Mind the CCS Gap

Carbon capture storage technology risks captivating business as usual – who will bear the cost of uncaptured carbon?

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Executive Summary

Carbon Capture and Storage (CCS) offers a technology solution for high carbon emitting assets and practices to remain an integral part of energy and industrial systems for coming decades. Climate models targeting goals set out by the Paris Agreement to achieve 2 degrees or beyond 2 degree targets rely on CCS as one of the technologies required to achieve these goals. The current development of CCS considerably lags these expectations, with significant implications for key industries such as utilities, steel, cement and chemicals which rely on CCS to achieve their decarbonization goals. We evaluate the impact of excluding CCS from the IEA scenarios and identify which sectors are more exposed to the risk/opportunities arising.

Carbon capture and storage (CCS) is a set of technologies capable of delivering significant carbon emission reductions from the use of fossil fuels in power generation and in multiple industrial applications. CCS is often presented as one of the key technologies in tackling climate change, to the point where in the majority of climate models, CCS is critical to meeting decarbonization goals set by the Paris Agreement to limit global warming to well below 2 degrees by 2100. In this report, we evaluate the status of CCS technologies, their role in decarbonization pathways and the risk and opportunities they present. We also show a simple sensitivity of what would need to happen in the power and industry sectors to meet decarbonization goals should CCS not be developed or not deployed as foreseen by the International Energy Agency (IEA) climate scenarios.

In the beyond-2-degree-scenario (B2DS) of the IEA (Energy Technology Perspective 2017), the deployment of CCS covers around 20% of the cumulative carbon abatement to 2060 compared to a reference scenario (RTS) where temperature rises by 6 degrees. This equates to a total of 227 Gt captured over the period. CCS deployment is expected to grow across all high emitting sectors in a B2DS. The technology plays a particularly vital role in sectors where Scope 1 emissions are a core part of the production process (e.g. cement, chemicals, steel), and where substitution is constrained because of the economics and scale of alternative technologies. Cumulatively, CCS is responsible for 37% of the emissions abatement in the industrial sectors and 14% in the power sector.

The appeal of CCS technologies is multi-faceted. Firstly, it allows fossil fuel and high emitting production practices to remain an integral part of the energy and industrial systems for years to come. In combination with bioenergy it is among the few existing methods to generate negative emissions – currently still largely a theoretical principle, but potentially a necessary feature in case of meaningful overshoots in decarbonization pathways. And in theory it can be applied at scale, given vast availability of storage, existing capture technologies, and available knowledge of infrastructure requirements.

Despite the intuitive potential of CCS, implementation has been slow at best, with limited investment and perhaps more worryingly, a widening gap between its presence in scenario analysis and absence from policy frameworks. Today, there are 17 operating plants which capture around 30Mt of carbon per annum and a pipeline of projects in development with a capacity of ~40Mt potentially coming on-line by the mid-2020s. This compares to a projected capture rate of 900Mt in the B2DS in 2025 (IEA, 2017).

One key reason for the slow development has been that in most cases, CCS is not commercial under the current carbon pricing backdrop and requires either stronger carbon pricing signals or for governments to fill the funding gap. Studies estimate carbon prices between €60 and €215 would be required to make the technology economic. However, the expectation is that these levels of carbon pricing are not likely to materialize in the near future, potentially opening a dangerous gap in terms of R&D spending, capital allocation decisions, piloting, and regulation development. Carbon capture and utilization (CCU) has potential to grow and is relatively established within the oil & gas sector with

Enhanced Oil Recovery (EOR), and in certain chemical processes. These however represent only a small fraction of the role CCS is expected to play across sectors in the future.

Policy uncertainty is the other main hurdle to development, on areas ranging from responsibility for long-term storage liability, projects spanning international boundaries and the flexibility of the contractual terms of grants. A clear policy framework which incentivizes corporates to early action coupled with government financing are therefore crucial to bridge the period-gap to commerciality, although often budgetary constraints and political motives create serious barriers to long-term planning.

The analysis we performed in our sector reports such as utilities shows that a number of companies will break their carbon budgets in years to come based on existing fossil fuel assets. Technologies like CCS might help to correct or even reverse the lock-in of emissions helping avoid capital being misallocated and stranded assets, but the continued delay in action increases the probability of these risks materializing. While there is no first mover advantage for any single company given the scale of investment required, collaborative cross-sectoral action can be taken to push forward policy makers at the highest level, a strategy that has worked with offshore wind. This matters particularly for some industrial sectors, where the alternative to early abatement strategies and CCS means a radical departure from current business models, with a substantial redefinition of core production processes and a complete overhaul of feedstocks.

Different sectors have so far taken different stances toward CCS and other abatement strategies, with some early-movers and others late in acting. The chemical sector stood out in our analysis as better placed and comparatively more proactive in the CCS value chain, where it plays a key role in developing and using CCS technologies, supplying them to other sectors, while being simultaneously an end user of CO_2. The fact that 6 out of the 17 currently operating plants are chemical plants, and the BASF collaboration with Air Liquide at the NCCC coal-fired power station in Alabama are just examples of this. At the other end of the spectrum lies in our view the cement industry, despite being one of the main users of CCS in most climate models. Currently none of the 37 operating or in development plants are cement ones, and there are only few pilots running globally. The sector's fragmented and localized nature, largely skewed to non-OECD countries, together with the low margins and low R&D intensity of its activities, explain its reluctance to engage in development of abatement strategies, and are likely to make this sector a relative laggard in any decarbonization pathway.

A simplified sensitivity analysis based on the IEA B2DS highlights significant challenges for a world without CCS. The power sector would require significant displacement from other low carbon technologies such as nuclear and renewables, with gas replacing coal in scenario analysis. Given the limitations posed by nuclear power and the large existing asset base in coal fired power generation, scope for maneuver is limited. Within industry the challenges are even greater, with CCS accounting for 37% of emissions abatement in the B2DS. Substitute technology options are even more limited with a number of substitute technologies in turn relying on CCS. Our sensitivity analysis on the cement sector for example, shows that if CCS needs to be replaced, material efficiency measured by the clinker ratio would need to improve by around 30% relative to a 10% improvement required in the IEA B2DS.

CCS carries with it numerous and far-reaching implications with the current risk/reward unbalanced, in terms of the benefits of success vs cost of failure, timing and who bears the cost of delayed deployment. This trade-off requires careful handling and active decision making amongst key actors such as corporates and policy makers which is largely absent. CCS development should be encouraged and forcefully pursued and should remain a technology option of decarbonization pathways given its abatement potential. At the same time however, the risk of failure should be hedged more credibly.

Introduction to CCS technologies and economics

Carbon capture and storage (CCS) is a set of technologies capable of delivering significant carbon emission reductions from the use of fossil fuels in power generation and in multiple industrial applications. By sequestrating and indefinitely storing plant specific CO_2, CCS facilitates emission reductions in sectors where the potential for abatement is low (e.g. cement, steel, chemicals) and provides a solution where coal- and gas-fired power plants are likely to remain an integral part of the future energy mix. Further, when combined with bioenergy, CCS can remove CO_2 from the atmosphere and generate "negative emissions" – an option to absorb potential overshooting in other sectors.

