and storage are presently outside the technical competences of these industrial sectors,[5] it is important that parallel efforts are made to confirm the availability of adequate well-regulated storage capacity. Business models for CO_2 transport and storage must emerge so that these services can be provided to all relevant sectors. Industrial producers interested in applying CCS to reduce their emissions need confidence that suitable sites for the safe and permanent storage of CO_2 will be available. There are strong public policy arguments for the mapping and development of storage capacity in the next decade. Success in these endeavours, especially in countries looking at onshore CO_2 storage, will be defined by the ability of all actors – governments, operators of CO_2 transport and storage, and major CO_2 emitters – to raise public awareness of the importance and safety of geological CO_2 storage.

[5] With the exceptions of the refining and gas-processing sectors.

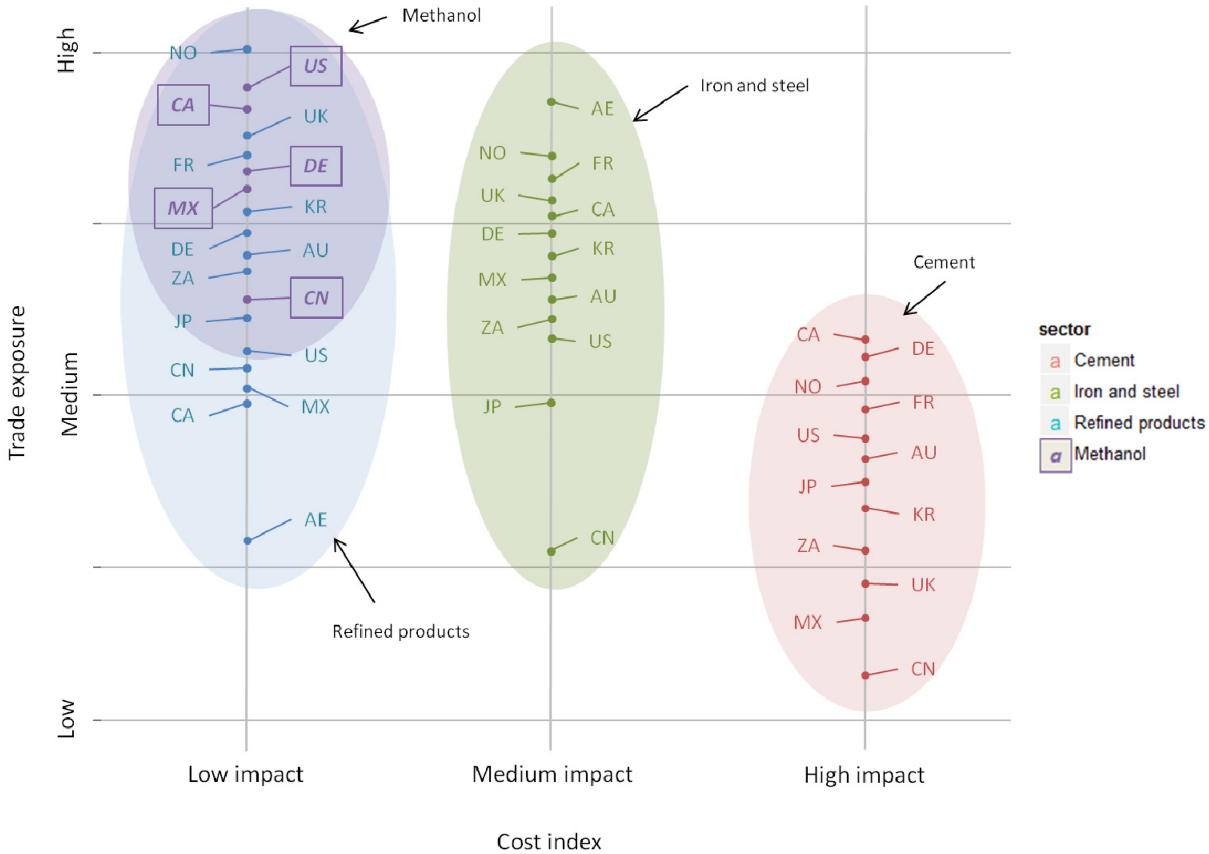
Tailor-made policies are required for sectors exposed to trade

All of the industrial sectors studied in this report are exposed to global trade to varying degrees. The products of these sectors are traded globally on international markets that are highly sensitive to production costs. CCS increases production costs, which could well undermine competitiveness in regions that pursue independent policies to internalise the social and environmental costs of CO_2 emissions.

Polices and measures to mandate or incentivise CCS in trade-exposed sectors are likely to have consequences in these markets. Besides an impact on competitiveness, if production outside the region increases because of a decline of less-competitive production in a CO_2-regulated region, overall emissions will be impacted. If the production that is displaced has a higher CO_2 intensity, the result is a reduction in global CO_2 emissions, assuming constant demand. This is often the case today, as regions that are expanding capacity, such as China and Korea, use modern, efficient and competitive technologies.

However, the opposite can also occur if highly competitive, but CO_2-intense production based on coal displaces CO_2-regulated production based on natural gas. This is known as carbon leakage, and can be a negative side effect of climate policy, which both European Union (EU) and Australian policy makers have sought to avoid in their emissions trading and pricing systems. Carbon leakage and damage to regional competitiveness can result from adjustments to capacity utilisation between regions by multinational companies in the near term, and from changes in the locations of capacity investments in the longer term.

Figure 5. CCUS Action Group countries plotted by sector as a function of their exposure to international trade and the relative impact that CCS would have on production cost



Notes: trade exposure is measured as a composite of various published metrics, including geographic market measures and trade intensity measures. Cost index represents likely relative increase in production costs, using cost ranges presented in Figure 7. AE = United Arab Emirates; AU = Australia; CA = Canada; CN = China; DE = Germany; FR = France; UK = United Kingdom; JP = Japan; KR = Republic of Korea; MX = Mexico; NO = Norway; US = United States; ZA = South Africa.

Source: analysis for the IEA by Vivid Economics.

Industrial sectors are heterogeneous and will therefore vary in terms of trade exposure and cost impacts of CCS, which can range from 2% of the market price for ammonia, to 100% of the price for cement, potentially doubling the price per tonne (Figure 5).

Companies with CCS projects in these sectors, including demonstration projects, will need to sell their output commercially in markets where CO_2 emissions are not uniformly regulated. They cannot be sure they will be able to pass their costs to consumers. However, production in countries where the sector is not exposed to international trade should be able to tolerate higher price increases; and production in countries where the cost increase is relatively low might still be able to operate in trade-exposed regions. The most attractive sectors and countries for CCS demonstration projects are likely to be those for which both trade exposure and relative cost increase are low, for example refinery projects in the United Arab Emirates or Canada, or projects in China. Pilot projects could valuably be undertaken in any country, however, and the lessons then applied elsewhere.

The information displayed in Figure 5 helps provide some insight into the success of CCS demonstration projects in 2012. As projects can cost upwards of USD 300 million and last for up to ten years, from planning to operation and monitoring of the stored CO_2, commitment to a project is a major decision for public and private institutions. Confidence in the medium-term outlook for production from the selected facility is important. In 2012, Royal Dutch Shell took a final investment decision on the Quest project in Canada's refining sector to store 1 $MtCO_2$ per year in a saline aquifer. The CO_2 capture technology to be used is mature; the trade exposure of Canada's oil sands products is not high; the relative cost increase is low; and the sector (and the resource it exploits) is seen as both a national and provincial asset. These conditions enabled governmental authorities and Royal Dutch Shell to commit to financing and operating the project over its 15-year lifecycle.[6]

In contrast, the Ultra-Low CO_2 Steel (ULCOS) demonstration project at Florange in France was postponed in 2012. Funding was available from the European Commission, the French government and the operator, but ultimately the market and cost conditions made it impossible for the partners to commit to the project when the perceived financial risks outweighed the expected rewards. The Florange steel site is internationally exposed to trade and cannot guarantee its continued operation in the near or medium term. The European iron and steel sector is under severe financial pressure due to overcapacity globally and is struggling to take decisions for the next five years, let alone the next 30 years. The relative cost increase from CCS would be of medium impact and the national industrial strategy for the steel sector is uncertain.