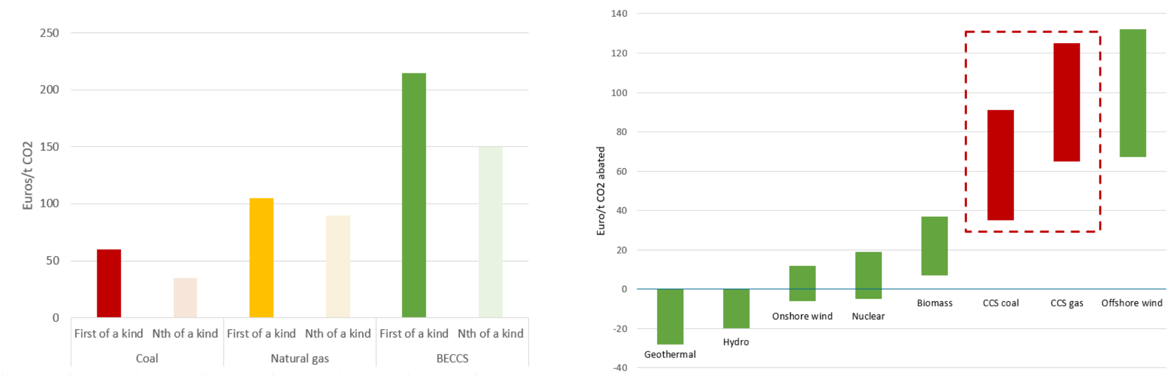
A wide variety of technologies fall within the definition of CCS, and can be broadly subdivided in 4 categories:

- **Post-combustion (PCC)**: CO_2 is captured from a blend of gases after the energy or industrial process is complete. This process of capture is the most mature relative to other technologies. This technology can be applied across most sectors, and is currently adopted in 2 of the 17 operating CCS plants (both power) and 4 of the 20 plants in development (power and chemical).
- **Pre-combustion**: CO_2 is captured through a process of gasification in which fuels are processed with oxygen or steam to produce syngas. No existing operating plants use this technology and only one of the plants in early development.
- **Oxy-fuel combustion**: CO_2 is captured by a process of combusting fuel with pure oxygen rather than air. No existing operating plants use this technology but 2 oxy-fuel plants are in early development.
- **Inherent separation**: capturing pure stream of CO_2 produced as an inherent part of an energy or industrial process. 15 of the 17 CCS operating plants use this technology and 10 of the 20 under development, for chemical and fuel transformation applications.

CCS technologies are typically highly capital-intensive, with an average investment for a small to medium sized plant (1MtCO_2) starting from USD 1 billion. Around three quarters of the investment is typically in the capturing phase, making the level of investment largely dependent on the extent to which the CO_2 capture requires a departure from the conventional energy or industrial process. CCS technologies are currently largely non-commercial, given the near absence of revenue streams from CO_2 utilization, low carbon prices, and a cost of carbon avoidance which compares unfavorably to most renewable technologies.

Carbon capture and utilization (CCU) has potential for growth, but currently EOR is the only real option for CO_2 utilization at scale. Utilization in certain chemical processes is also promising, but its current application is marginal (IEA, 2017). Carbon prices which would be required to make CCS competitive against renewable energy have been estimated to lie in a range between € 60 and € 215 (ETI, 2014 and Akgul, 2014), levels which are not expected to be reached in the near term. The cost of carbon avoidance also compares unfavorably against renewable energies, with off-shore wind being the only renewable technology more expensive than CCS (see Figure 1 below, CCCEP, 2015).

Figure 1: Range of carbon pricing and cost of carbon avoided across low carbon technologies



Source: CDP adapted from ETI 2014, Akgul 2014 and CCCEP 2015

Despite the lack of commercialization of such a wide array of technologies and the early stage of development, CCS is widely relied on by traditional climate models as a key driver of emissions abatement. In a recent meta-analysis of IAMs (Peters et al, 2017) the authors show that without large scale CCS, most models cannot produce pathways consistent with a 2-degree goal. Similar reliance is placed on CCS by the IEA in their 2-degree (2DS) and beyond-2-degree scenarios (B2DS), as we explore in more details in the next sections. As climate scenarios are important tools to guide policy and corporate decision making, their bias toward CCS exposes us to the risk of locking-in emissions in an overshooting trajectory should the technology not be available or not be deployed. This is particularly relevant where scenario analysis is being used within the TCFD framework to gauge how well companies are positioned for a low carbon transition and the scenarios used often rely on the IEA scenarios.

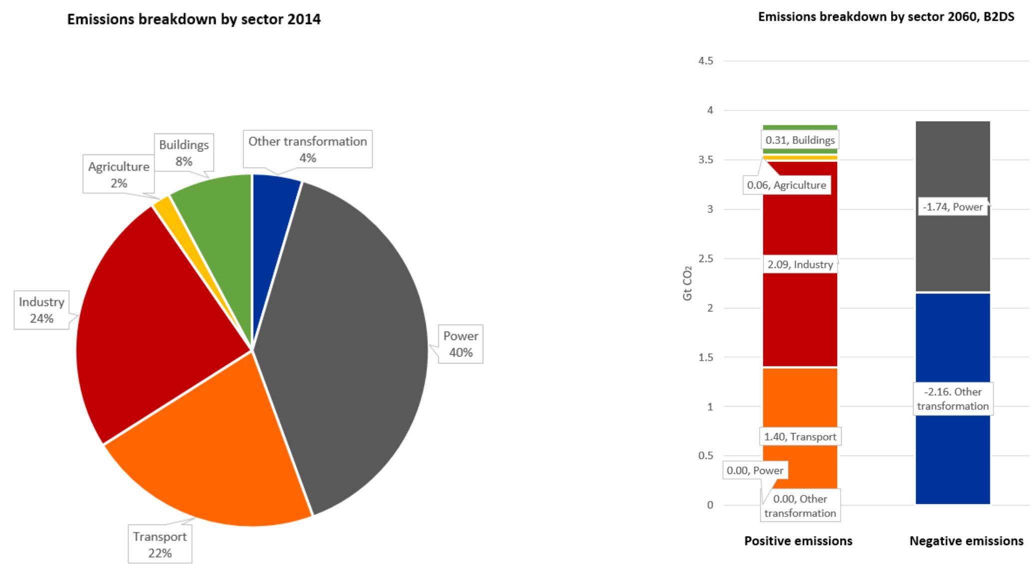
Both the power sector and the high-emitting industrial sectors would need to look significantly different in a scenario where CCS is not developed or not deployed as foreseen by many climate models with radical changes needed over the next 10-20 years to avoid a rapid and irreversible overshoot. In a sensitivity analysis, we detail in a later section, we show how limited the scope for maneuver is. The large existing asset base of coal-fueled power and the political and risk management implications of a large nuclear power base create fairly set boundaries between which action can take place. High-emitting industries have an even narrower scope for action, relying either on the power sector to absorb their excess emissions or requiring a radical departure from current business models.

Most high-emitting sectors are seen relying on CCS in the future

Policy-makers typically rely on integrated assessment models (IAMs) to inform their views on climate and decarbonization pathways. These models integrate multiple disciplines into a single framework and support policy-making decision process through scenario analysis.

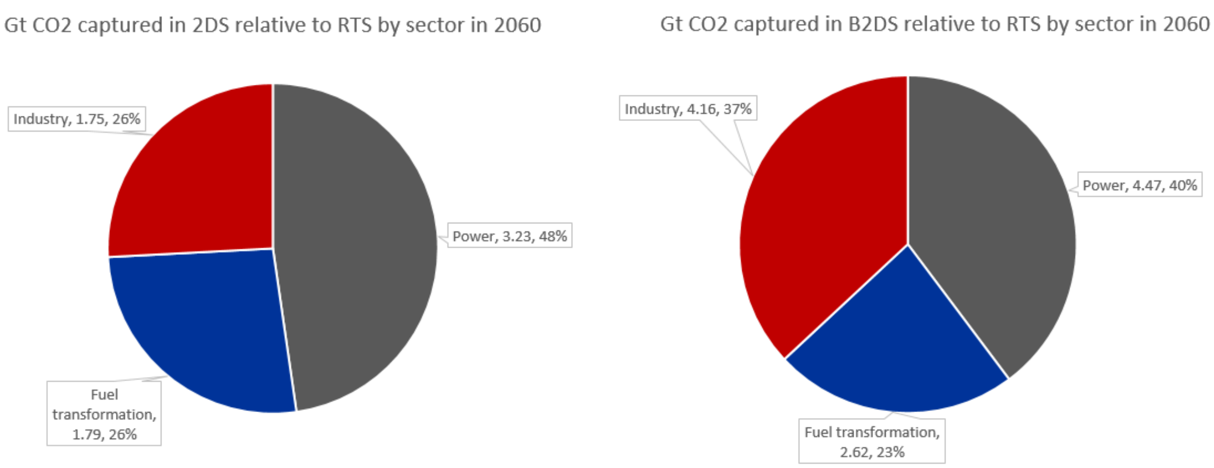
In this section, we explore the IEA scenarios and the role played by CCS. The IEA's scenarios are widely used as a basis for analysis as they provide robust, up-to-date and global data. These scenarios model technology pathways based on a partial least cost optimization analysis. For our analysis, we have focused on the IEA's 2017 B2DS (ETP, 2017) as the Paris Agreement commits parties to limiting temperature rise to "well below" 2 degrees and pursuing efforts to limit the temperature increase even further to 1.5 degrees (UNFCCC, 2016). In addition, the IEA's scenarios model the emissions trajectory required to limit temperature rise to 2 degrees with only 50% confidence. Using B2DS as a reference scenario leaves a reasonable buffer for execution and estimation errors.

Figure 2: Emissions breakdown by sector 2014, 2060 (B2DS)



Source: CDP adapted from IEA 2017

Figure 3: CCS capture breakdown by sector 2DS, B2DS in 2060

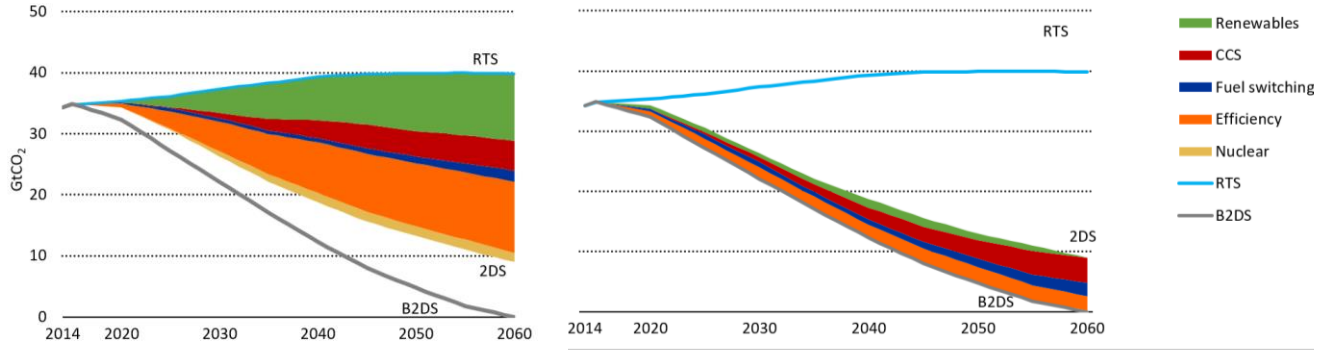


Source: CDP adapted from IEA 2017

In B2DS, the role of CCS is prominent, capturing 227Gt of CO_2, or around 20% of the cumulative emissions abatement relative to the RTS. Compared to the 2DS, CCS captures 32% of the incremental abatement required to get to B2DS.

In the power sector, fossil fuels are likely to remain a key feature of the energy mix for the foreseeable future, given current investment plans and the long life-span of generating assets. According to recent research (Pfeiffer et al, 2016) emissions from the current power plants run through their economic life imply a >50% probability of exceeding 2 degrees and this is before considering the coal-plants currently under construction or in development stage. Greater emphasis is now placed on gas as a 'cleaner' substitute for oil/coal, but gas will also require significant emissions reduction which is hard to envisage without CCS (see sensitivity of alternative scenarios, including gas below).

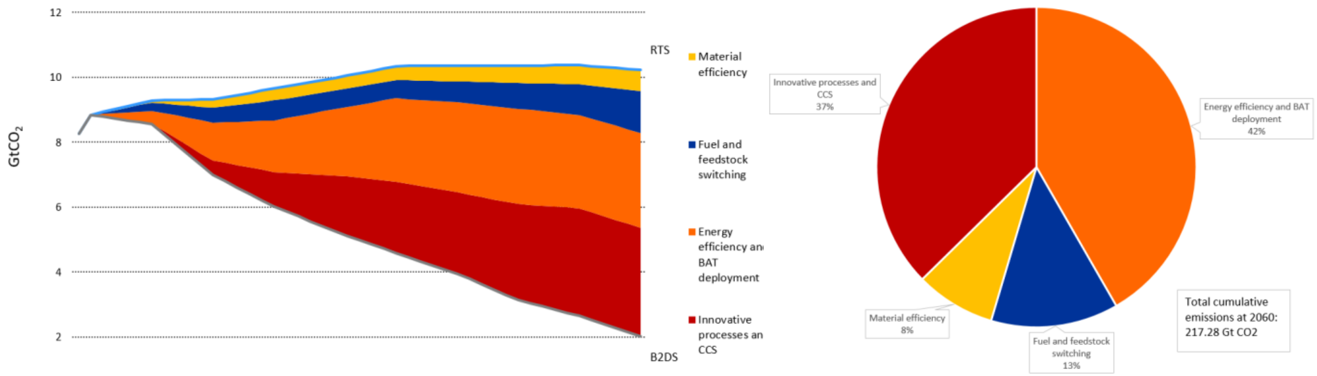
Figure 4: Emissions reduction pathways RTS, 2DS, B2DS



Source: CDP adapted from IEA 2017

Other industrial sectors currently account for around a quarter of total emissions. Process substitutes are limited or not economical for these sectors, with CCS the only viable option for CO_2 reduction across a number of processes. CCS is responsible for 37% of the cumulative emissions abatement taking place in the industrial sectors between 2015-60 in the B2DS.