To be able to take a long-term view of investments to secure a place for CCS, and therefore low-carbon production in a decarbonising world, trade-exposed sectors are looking for an industrial policy architecture that secures their futures and enables them to plan ahead with confidence. Today, most private sector investments in, for example, efficiency improvements are generally undertaken by energy-intensive industries if they have a payback period of around three years or less. Given that CCS projects have a much longer payback period, funding of CCS projects at a national level in CCUS Action Group countries may be almost entirely reliant on public subsidy due to the current fiscal stringencies in sectors like iron and steel.

Ingredients of long-term policy architecture

Appropriate policy architecture evolves as a technology matures (IEA, 2012c). It begins as technology-specific support, which explicitly targets the development of CCS into a commercial activity though provision of capital grants, investment tax credits, credit guarantees or insurance

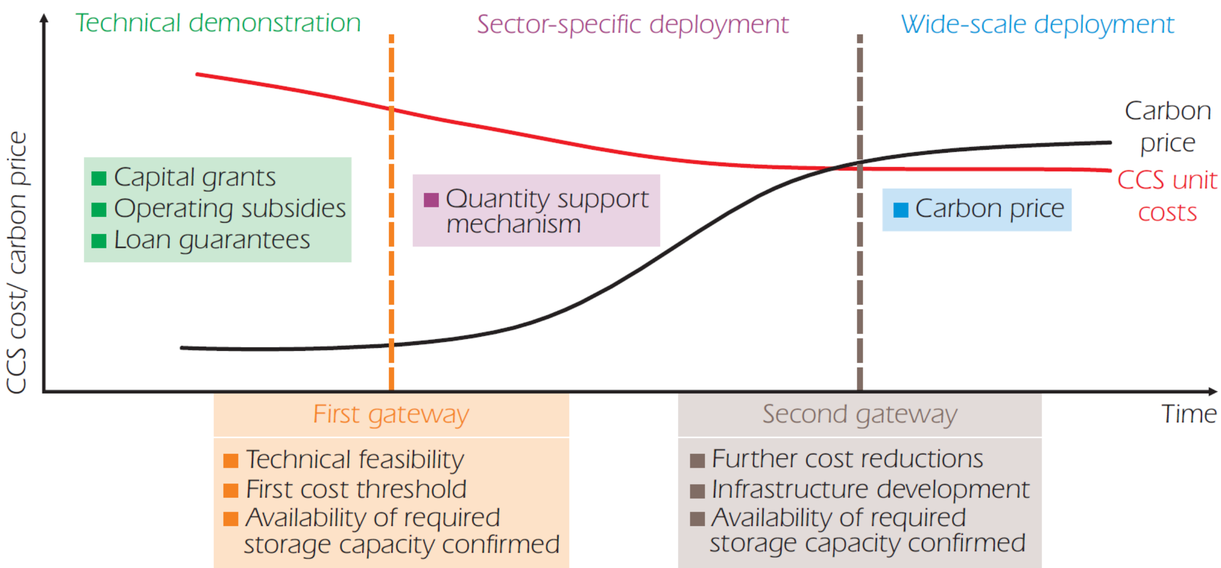
[6] The government of Canada is providing 14% and the government of Alberta is providing 86% of the additional costs of CCS for this approximately CAD 865 million publicly funded project.

(Figure 6). Early stage measures seek to enable projects to move ahead and generate replicable knowledge. There is general agreement among public and private actors alike that in the long term CCS will only need the incentive of a carbon price, but that in the meantime targeted sector-specific industrial strategies are needed to convey CCS from the pilot project phase to the demonstration and then deployment phases.

Today, in CCUS Action Group countries that have created a price for CO_2, provisions are made to shield energy-intensive industries from the full price of carbon. The most common mechanism is the free allocation of emissions allowances to sectors at risk of losing competitiveness or of carbon leakage. To encourage improvements, the free allocation can be linked to a benchmarking of plants' CO_2 performance, but this does not provide a sufficient incentive to develop or deploy CCS.

Furthermore, in the near term, regional CO_2 pricing systems may only incentivise incremental efficiency improvements towards theoretical efficiency limits. CCS – a big impact, capital-intense, long-term technology – would be neglected. Yet, CCS projects can take over a decade to plan, construct, operate and optimise. Prospective operators need confidence that CO_2 prices are rising and that their industrial base will be maintained over this time period.

Figure 6. Possible gateways on the way to wide-scale deployment in a CCS policy framework



Source: IEA (2012c).

Despite these challenges, there will be positive side effects to encouraging CCS in industrial applications. Initial, supported deployment of CCS on processes like hydrogen production or fermentation in sectors such as biofuels, refining or chemicals will contribute valuable learning for CCS in general, while helping to reduce emissions at minimum cost. In the United States, CCS projects with an EOR component are proceeding with some government funding on ethanol, ammonia (hydrogen), refining (hydrogen), methanol (hydrogen) and gas processing facilities. However, much of this generic learning relates to CO_2 transport, CO_2 storage, regulations and liabilities. Because sector-specific knowledge from operating large-scale projects in all industrial applications is required, an industry's option to remain a free-rider and expect others to develop appropriate CO_2 capture technologies appears very limited.

Targeted support to technology learning and early deployment in additional sectors and regions could be supported by the types of instruments listed in Table 1. These measures could be tailored on a sector-by-sector basis. They could help stimulate first-mover investments by complementing an insufficient or non-global carbon price. It is likely that as the policy framework evolves, the costs and risks of CCS development will be borne increasingly by the private sector.

Table 1. Selection of potential incentive mechanisms that could be considered for CCS in industrial applications, with an indication of their possible impacts on competitiveness