Figure 5: Emissions reduction pathways in industry RTS, 2DS, B2DS and cumulative abatement in B2DS

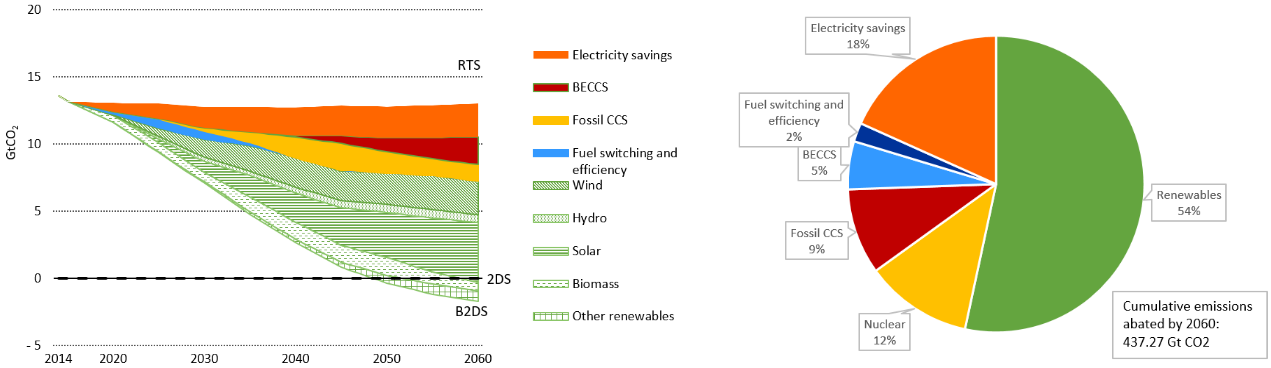


Source: CDP adapted from IEA 2017

Power sector – over a third of global emissions

In the B2DS the power sector sees its emissions reduced from 14Gt CO_2 in 2014 to -2 Gt CO_2 by 2060. More than half of the abatement comes from renewable energy sources, a quarter from nuclear and 14% from CCS. CCS deployed in the power sector represents 40% of the global capture in 2060, and is critical in making the power sector a net negative emitter to allow absorbing positive emissions in other sectors.

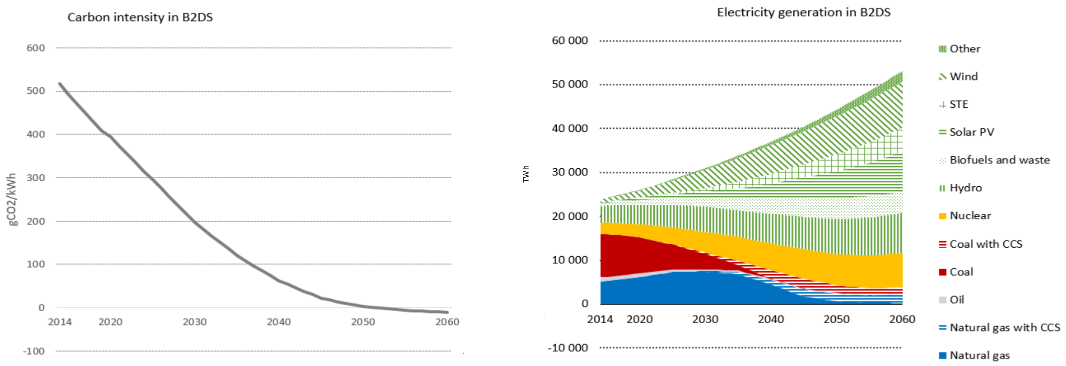
Figure 6: Emissions abatement in the power sector RTS, 2DS and B2DS and cumulative abatement B2DS



Source: CDP adapted from IEA 2017

Fossil fueled power generation continues to be a feature of both 2DS and B2DS scenarios based on a large existing asset base but also as balancing capacity in a system with a growing dependence on intermittent renewable energy. However, the carbon intensity of fossil fuel power generation without CCS becomes unsustainable by 2040-45 in both 2DS and B2DS, increasing the risk of early retirements for coal plants built in the near term (IEA, 2017) with risks heightened further if CCS is not available. In the 2DS, CCS is expected to start in earnest around 2021 and by 2045 fossil fueled power generation without CCS is phased out (4% of global electricity generation vs 45% in the reference scenario). Gas-fired generation without CCS increases until 2025 and then becomes too carbon intensive for the transition, leading to a steep decline post 2035.

Figure 7: Global electricity generation in B2DS



Source: CDP adapted from IEA 2017

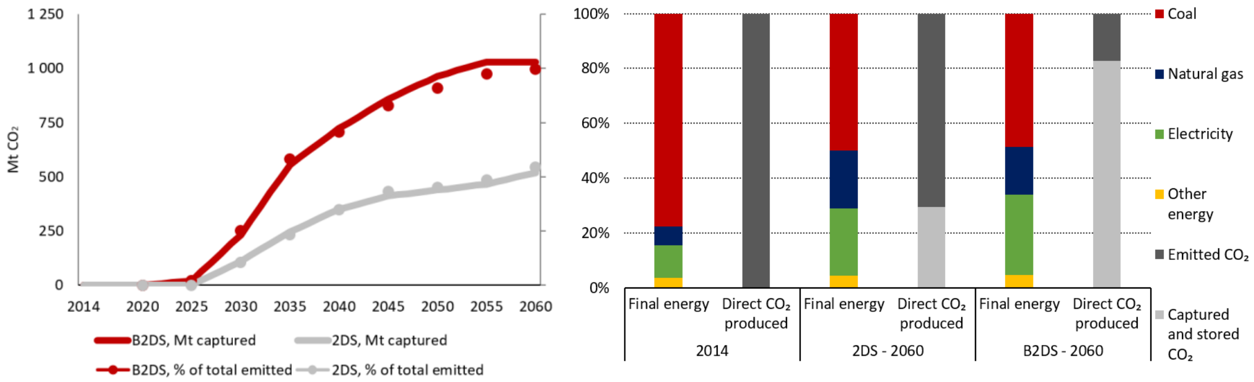
The B2DS requires an even more demanding step change. By mid 2040s even CCS fossil-fueled generation becomes too CO_2 intense (given a capture rate of 85-90% based on current technologies) and CCS-coal in 2060 is reduced by one-third compared to its peak in the mid-2040s. Deeper penetration of BECCS power plants (bioenergy fitted with CCS, see BECCS section below) is also necessary to reach net negative emissions.

Iron and Steel sector – 28% of industrial emissions

The iron and steel sector is the largest CO_2 emitting industrial sector and the second-largest energy consumer. The sector plays a key role towards achieving global industrial abatement targets, accounting for 44% of the cumulative CO_2 industrial emission reduction by 2060, and 40% in the B2DS. The sector sees its emissions reduced from 2.3Gt CO_2 in 2014 to 0.2Mt CO_2 in 2060, with around a quarter of the reduction coming from CCS deployment.

In the IEA 2D and B2D scenarios, blast furnaces are expected to be replaced by direct reduced iron steelmaking over the coming decades and smelting reduction processes, both of which rely extensively on CCS. At the same time energy efficiency has to improve significantly in both 2DS and B2DS, with aggregated energy intensity down around 40-50% between 2014 and 2060. Meanwhile direct carbon intensity declines from 1.4 tCO_2/t crude steel to 0.6 and 0.1 in 2DS and B2DS respectively. The dramatic decline in the B2DS requires a radical change in production methods, with increased reliance on low carbon alternatives, and more than 80% of 2060 emissions captured by CCS (all the ones from high carbon intensity methods). By 2060 almost half of steel production in the B2DS takes place via low carbon emitting processes, and the remaining half is covered by CCS.

Figure 8: CCS in 2DS and B2DS, direct emissions and final energy in the iron and steel sector



Source: CDP adapted from IEA 2017

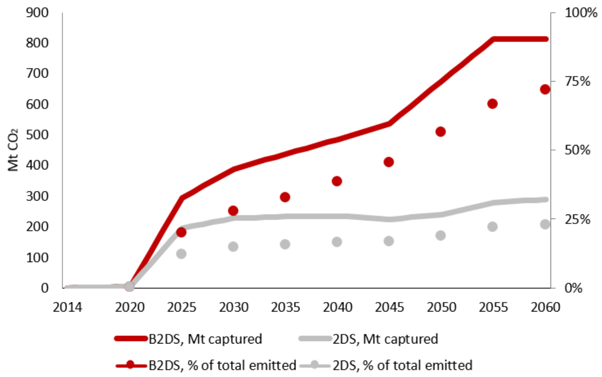
Chemicals sector – 13% of industrial emissions

The chemical sector is the largest consumer of energy in the industrial sector, and the third highest CO_2 emitter. In the B2DS it accounts for 16% of industrial cumulative emissions abatement by 2060, with direct emissions reductions reaching 321 $MtCO_2$/year (one third of current emissions). CCS plays a significant role in this abatement accounting for 21 Gt CO_2 cumulatively captured between 2014 and 2060. This equates to one third of the emissions abated in the period relative to the "business as usual" reference scenario (RTS).

Energy efficiency and material efficiency also play a role in achieving abatements targets in the sector. In B2DS, material efficiency in the form of improved collection and processing rate of plastic-based consumer products results in an abatement in the primary production of chemicals by 4% by 2060. Steep energy efficiencies are also envisaged, with 40% decrease in process energy intensity for ammonia, 10% for methanol and 21% for high value chemicals (HVC). Even so, according to the IEA (2017) achieving the decarbonization targets will depend on introducing altogether new technologies, as even achieving current best-available techniques (BAT) energy efficiency levels and steep material efficiency improvements will not suffice.

In the 2DS, CCS is applied to 60% of ammonia production and 48% of methanol production, with minimal deployment in processes for HVCs given its lower cost-effectiveness. In a B2DS, CO_2 intensity is drastically reduced, down more than 90% from current levels across all three primary chemicals (IEA, 2017). This reduction is achieved via multiple changes including energy efficiency improvements, lower use of carbon-fuels and feedstocks and advance toward BAT level processes. CCS penetration rates are estimated to reach 93% for ammonia, 100% for methanol, and 91% for HVC in 2060.

Figure 9: CCS in the chemicals sector 2DS, B2DS



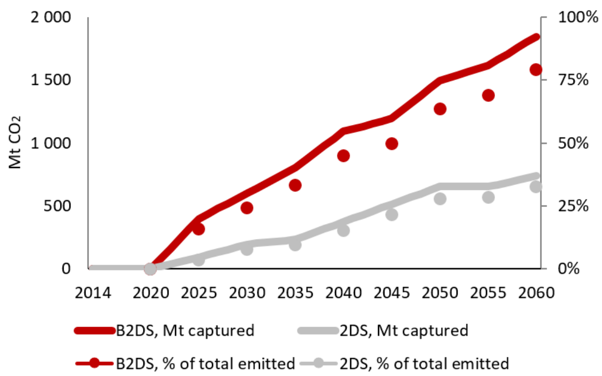
Source: CDP adapted from IEA 2017

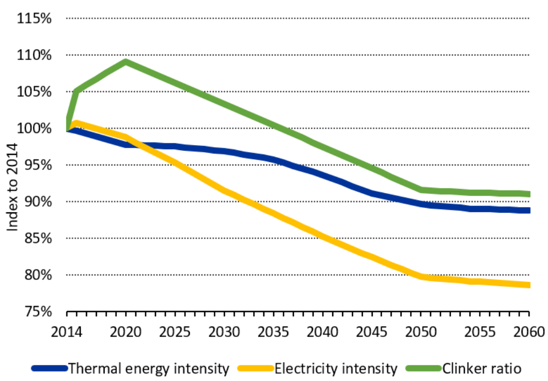
Cement sector – 27% of industrial emissions

The cement industry is the third largest industrial energy consumer and the second largest emitter due to the high level of process related emissions inherent in the production process. The challenge for abatement is therefore significant as emissions resulting from the calcination process cannot be mitigated via energy efficiencies and fuel switching. In both the 2DS and B2DS the sector accounts for the biggest share of carbon capture amongst the industrial sectors, with 44% of cumulative industrial emissions captured in 2DS and 47% in B2DS. In the 2DS, half of global production is fitted with CCS in 2060, capturing 30% of total emissions. In the B2DS, virtually the entire global production of cement is equipped with CCS by 2060, capturing 83% of emissions. This translates to 0.7Gt in 2DS and 1.8Gt in B2DS captured annually in 2060.

Clinker ratio reduction (the ratio of clinker to cement), energy efficiency and fuel switching complement CCS (in 2030 in B2DS one quarter of emission reductions comes from energy efficiency and fuel switching). The share of fossil fuels in the energy mix decreases from 83% to 59% (in 2060 B2DS), with natural gas making up 48% of this compared to 11% in 2014. Thermal energy intensity goes from 3.5 GJ/t clinker to 2.9 GJ/t by replacing remaining wet-kilns with dry ones equipped with preheaters and pre-calciners. The global average clinker ratio is estimated to decline to 0.59 by 2060 from 0.65 in 2014.