Mechanism	Description	Possible impact on competitiveness
Policies used to accelerate technology learning in the near to medium term		
Capital grant	Public body provides direct capital funding for investment. Requires expertise in selecting recipients and setting grant level.	Cost burden on public body. Minor impact on competitiveness unless a high level of private co-financing is stipulated. Possibility to use contributions from the private sector by dedicating revenue from a levy on companies in relevant sectors to this purpose.
Investment tax credit	Reduction of tax liabilities based on investment in CCS equipment.	
Production tax credit	Reduction of tax liabilities based on operating CCS assets.	
Production subsidy	Direct payment for each unit of output produced from CCS-equipped facilities, or each tonne of CO_2 captured/avoided/stored from an installation.	Cost burden on public body. No impact on competitiveness if impact of CCS costs is balanced by the revenues from the mechanism.
Emissions reduction subsidy	Direct payment for each tonne of CO_2 captured/avoided/stored from an installation.	
Policies used to control CO_2 emissions and incentivise CCS in the longer term where it is most cost-effective among other abatement opportunities		
Baseline and credit	Establishes a baseline or benchmark level of CO_2 emissions per unit of production for a sector, firm or facility. The scheme rewards reductions below the baseline by providing CO_2 credits or direct payments. Requires expertise in setting the baseline, in setting the rate at which it tightens, and in monitoring and verification.	Performance that is rewarded is a cost to the public body. If performance above the baseline is penalised then the cost is passed to the consumer and the competitiveness of installations without CCS will be impacted relative to similar installations in regions that do not apply an equivalent scheme.
Emissions performance standard	As above, but the level is set higher and acts as a limit above which operation is prohibited. For example, it could set a date after which production from a sector without any CCS is effectively prohibited, thus creating an indirect incentive for alternative production routes. Can be applied to individual installations or to firms/sectors that internally share the cost of meeting the target through a tradable certificate scheme, for example.	If applied to installations, at a level effectively mandating CCS, it will have a negative impact on competitiveness relative to facilities in regions without equivalent schemes. If production processes exist that can meet the standard without CCS but cannot fully meet demand, high emissions facilities will become marginal producers. If applied to firms, or a whole sector, incremental CCS investments can be shared without affecting internal competitiveness. If costs are passed to consumers, installations in regions with standards could lose competitiveness relative to those without.
Feebate	Firms/installations pay fees in accordance with their level of CO_2 emissions. The resulting fund is shared among firms covered by the instrument at the end of each time period, to the benefit of those with lower CO_2 emissions. Payments could be direct or in the form of CO_2 credits.	If the system is cost neutral then the cost burden is spread between firms/installations with higher CO_2 emissions. The competitiveness of installations without CCS will be impacted relative to similar installations in regions that do not apply an equivalent scheme.

Policies used to facilitate access to capital		
Co-investment equity	Public authority takes part directly in investment by providing equity. Gives investor confidence on policy stability, as a public authority is involved.	Cost shared between public authority and private investor. Return on investment expected if the policy environment successfully rewards low-carbon production. Impact on competiveness depends on the wider policy environment. Acceptability depends on political/economic situation.
Credit guarantees	Public authority guarantees credits from financial institutions by firm/installation. Most effective where projects are close to financial close.	
Provision of debt	Public authority provides a loan to a company or project that invests in CCS. May give assurance to other debt providers.	

As a first step, governments are advised to carefully consider in which sectors domestic production will be important to their country's industrial future. Engaging these sectors in a foresight process that charts a course to addressing emissions reductions in line with competitiveness needs will be important to building consensus around CCS development. The design of appropriate policy architecture, incorporating suitable elements from Table 1 can proceed from this basis in the near term and involve international partners. Policy approaches that are sectoral and international could overcome challenges of market imbalance between countries. Technology development and demonstration approaches that are cross-sectoral and international could reduce overall costs through collaboration on common problems.

Due to remaining knowledge gaps related to costs, flexible policy frameworks will be needed that incentivise opportunities for CCS deployment in each sector with regard to its costs and industrial acceptability. This will be important if more than one sector, including power, is considered important to a given country. In terms of enabling deployment, locational factors that stimulate the evolution of clusters of CCS-equipped industrial sites sharing a local CO_2 transport and storage infrastructure will be relevant. Co-location could be promoted to help sectors be "CCS-ready".

Finally, deployment of CCS in industrial sectors faces obstacles that are common to all applications of CCS. Among others, these include: the slow progress of delivering proven CO_2 storage capacity that can be accessed by plants that capture their CO_2; a lack of understanding of the risks associated with CO_2 storage in society at large; and, insufficient clarity among many countries of the business model that will enable the providers of CO_2 transport and storage to raise revenue. At present, many industrial sectors are not engaged in cross-sectoral activities that seek to address these issues.

This section has identified three main impediments to CCS deployment in industrial applications: remaining knowledge gaps regarding costs and technical performance; potential impacts of CCS on competitiveness; and, limited engagement of industrial sectors in tackling common CCS challenges. The next section focuses in more detail on the challenge of better understanding costs.

Section 3
What do we know about CO_2 capture costs in these sectors?

➢ ***CCS costs are dependent on numerous factors, including the concentration and volume of the CO_2 from different processes at an industrial site; costs therefore vary widely and within sectors. To reduce uncertainty, more projects are needed in the near term.***

The variance of CO_2 capture costs among sectors is due to different technical characteristics and the industrial environment in which the sectors trade. Studies have shown a number of factors to be highly influential. These are discussed in Annex II and listed below.

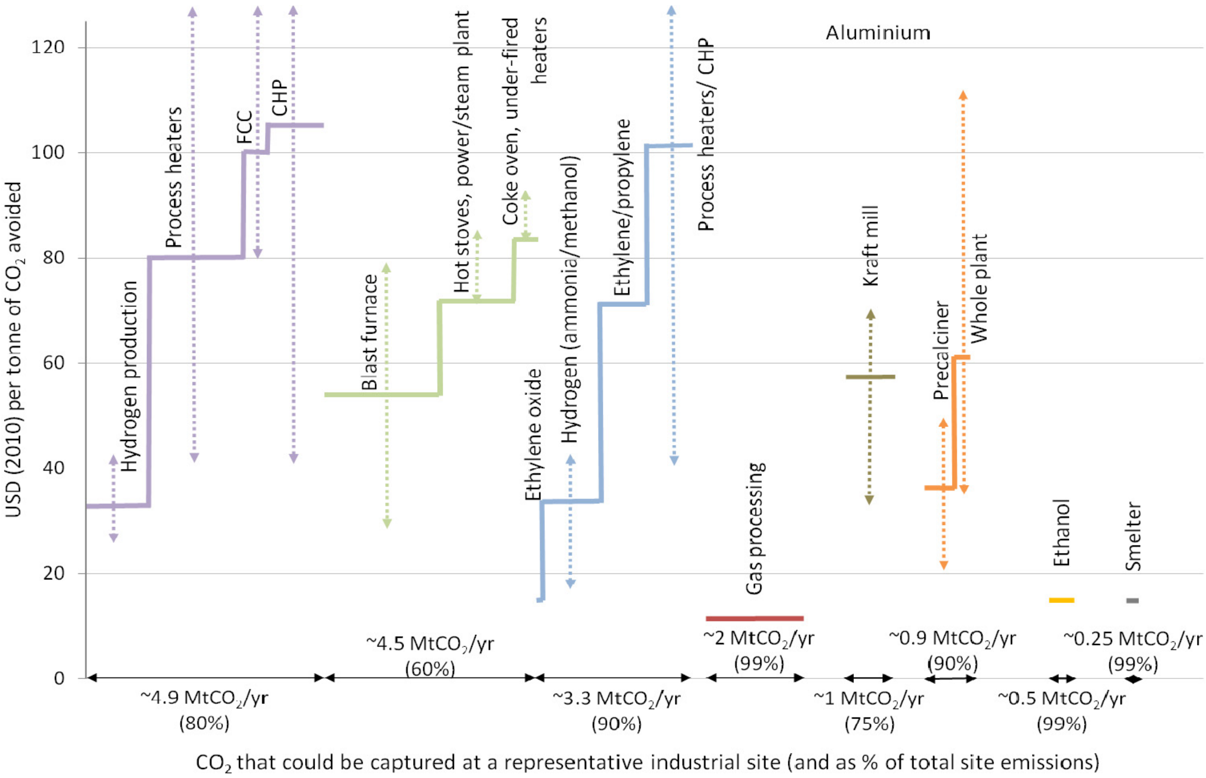
- **CO_2 concentration**. Whether the CO_2 is pure or mixed with impurities is an important driver of costs. Mature technologies, such as CO_2 capture from ethanol fermentation, deal with CO_2 sources that are highly pure and for which capture is relatively cheap. Some sectors yield a highly pure CO_2 stream because separating out the CO_2 is integral to the purification of the desired product, such as hydrogen or natural gas.
- **CO_2 partial pressure**. Even if the CO_2 source is not greater than 90% pure, it can be more easily and cheaply captured if it is at a higher pressure. Gas processing is an example of a process that has low costs because the partial pressure of CO_2 is high.
- **CO_2 volumes**. Larger CO_2 sources offer better economies of scale for CO_2 transport and storage, while scale-up of smaller sources from pilot to full-scale plants could involve lower magnitude and commercial risk. A modern large BF site can produce 10 $MtCO_2$ to 20 $MtCO_2$/yr, which is more than a coal-fired power plant. Plants based on coal produce more CO_2 than plants based on natural gas or naphtha.
- **Availability of local excess heat**. The ability to redirect excess heat from other processes to supply the heat for CO_2 capture could reduce costs significantly, but as efficiency gains are sought by all sectors, competition exists for any such "waste" heat at industrial sites. This issue will be highly important for refineries and chemical sites.
- **Need for plant redesign**. In some production processes, capturing CO_2 will be relatively straightforward and low-cost, but existing plants may need to be significantly altered and prospective plants redesigned to accommodate CO_2 capture. This could be the case for oxy-firing of cement kilns and top gas recycling at BFs. These redesigns could be seen by investors as radical changes to relatively conservative industries and thus additional support will be required to help demonstrate that product quality and reliability are preserved.
- **Location**. The distance of a CO_2 source to a storage site will influence transport costs.[7] Of equal importance could be the distance to other CO_2 sources that can share infrastructure and stimulate the provision of transport and storage services. Industrial centres that reduce costs by evolving into clusters of CO_2 sources, for example by sharing excess heat and services, will find their location to be advantageous in a carbon-constrained world.

  The country in which a project is situated will have a bearing on cost. The IEA 2DS anticipates that 72% of CO_2 captured from industrial facilities by 2050 could be in developing countries and these projects could have lower costs (IEA, 2012b).

[7] CO_2 transport costs are the lower cost element of the value chain of capture, transport and storage.

The cost levels shown in Figure 7 reflect these factors and underline specific considerations. Many industrial sites comprise multiple CO_2 sources with various costs of capture. For example, the cost for every tonne of CO_2 captured from hydrogen production on a refinery site might be low, but the cost of CO_2 capture from the other 80% of onsite emissions is likely to be higher and highly variable depending on the process. Furthermore, all sites are likely to start by capturing the lowest cost CO_2 and then integrating the other CO_2 sources over time, as costs and risks are reduced.[8] It is therefore incorrect to assume that, for example, a 90% capture rate is possible for every industrial site that applies CCS. Unlike the power sector, the CO_2 associated with providing additional energy for CO_2 capture may not itself be captured; *i.e.* it may be emitted from a separate boiler to which CCS has not (yet) been applied.

Figure 7. Marginal abatement costs for representative individual industrial sites



Note: figures are indicative and show ranges of cost estimates from the sources of the data used for this figure.
Sources: see Annex III.

Figure 7 also shows the wider ranges of cost figures for CO_2 capture processes that are not yet technically mature. These ranges arise in part due to the paucity of different available engineering studies and the different assumptions and locations on which they are based. Uncertain costs are a hindrance to policy and, although some of the differences relate to site-specific factors, uncertainty needs to be reduced through additional comparable studies, pilot projects and, most importantly, demonstration projects. As there are knowledge gaps common to different sectors – for example in the development of better solvents for scrubbing low-concentration CO_2 from flue gases, or design of oxyfuel combustion chambers – research synergies should be targeted and promoted. Where public funds are allocated to projects, value could be maximised by identifying projects that will fill important knowledge gaps and reduce uncertainty for policy making globally.

[8] An exception to this could be in the iron and steel sector, where there is some investment risk related to refurbishment and construction of blast furnaces due to overcapacity and prevalence of other production routes, such as electric furnaces and DRI. Consequently, it may make sense for blast furnace sites to commence with CO_2 capture on their power generation flue gases, where there may be much less uncertainty and less need for redesign.

Section 4
What actions have already been taken?

- *CCUS Action Group governments and the private sector have put in place a number of measures to develop CCS technologies for industrial applications, but examples of policies that chart a course to a supportive long-term policy environment are rare.*

Which policies and initiatives have been successful for moving CCS through the stages of technical readiness?

Table 2. Selected measures taken by governments in CCUS Action Group countries to develop CCS in industrial applications

Country	Sector	Project type	Summary
Australia	Gas processing	Demonstration	The Australian government has made development of Chevron's Gorgon liquefied natural gas project conditional on application of CCS. AUD 60 million in public funds have been allocated.
Canada	Refining (hydrogen); Chemicals (ammonia)	Demonstration	The federal government provided CAD 120 million to the Shell Quest CCS project that will store CO_2 from an oil sands upgrader. The provincial government of Alberta will support this project with CAD 750 million and will also support the capture of CO_2 from the North West Redwater Partnership's oil sands upgrader/refinery gasification process, as well as an Agrium fertiliser production facility.
France	Iron and steel (BF)	Demonstration	The French government expressed its preparedness to co-fund the ULCOS CCS demonstration project on a BF. The project will not go ahead by 2016, as originally planned, due to economic issues at the plant.
China	Refining (CTL)	Pilot	40 kilotonnes of CO_2 have been captured and stored from a CTL plant in Inner Mongolia, sanctioned and supported by the Chinese government.
Japan	Iron and steel (BF)	Pilot	Since 2008, the COURSE50 programme has targeted reducing CO_2 emissions from Japanese steel plants by more than 50%. A pilot CO_2 capture plant at a BF was successful and extension to demonstration scale is anticipated. Public spending of USD 300 million up to 2020 is foreseen alongside private investment.
Korea	Iron and steel (BF)	Pilot	The CO_2 Breakthrough Framework has piloted CO_2 capture at a BF operated by POSCO with both government and private funding.
Norway	Refining (FCC); cement	Pilot	Technology Centre Mongstad is a large pilot project that captures CO_2 from an FCC plant at a nearby refinery. The project has thus far received around NOK 6 billion from the government. Statoil, Royal Dutch Shell and Sasol are also shareholders. The Brevik cement CO_2 capture pilot has been granted NOK 70 million in public funds.

United Arab Emirates	Iron and steel (DRI)	Demonstration	A CO_2 capture plant at a large DRI facility is planned for operation in 2015 and will be integrated with CO_2 transport for EOR. The project aims to secure additional financing via the Clean Development Mechanism.
United States	Refining (hydrogen); biofuels; chemicals (fertiliser); chemicals (methanol)	Demonstration	Recovery Act funds have been allocated to demonstration projects in the refining, biofuels and chemicals sectors, each planning to capture and inject over 1 $MtCO_2$/yr. The total public funding allocated to five projects is expected to reach USD 1.3 billion and will be complemented by private investment. Two ammonia projects will also produce power electricity (polygeneration).

Further to the public and private activity in the government initiatives listed above, support from private sector initiatives complements overall funding activity for CCS projects. Table 3 underlines the importance of collaborative approaches for mobilising public and private financing. The ULCOS and European Cement Research Academy (ECRA) programmes indicate that collaboration by the players within a sector can foster technological advances and knowledge exchange, both of which are difficult to achieve through government funding systems that invite firms to compete against each other.