Figure 10: CCS in the cement sector in B2DS, 2DS and reduction in the clinker ratio in B2DS





Source: CDP adapted from IEA 2017

Current status and risks and opportunities for sectors and regions

Readiness of high emitting sectors varies

The significant role of CCS as a contributor to emissions reductions in decarbonization pathways potentially creates profound risks for companies operating in high emitting sectors, while also opening opportunities for early movers. In both 2DS and B2DS the assumption is that by 2025, CCS will see a significant increase (IEA, 2017), with capture rates more than 10 times (in 2DS), or 30 times (in B2DS) current rates. This is a very steep ramp-up, and in contrast with the slow progress we have seen so far. Risks to CCS estimates are therefore tilted to the downside, potentially causing a delay which would progressively shift the burden of abatement toward high emitters' BAU processes.

Analysis in our sector reports such as utilities shows that a number of companies will break their carbon budgets in years to come based on existing fossil fuel assets. Technologies like CCS might help to reverse the lock-in of emissions and potentially avoid capital being misallocated and stranded assets, but the continued delay in action makes these risks more real. Different sectors have adopted different stances toward CCS and other abatement strategies, with some early-movers and other late in acting. Ultimately the availability of abatements technologies and companies proactiveness in developing them, combined with the flexibility of their business models will likely create winners and losers in any decarbonization pathway.

The chemicals sector (Catalyst for change, 2017) has been proactive in early implementation (with 6 out of the 17 currently operating plans being chemical plants) and engaging in innovation to supply other sectors with CCS technologies (e.g. power, steel). BASF and Linde for example have worked together to develop an amine-based solvent and a novel post-combustion capture technology for a coal plant in the US. A number of companies are also looking at carbon capture and utilization (CCU), using waste CO_2 as feedstock for other industrial applications. Pilots in this area involve collaboration with other sectors (e.g. power generators) as potential sources of CO_2 to use as base to produce polyurethane (Bayer's pilot in Germany) or polycarbonate resin (Novomer with DSM).

Box 1: BASF and Linde NCCC Alabama project

In 2016 BASF and Linde successfully completed a pilot project involving the capture of CO2 from flue gas at a coal fired power plant at the National Carbon Capture Centre (NCCC) in Alabama. The project achieved a 90% capture rate, extracting CO_2 at a purity level of over 99.9%. The project applied BASF's amine based solvent and process technology with a novel CO_2 capture process and engineering developed by Linde. BASF and Linde are now exploring larger scale testing and commercial opportunities for these technologies.

The cement sector has been a late mover and at the moment there is limited activity on piloting CCS plants, with none of the 37 plants currently operating/in development being cement ones. Heidelberg is leading a CCS pilot test in Brevik, Norway (2013-2017), which uses excess heat from cement production to capture CO_2 using four different techniques. The project costs €12.5m and is expected to capture up to 250,000 tons of CO_2 (30% of total plant emissions) (GICCC, 2013). Chemical companies have also been collaborating with the cement industry, for example Air Liquide working to provide new equipment for CO_2 injection that cures concrete with CO_2 instead of water, which could reduce concrete environmental footprint by up to 70%.

In the steel sector, there is one operating plant today (Abu Dhabi CCS), with an 0.8Mtpa capture capacity. The captured CO_2 is transported via pipeline to ADNOC oil reservoirs for EOR. Aside from the Abu Dhabi CCS plant, there haven't been major new initiatives or investment decisions since the cancellation of the Arcelor Mittal top gas recycling (TGR) pilot in late 2012 (the company states that the project may still proceed in the future) and none of the 20 plants currently in construction/under development are in the steel sector. If deployed more widely, CCS implementation could sharply enhance the emission reduction potential of several other abatement technologies (e.g. Hisarna, FINEX, TGR). Carbon utilization could also play a role in the steel sector, in the production of products like chemicals and biofuels. Lanzatech and Carbon2Chems are two prominent CCU initiatives for steel, although questions remain over the abatement capacity of these projects.

In the power sector CCS is expected to play a significant role, particularly applied to coal-fired plants. Progress in reality has been erratic and mainly concentrated in EU utilities. Only 2 out of the 17 currently operating plants being power ones. None of the plants in construction/advanced development are power plants but 7 out of 11 early development CCS plants are, and forecast to come online in the 2020s. One of the two operational projects is the Boundary Dam project. This is a coal fired power station in Canada which underwent a refurbishment program in October 2014 involving retrofitting CO_2 capture facilities using post combustion capture technologies with a capture capacity of 1Mt CO_2 per annum. The majority of the captured CO_2 is transported via pipelines and used for enhanced oil recovery at the Weyburn Oil Unit.

If CCS is deployed at scale, a number of opportunities could emerge for those sectors who are early movers and are strategically placed in CCS value chain. In our sectorial analysis, the chemical sector stood out as better placed in the CCS value chain, being simultaneously a key developer and user of CCS, a supplier of capture technologies to other sectors, and a candidate to become an important end-user of CO_2. Furthermore, the global scale of leading chemical companies, the sector's wide margins and its R&D intensity put it in a favorable position compared to other sectors.

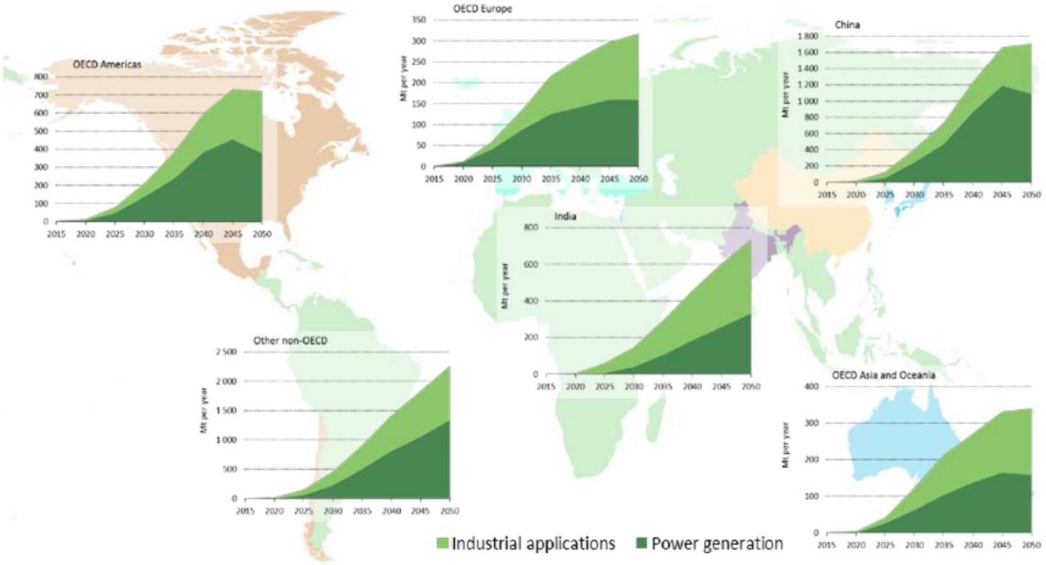
At the other end of the spectrum lies the cement industry, notwithstanding the significant use of CCS it is expected to make in most climate models. The sector's fragmented and localized nature, largely skewed to non-OECD countries, together with the low margins and low R&D intensity of its activities, explain its reluctance to engage in development of abatement strategies. A small group of global companies are in a position to take the lead and create some momentum in the development of sector specific technologies, but for the majority of the smaller or non-OECD players the conditions described above are unlikely to change any time soon, making the sector a likely laggard in any decarbonization pathway.