Table 3. Selected measures taken by the private sector in CCUS Action Group countries to develop CCS in industrial applications

Country/region	Sector	Name	Summary
Australia	Coal	COAL21	Since 2006, the Australian Coal Association has managed a voluntary levy on production from the Australian coal industry on a per-tonne-of-production basis to support the development of clean coal technologies. The COAL21 fund expects to raise AUD 1 billion over ten years to commit to low-emission demonstration projects on coal, including CCS.
Australia	Aluminium	Alcoa	In recognition of the high indirect emissions caused by aluminium smelting in a region dependent on lignite-fuelled electricity, Alcoa has included in its power supply contract power purchase an agreement to allow co-investment in low-carbon electricity projects, which could include CCS.
Europe	Cement	ECRA	CCS is one of the main research streams for ECRA, a consortium of over 40 leading cement producers (and three of the four main global equipment suppliers) established in 2003 without public funding. ECRA has spent over USD 3 million on three phases of research into optimum CO_2 capture designs and economics, including operation of a lab-scale test. The next phase will involve the design of a pilot project, which the consortium does not think can be self-financed without public support. Intellectual property rights (IPR) from collaborative research are waived by members, who share all results.
Europe	Iron and steel	ULCOS	The ULCOS consortium includes 48 European companies that aim to achieve a 50% reduction in emissions from steelmaking, primarily via CCS. Between 2004 and 2010, the EUR 75 million budget was split between the European Commission (40%) and the project partners (60%) and this financed pilot testing of CO_2 capture at a redesigned BF. Patents are owned and managed by the inventor's firm, but the right of use is shared by consortium members.

Which policies have been employed for charting a course to a supportive long-term policy environment?

Only a few CCUS Action Group countries have adopted climate policies that steer a path towards a low-carbon future for the sectors studied. Several examples in Table 4 below show that a foundation is nevertheless emerging that could be complemented by sector-specific measures.

Table 4. Selected climate policies in CCUS Action Group countries that could provide some incentive for CCS in industrial applications

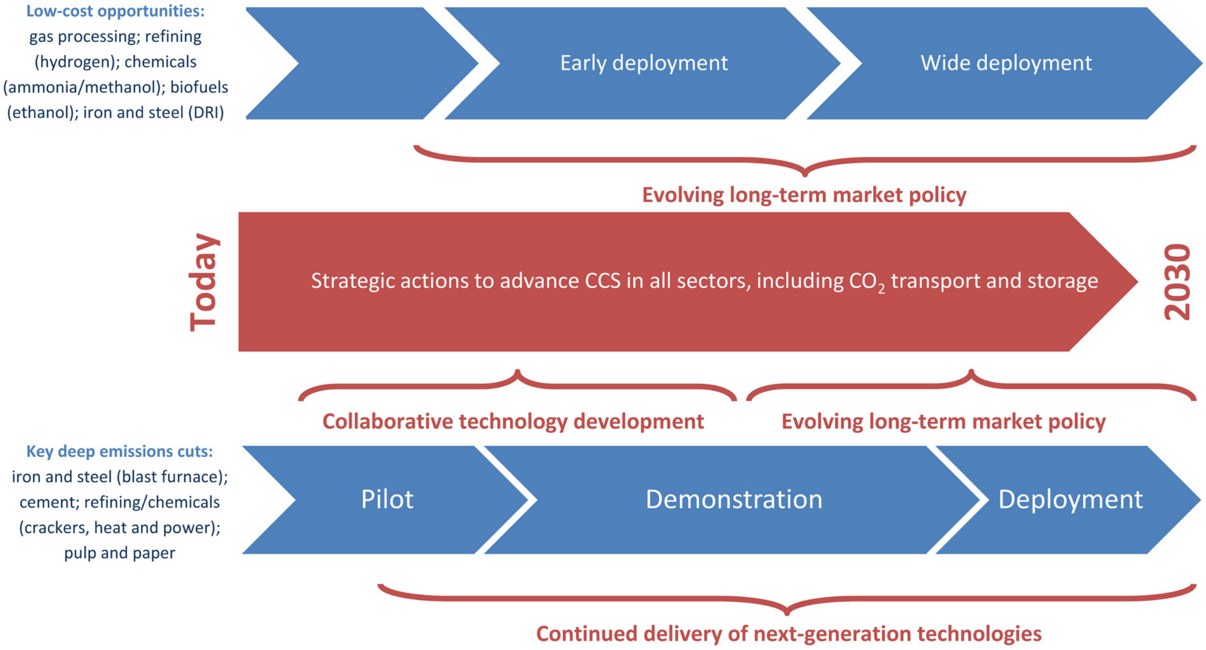
Country/region	Name	Summary
Australia	CO_2 tax	The CO_2 tax is not scheduled to rise to a level that would justify investment in CCS in the foreseeable future, but is likely to be a primary instrument to encourage technological change. CO_2-intense industrial sectors exposed to global trade are exempt from up to 95% of the tax depending on performance against a benchmark. While this provides no incentive for CCS, it could reduce carbon leakage.
Canada	Targets or standards	To meet the target of reducing GHG emissions by 17% from 2005 levels by 2020, the development of GHG regulations for the oil and gas sector is underway, and draft regulations are expected from the federal government in 2013.
European Union	Emissions trading system (ETS)	Industry sectors under the ETS receive free allowances up to a benchmark, partly shielding producers from most of the CO_2 price and some of the risk of carbon leakage. To shield trade-exposed sectors from the impact of indirect costs from purchased electricity, several EU member states are currently preparing compensation schemes.
European Union	Fuel quality directive (FQD)	Article 7a of the revised EU FQD obliges transport fuel suppliers to reduce lifecycle GHG emissions from transport fuel by 6% by 2020. Implementation may involve assigning higher reference values to fuels with higher lifecycle emissions, which could be reduced by application of CCS to refining of oil sands, for example.
Norway	CO_2 tax	The Norwegian CO_2 tax has been highly successful in incentivising the world's only fully commercial CCS projects in the gas processing sector. The tax does not apply to sectors such as power production or refining.

Section 5
What policies are recommended for the path ahead?

> *Maintaining and increasing competitiveness is a long-term goal. CCS policy frameworks should be designed to create a sustainable market starting with support for individual CCS projects and leading to business cases based on the value of low-carbon production processes.*

On the basis of the preceding discussion, a comprehensive climate policy for the delivery of emissions reductions of over 50% in the sectors studied should include the following steps (Figure 8).

Figure 8. Charting a policy path to wide deployment of CCS in industrial applications



Develop, demonstrate and deploy

All technologies should aim to progress to the next stage by 2020. A valuable and feasible level of ambition would be to have five (or more) new operational, pilot or demonstration projects in each sector to support continuous technological progress. Collaborative and cross-sectoral technology development and deployment should be supported wherever possible.

Due to the high levels of investment required and uncertainties relating to the necessary timing for technologies, firms that could benefit from CCS in the future may not be motivated to invest in its development. Due to sector-specific aspects of technology application, and because development could take 10 to 15 years in some sectors, the risk of insufficient investment must be mitigated. Potential steps to avoid this risk include:

- Undertake country-specific studies to determine whether a sector is more likely to apply CCS to existing or new industrial sites, and through what type of production technology.
- Explore how regional or international consortiums of relevant firms in each sector could be supported, ensuring that intellectual property (IP) considerations are taken into account. In this regard, ULCOS and ECRA are both good models. Lessons about the risks and challenges

can be learned from these and from other approaches to coordinate efforts between companies and countries and share the resulting IP between contributing partners. Consortium partners should be encouraged to undertake engineering and cost studies of CO_2 capture options and process integration, and to jointly lead promising technologies through sequential stages from pilot to demonstration scale. To the extent possible, the focus should be on topics that do not currently impact competitive advantage for the firms involved.

- Differentiation between sectors will be necessary to target public funds, including capital grants and loan guarantees, to where they can be most effective. Consortium partners may be able to fund some pilot-scale facilities but a combination of public funds, consortium partners' investments and other schemes will be needed for larger projects.
- In addition to recycling revenues from CO_2 certificate systems, funds for pilot and demonstration projects in CO_2 capture or storage could be accrued though levy systems on production volumes. The Australian Coal Association voluntary contribution scheme is a good example. Global systems established at low levels could be designed to be non-trade distorting.
- CCUS Action Group countries should consider the role for UNFCCC funding mechanisms to assist projects that will contribute CO_2 reductions through CCS projects in industrial applications.
- Competitions for available public funds should be designed to support technologies at their appropriate stages of development. Sectors with very different CCS costs should not compete against one another for public funds on the basis of a single uniform metric, but be targeted according to their development stage, CO_2 avoidance costs and the knowledge they will generate. In some sectors, large-scale demonstration projects will be appropriate, whereas others would suit smaller projects as their subsequent scale-up will be less demanding due to the smaller scales of their CO_2 sources. Both project types will contribute to reducing cost uncertainty and moving towards off-the-shelf solutions.
- CCS is common to long-term emissions reductions strategies across all the sectors studied in this paper. As such, knowledge developed for one sector will have valuable consequences for others, including power generation, and more broadly, for society at large. Firms in different sectors are not in competition with one another and have an incentive to identify non-competitive technology areas. Cross-sectoral collaboration to test various flue gas capture options on different flue gases could be of interest in this respect. Knowledge from this work should be published as widely as possible and, as a collaborative effort, IPR regimes should be structured to be favourable to cooperation. Pilot-scale open-access testing facilities for different flue gas streams could be considered.
- Pilot projects on CO_2 capture technologies that are most relevant for the following sectors and CCUS Action Group countries include:[9]
  - cement – AE, AU, CA, CN, DE, FR, JP, KR, MX, NO, UK, US, ZA ;[10]
  - iron and steel (BF and smelting) – CN, JP, KR, DE, FR, CA, UK, US, AU;
  - refining (FCC and process heater flue gases) – US, CN, CA, DE, JP, KR, NO, AE, FR, UK;
  - pulp and paper – CA, US, CN, KR;
  - biofuels (biomass-to-liquids) – US, DE, CA, NO.

[9] Other countries also have large industrial emissions in the sectors covered in this report, and several of these, such as Russia, India, Brazil and countries in the Middle East, have growing levels of emissions. See Geogreen (2011) Sectoral assessment: source-to-sink matching. Contribution to the UNIDO/IEA *Technology Roadmap : Carbon Capture and Storage in Industrial Applications*.

[10] AE = United Arab Emirates; AU = Australia; CA = Canada; CN = China; DE = Germany; FR = France; UK = United Kingdom; JP = Japan; KR = Republic of Korea; MX = Mexico; NO = Norway; US = United States; ZA = South Africa.

- Demonstration projects for CO_2 capture technologies that are most relevant for the following sectors and CCUS Action Group countries include:
  - refinery (CTL) – ZA, CN;
  - chemicals (ethylene crackers) – ZA, DE, CN, US, JP, KR, NO, CA, AE.
- Integrated demonstration projects for full-chain CO_2 capture, transport and storage that are most relevant for the following sectors and CCUS Action Group countries include:
  - gas processing – US, NO, AE;
  - iron and steel (DRI) – AE, US;
  - refining (hydrogen) – CA, US, CN, NO, DE, FR, UK, AE, KR, JP, MX;
  - chemicals (ammonia and methanol) – CN, ZA, AU, US, CA, DE;
  - biofuels (ethanol) – US, DE, CA, FR, UK, CN.

Create a policy environment to support deployment

Without a supportive policy environment that creates confidence that switching to low-carbon production will be rewarded over the long term, CCS will not be deployed. A significant intensification of action to develop forward-looking policies is required. As CCS is a technology for the medium to long term in most sectors, policy makers will also need to take into account the ways in which industrial production technologies and sectoral dynamics could evolve in the next 20 years. Steps to be taken include:

- Define and expand national policy plans to address CO_2 emissions from industrial applications and introduce CCS as a necessary solution. In the near term, industrial strategies need to allow investors to take a long-term view of investment planning in a specific sector and country. At the same time, attention should be given to developing climate policy architectures that will effectively reduce emissions, while also being sensitive to technology investment challenges and competitiveness concerns.
- A long-term perspective on how to incentivise emissions cuts in the absence of a global CO_2 price is recommended so that competiveness concerns are addressed and investors are given security to plan for a low-carbon future.[11] Regional CO_2 pricing systems could prevent carbon leakage by shielding at-risk sectors from the full price; however, this should be complemented by other measures to support CCS. Instruments for further study include:
  - lifecycle standards for fuel production and use;
  - sectorally applied emissions performance standards, including tradable certificates;
  - sectoral quantity measures for introducing CCS in a sector to a known timetable with a commitment to public financial support;
  - border adjustment measures or CO_2 prices applied to regional consumption as well as production. Revenues could be recycled to meet the additional costs of CCS projects in the region. Such a measure would need to carefully manage any negative side effects for local competitiveness or for secondary industries and manufacturers of finished goods. For example, higher steel prices in a region with this policy could

[11] A global CO_2 pricing system is the only type of CO_2 pricing system that, if there is confidence that the price will reach a sufficient level, can deliver lowest cost emissions reductions of a sufficient scale in sectors that are exposed to global trade without further measures.

disadvantage local automobile producers who export cars unless a compensation mechanism is also in place. In addition, it would need to be designed to be compatible with World Trade Organisation (WTO) requirements.

- Communicate the long-term emissions reduction plan publicly with support from both public and private institutions. It will be crucial to nurture public awareness of the infeasibility of addressing climate change globally without CCS in industrial applications.

Engage all sectors in strategic CCS activities

A number of critical actions to advance CCS development and deployment worldwide should involve all relevant stakeholders, including relevant industrial sectors on an equal footing. Steps to be taken include:

- Involve firms and other relevant actors as observers initially, graduating to equal partnership over time. Overall levels of funding contributions may increase for these activities by engaging more stakeholders. Activity areas that should be expanded to involve industrial sectors include:
    - public engagement – an inclusive approach will recognise that the local endorsement of CCS will be crucial to the sectors' future existence in a region;
    - knowledge sharing on technical, regulatory and project development aspects of CCS;
    - CO_2 storage capacity mapping and exploration;
    - development of injection techniques and CO_2 measuring, monitoring and verification;
    - R&D initiatives across the CCS value chain in order to exploit synergies between sectors;
    - commercialisation of CO_2 storage.
- Stimulate discussion and planning for the stepwise deployment of CCS in major industrial clusters. This includes investigating accessible CO_2 storage sites and considering requirements that would make local sectors increasingly CCS-ready, thereby potentially lowering future costs of CCS deployment, while enabling sectors that already have commercial capture technologies to start deploying CCS as policy drivers are in place. Even during the demonstration phase, smaller industrial CCS projects (*e.g.* on hydrogen, methanol or ammonia plants) in a cluster could be anchored by the presence of CCS on a major local emitter in the power sector, or a different industrial sector. Infrastructure and CO_2 storage sites could be shared, which would help to reduce risks and overall costs.
- Involve industrial sectors and clusters in the development of infrastructure development plans and a business case for commercial CO_2 transport and storage operators. As it is unlikely that many heavy-emitting firms, with the possible exception of refiners and gas producers, will evolve to become integrated into the CO_2 storage business in the near to medium term, it is important to have third-party service providers available. Energy-intensive industries highlight the acute need for a commercial CO_2 transport and storage business to become available for the off-take of captured CO_2, within a well-defined and operational liability and regulatory regime.