Somewhere in the middle of the spectrum are the power and steel sectors. They are expected to be respectively first and second largest user of CCS technologies, and yet progress has been limited, particularly in steel. Both sectors could however play important roles in the development of the CCS supply chain, given the size of the operations, the regulated nature of a lot of their business activities (particularly power) and the large and relatively constant streams of CO_2 generated by single plants, which could become key providers of carbon for CCU activities elsewhere (EOR or other).

Regional review shows importance of deployment outside of the OECD

In the 2DS (IEA, 2016) three-quarters of CCS deployment occurs outside of OECD countries, with China exhibiting the highest rates of deployment (28%, or 26Gt through to 2050). OECD Americas is the second largest capturing region with 12Gt. India captures approximately 10Gt, Europe and Australasia around 5Gt each. Majority of CO_2 is captured from power generation. Power represents the largest component, particularly in China (67% of total capture), US (67%). Europe and Australasia have an equal capture rate in power and industry, while India captures 60% of CO_2 from industry.

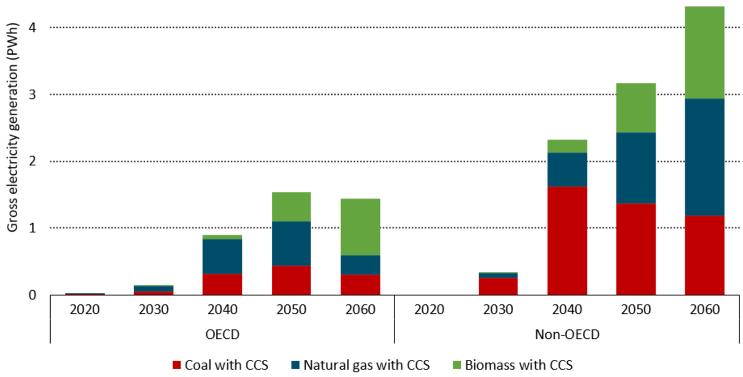
Figure 11: Global distribution of power vs industrial emissions captured



Source: IEA 2016

In the power sector, by 2060, non-OECD countries are estimated to generate approximately 4.3 million GWh per annum with CCS (B2DS), and around 1.4 million GWh in the OECD countries. Coal sees the largest application of CCS in non-OECD countries until around 2040s (around 70%), while in the 2050s-60s gas is expected the take over as the biggest CCS-fuel while coal is retired. In OECD countries CCS is applied mainly to gas-power, until 2060 when biomass fitted with CCS takes up the majority of CCS-power generation.

Figure 12: CCS distribution between OECD and non-OECD countries

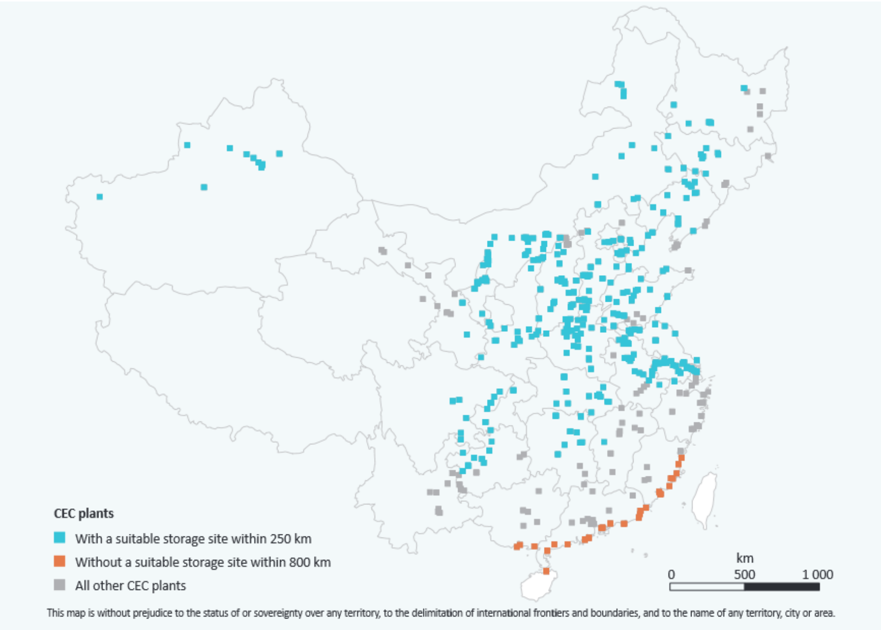


Source: CDP adapted from IEA 2017

Retrofitting is an available option, and represents a valuable opportunity particularly in non-OECD countries where the coal-power asset base is still expanding. While in theory its application could be as wide as the existing operating network, in practice a number of basic conditions need to be met to make the CCS deployment/retrofitting feasible and worthwhile (IEA, 2017). Geologically, suitable storage needs to be in the vicinity to CCS plant (around 800km or less), for example depleted oil and gas reservoirs, or adequate rock formations. Based on technical requirements, the plant would need to have a load factor above 50%, with unit size above 600MW or 300MW if in a cluster of units. From an infrastructure perspective, clustering of power or industrial CCS plants would be required to create economies of scale to share infrastructure investment, running costs and management.

Taking China as an example, it currently has around 900GW of coal-fired power and around one-third of these are estimated to be suitable for CCS retrofitting (IEA, 2016). In the 2DS this represents around 80% of global retrofitted capacity.

Figure 13: Proximity of potential capture and storage sites in China



Source: IEA 2016

This highlights how many locations and regions simply won't have the physical or technical conditions to meet retrofitting requirements, and large-scale CCS deployment will in practice require plant-by-plant feasibility studies that may take several years (before any implementation actually starts).