Annex I
Actions recommended by the 2011 *Technology Roadmap: Carbon Capture and Storage in Industrial Applications*

- Ensure adequate funding for CCS demonstration projects in major industrial and fuel transformation sectors, such as ammonia, gas processing, biomass conversion, refineries, iron and steel, and cement manufacturing. By 2020, investment worth USD 27 billion will be needed to fund about 60 early, large-scale projects.
- Ensure that funding mechanisms are in place to support demonstration and deployment of CCS in developing countries, where the largest opportunities exist for CO_2 capture in industrial applications.
- Review the opportunities for industrial CCS in each country and ensure that industrial CCS is given prominence in the near term, especially in low-cost applications. More data need to be made available on emissions, technologies, costs and projections.
- More global assessments of CO_2 sources and potential reservoirs are needed, including storage opportunities in EOR operations. The identification of geological structures with high levels of injectivity and strong, deep cap rocks is critical to the successful deployment of CCS.
- Public R&D programmes on CCS in industrial applications are required to bring more information to the public domain.
- Best practices for CCS in industrial applications need to be developed and disseminated so that interested parties can learn how to apply the relevant technologies.
- CCS opportunities in industrial applications need to be mapped more precisely and consistently at the national and local level, including CO_2 storage opportunities in EOR operations.

Annex II
Factors influencing the costs of CCS in industrial applications

A survey of the technical aspects of CCS in industrial applications was undertaken in late 2012.[12] The following factors were found to be influential, as listed in Section 3.

CO_2 concentration

It is much easier to capture CO_2 from fermentation, which has few impurities, than from the dilute CO_2 stream from a refinery boiler exhaust. The latter requires more energy and solvent, which increases costs substantially. Whether the CO_2 stream in the flue gas or process emission is nearly 100% pure, or is mixed with other gases such as water, nitrogen, nitrogen oxides (NO_X) or sulphur oxides (SO_x) is an important factor in determining capture costs.

CO_2 partial pressure

Even if the CO_2 source is not greater than 90% pure, it can be more easily captured at a higher pressure. The partial pressures of CO_2 in flue gases shown in Table 5 are one indicator of capture costs, with the lower partial pressures giving higher costs per tonne of CO_2 captured. Furthermore, if CO_2 capture can be performed at higher pressures then the need and the cost for subsequent compression can be avoided.

Table 5. Suitable CO_2 capture technologies for CO_2 streams of varying concentrations and partial pressures

CO_2 source		CO_2 purity (by volume)	CO_2 pressure		Possible capture processes					
Process	Sector	High purity ← Oxygen enhanced ← Syn-gas ← Flue gas	Typical stream pressure (kPa)	Typical partial pressure (kPa)	Clean-up only (*e.g.* dehydration)	Cryogenic	Physical solvents	Adsorbents	Membranes	Chemical solvents
Ethylene oxide	Chemicals	100%	2 500	2 500	☑					
Fermentation	Biofuels	100%	100	100	☑					
Cement kiln (oxyfuel)*	Cement	>90%	100	95	☑					
Oxyfuel and chemical looping coal	Power	80%-98%	100	90	☑	☑				
DRI (coal- or gas-based hydrogen)	Iron and steel	20%-96%	100 to 500	uncertain			☑	☑	☑	☑
IGCC (oxyfuel)*	Power	20%-40%	2 000 to 7 000	500 to 3 000			☑			
Acid gas clean-up	Gas processing	2%-65%	900 to 8000	20 to 5 000			☑		☑	☑
BF gas (top gas recycling)	Iron and steel	60%-75%	100	60 to 75				☑		
Ethylene production	Chemicals	8%-18%	2800	200 to 500				☑	☑	
Hydrogen production	Chemicals (ammonia, methanol etc.), refining	15%-20%	2 200 to 2 700	300 to 550				☑		
IGCC (airblown)	Power	12%-14%	2 000 to 7 000	250 to 1 000					☑	
BF gas	Iron and steel	14%-33%	100	14 to 33						☑
Cement kiln (airfired)	Cement	14%-40%	100	14 to 40						☑
Pulverised coal	Power	12%-14%	100	12 to 14						☑
Process heaters	Refining, chemicals	3%-13%	100	3 to 13						☑
Gas boiler	Power	7%-10%	100	7 to 10						☑
Gas turbine	Power	3%	100	3						☑
			Need for subsequent compression:		Medium	Low	High	Low	Medium	High

* Oxyfuel requires additional energy for the separation of air to produce oxygen.

[12] Results are available in a background paper: www.iea.org/newsroomandevents/workshops/workshop/name,34219,en.html.

CO_2 volumes and feedstock

A modern, very large BF site that produces 10 Mt/yr of steel can produce up to 20 $MtCO_2$/yr, over half of which could be captured by CCS. This represents a much bigger CO_2 source than a coal-fired power plant. In the chemical sector, connection to an economically viable CO_2 storage system would allow a significant CO_2 emissions reduction to be readily achieved from ammonia production plants which typically already capture 65% to 70% of their total CO_2 generation.

Although many ammonia plants sell much of their produced CO_2 to urea producers, an ammonia plant based on natural gas that produces over 500 kilotonnes/yr of ammonia and is not integrated with urea production typically vents over 0.5 $MtCO_2$/yr. The same is true for coal-based ammonia plants of similar capacity, even if half of the separated CO_2 is used for urea production. Around 42% of process CO_2 emissions from ammonia production are used for urea manufacture in the United States, and higher percentages are seen in the Middle East and Asia, where urea is the dominant fertiliser, but European ammonia production is generally not integrated with urea production. Approximately 97% of coal-based ammonia capacity is in China, representing 26% of global ammonia capacity.

Larger CO_2 sources offer better economies of scale for CO_2 transport and storage, while smaller sources require less risk in scale-up from pilot to full-scale. In sectors that can utilise coal or other hydrocarbons as feedstock – refining, chemicals, iron and steel – plants that use coal generally produce CO_2 at a rate that would make CCS significantly more attractive than gas- or naptha-based plants. New coal-based plants are clear candidates for CCS.

Availability of local excess heat

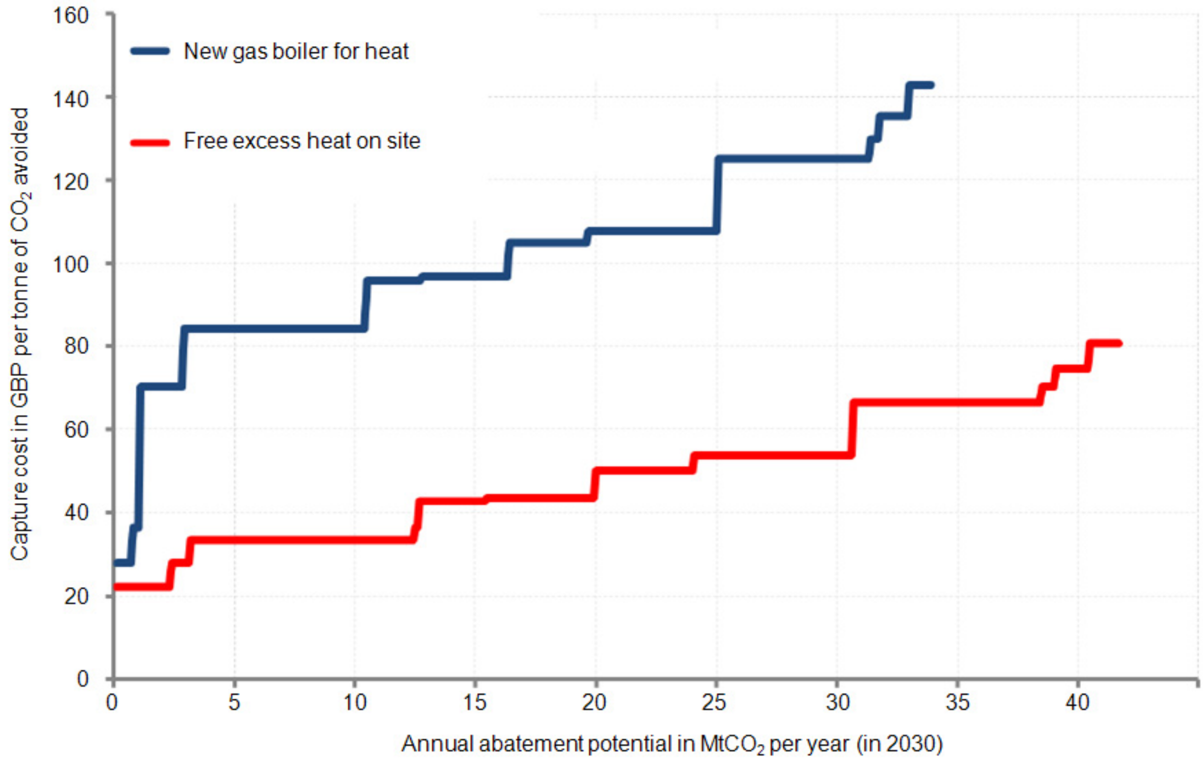
One of the main economic obstacles to CCS in these sectors is the energy required to separate CO_2 from flue gases that are not high purity. The ability to redirect excess, or waste, heat from other processes to supply the heat for CO_2 capture could reduce costs very significantly. This could lead to a preference for an apparently more expensive CO_2 capture solvent that can be regenerated at the lower temperatures of available excess heat. In a quest to increase efficiency, many industrial sites are already integrating excess heat into processes or local district heating schemes. This competition for excess heat may influence the cost of CCS and will require adequate planning at the project site. Figure 9 shows that availability of excess heat for some processes can lower capture costs by around one-half.

Need for plant redesign

In all sectors, optimal production processes are a careful balance of CO_2 capture costs and fuel and feedstock costs, which vary with market conditions and process integration (excess heat and off-gas recycling). This balance must be all the more carefully sought when considering the addition of CCS. Current commercial production processes are largely the result of decades of development that have reduced risks and have led to reliable and replicable methods.

Many of these processes have not changed for many years and have not been disruptively challenged by new processes. As a result, the sectors' outlooks on new technologies tend to be relatively conservative. For example, ECRA has concluded that oxy-firing of the cement kiln is likely to be optimal in terms of cost and could improve thermal energy efficiency by up to 10%, while increasing electricity consumption – which could be low-carbon electricity – by 100%. However, the change required in the cement manufacturing process to incorporate oxy-firing is considered to be a more fundamental redesign than the move to dry kilns and pre-calcination in the 1960s. The supply chain will need to be convinced that the new production method does not have a negative impact on clinker quality.

Figure 9. The difference that the availability of free excess heat on site can make to CO_2 capture costs for a range of CO_2 sources in a number of industry sectors



Note: figures are given for a range of UK CO_2 sources in GBP for nth of a kind plants, which are those in the deployment phase.
Source: Element Energy (2012).

In sectors such as iron and steel and cement there is a trend towards more use of the off-gases from the process because they contain carbon monoxide and hydrogen, which are reducing agents and fuel. For iron and steel, this can have a significant benefit of reducing the cost of purchasing coking coal, for which prices are currently high, and this is exploited by designs that simultaneously incorporate CCS and reduce coke consumption. The cost of CCS is therefore highly dependent on the cost of coke and is lower at plants with high coke costs. On the other hand, by using off-gases as fuel, a relatively concentrated flue gas CO_2 source can be lost and the subsequent cost of capture could be higher.

Location

The distance of a CO_2 source to a storage site will influence transport costs, but these are generally a lower cost part of the CCS value chain than CO_2 capture.[13] CO_2 sources of over 1 $MtCO_2$/yr are generally good candidates for the application of CO_2 to control emissions and could easily justify a dedicated pipeline if storage were accessible at a distance of under 500 kilometres (km). Smaller CO_2 sources with low capture costs could apply CCS commercially during the early deployment phase, even with a dedicated transport infrastructure, if the storage is located nearby. However, CO_2 sources of 0.5 $MtCO_2$ and below would likely only consider commercial use of CCS if the CO_2 could be combined ("clustered") with CO_2 from nearby plants using a common pipeline infrastructure.

[13] ZEP (2011). Transport costs range from 7 USD to 25 USD/tCO_2 for distances up to 500 km, with the higher values referring to long-distance offshore transport. Storage costs vary with the type of storage geology and whether the site is onhore or offshore, they also vary slightly with the volume stored due to economies of scale. Storage costs range from 2 USD to 25 USD/tCO_2, with the higher values referring to storage in an offshore saline aquifer with no legacy infrastructure that can be reused.

Annex III
Abbreviations and acronyms

AUD	Australian dollar
BF	blast furnace
BOF	basic oxygen furnace
BTL	biomass-to-liquids (thermal conversion route)
CAD	Canadian dollar
CCS	carbon capture and storage
CEM	Clean Energy Ministerial
CCSA	Carbon Capture and Storage Association
CCUS	carbon capture, use and storage
CO_2	carbon dioxide
CTL	coal-to-liquids
DRI	direct reduced iron
ECRA	European Cement Research Academy
EOR	enhanced oil recovery
ETS	emissions trading system
FCC	fluid catalytic cracker
GBP	Great British pound (sterling)
GHG	greenhouse gas
IEA	International Energy Agency
IP	intellectual property
IPR	intellectual property rights
NOK	Norwegian krone
R&D	research and development
UAE	United Arab Emirates
ULCOS	Ultra-Low CO_2 Steel
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organisation
USD	United States dollar
WTO	World Trade Organisation

Annex IV
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Annex V
Organisations involved in the preparation of this work

The CCUS Action Group governments are: Australia, Canada, China, France, Germany, Japan, Korea, Mexico, Norway, South Africa, United Arab Emirates, United Kingdom, United States.

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Global Action to Advance Carbon Capture and Storage

A Focus on Industrial Applications

Carbon Capture and Storage (CCS) is the only option to decarbonise many industrial sectors.

Representing one-fifth of total global CO_2 emissions currently, industrial sectors such as cement, iron and steel, chemicals and refining are expected to emit even more CO_2 over the coming decades. CCS is currently the only large-scale mitigation option available to cut the emissions intensity of production by over 50% in these sectors. Industrial applications offer low-cost opportunities for early deployment of CCS, but individual technical development status and policy requirements vary across countries. CCS is already proven in some industrial sectors, such as natural gas processing. Yet, the commercial-scale demonstration stage in key sectors such as iron and steel, cement or some processes in the refining sector has not yet been reached. To achieve decarbonisation goals, policy makers must pay more attention to industrial applications of CCS, while not undermining the global competitiveness of these sectors.

This document complements the IEA report, *Tracking Clean Energy Progress 2013*, for the 4th Clean Energy Ministerial meeting in April 2013.

Annex to Tracking Clean Energy Progress 2013

Carbon Capture, Use and Storage (CCUS) Action Group

CLEAN ENERGY MINISTERIAL
Accelerating the Transition to Clean Energy Technologies