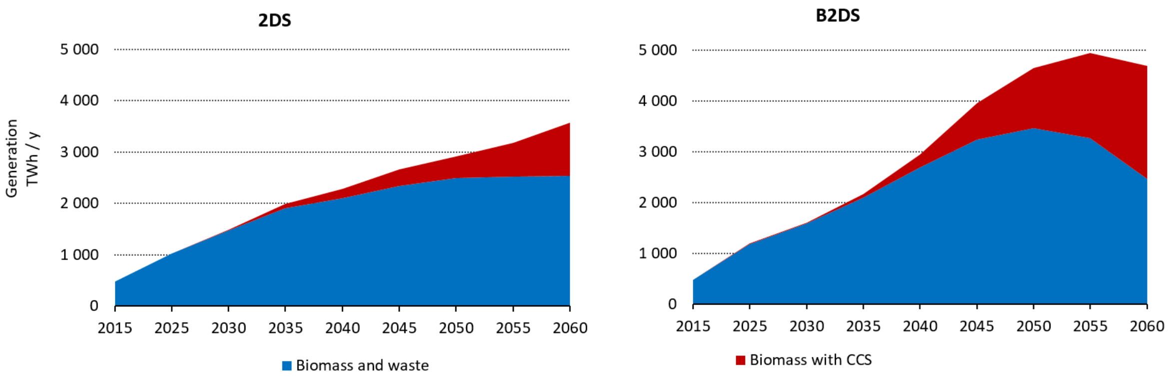
Different regions and countries across the world will face different risks and opportunities in relation to CCS implementation. These will depend on multiple factors, including sector exposure, geological limits, and distribution of emitting plants in the territory, even before considering capital availability and political willingness. For example, India's task of capturing a majority of its emissions from industry may prove challenging, particularly in light of the significant exposure to the cement and steel industries, and given wide territorial spread with relatively limited access to storage (IEA, 2008). On the other hand countries and regions with concentrated exposures to proactive sectors, available infrastructure and suitable storage could emerge as drivers of CCS development and net suppliers of technologies. Geography and territorial morphology also play a key role for bioenergy combined with CCS, one of the most controversial and possibly promising capturing technologies, which we will discuss in the next section.

CCS is integral to negative emissions expectations

BECCS has been proposed as a "negative emissions" technology, together with afforestation, soil sequestration, oceans fertilization, ocean liming, and others (see 'Alternative sequestration technologies' in the appendix). BECCS works by integrating bioenergy production with CCS, thus sequestrating and storing the carbon dioxide generated during the process of biomass-fueled power generation, which is considered emissions neutral.

The use of biomass in the power sector plays an important role in the decarbonization pathway. In the B2DS (IEA, 2017) it increases from ~500TWh per year to 4500-5000TWh (4% of the electricity generation mix), with almost half of it integrated with CCS in a B2DS. BECCS cumulatively captures 72Gt in the period to 2060 in the B2DS (roughly a third of total capture) and 36Gt in the 2DS (roughly a quarter of total capture). In 2060 BECCS covers 44% of globally captured emissions in B2DS and 40% in 2DS. BECCS can be applied across various industries, but power and fuel transformation are the two key sectors for deployment.

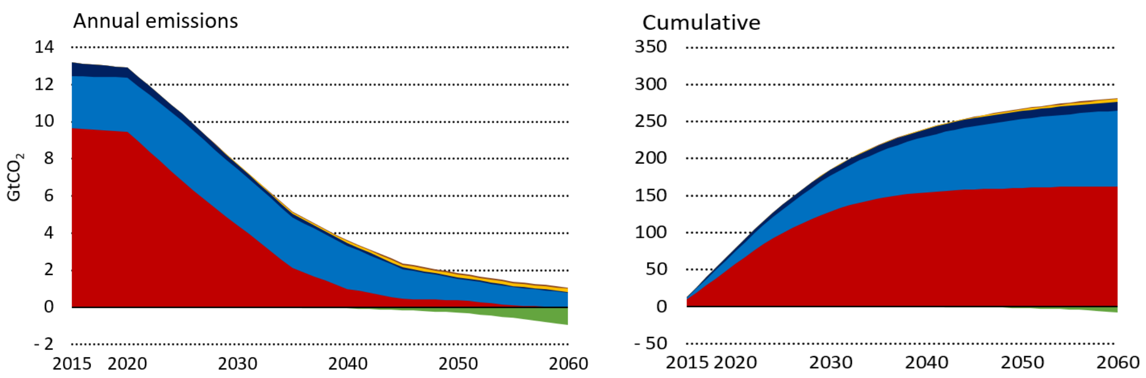
Figure 14: Energy generation from biomass and BECCS in 2DS, B2DS



Source: CDP adapted from IEA 2017

Negative emissions are key for the power sector becoming a negative emitter in 2060 in B2DS with BECCS more than off-setting the 1Gt still emitted by ex-CCS gas and CCS gas/coal fueled power generation. BECCs accounts for 5% of the total cumulative carbon abatement in the power sector to 2060 in the B2DS relative to the RTS (23Gt).

Figure 15: Power sector emissions profile in 2DS and BECCS role



Source: CDP adapted from IEA 2017

Currently BECCS is in its prototypical phase, being largely a theoretical concept. At the moment, there is only one commercial BECCS plant in operation (see "Case studies" in appendix). Plans for large-scale deployment would first need to address issues regarding biophysical and economic implications (Smith et al, 2016), given significant impact on land, albedo (earth's reflectance), biodiversity and water.

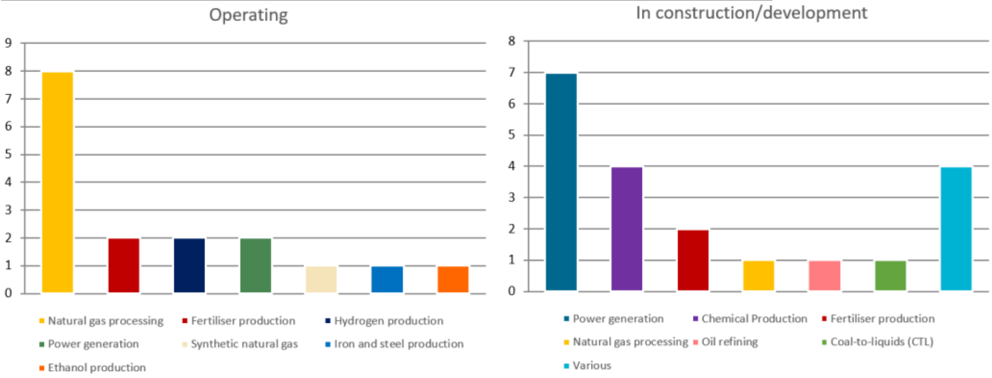
Estimates on land required to accommodate BECCS contributions vary significantly between models, but in some models would require an area twice the size of India (Andersen and Peters, 2016). This would in turn have dramatic impacts on albedo, which could limit or reverse the impact on temperatures of decarbonization, although this could be partly managed through appropriate choices of location and crop used. Water is also a fundamental input to BECCS. CCS in itself is a highly water intensive technology (water intensity almost double in CCS-coal plants, with a 60/80% increases in gas (Gerdes and Nichols, 2009). Water intensity increases further when coupled with bioenergy, to varying degrees based on the biomass feedstock used. There are then open questions on the impact of large-scale BECCS on biodiversity and alternative land-use which require careful consideration.

BECCS plays a relatively contained but absolutely key role in many scenarios, including the IEA's. Critically, it represents a potential insurance against overshooting. In practice, the complexities that it presents are multiple, with slow progress so far and limited understanding of the systemic implications of large scale use.

CCS faces several implementation challenges

The high potential of CCS technologies has not been matched by commensurate investments and implementation. There are currently 17 CCS plants operating globally, with a capacity of around 30Mt. Four plants are currently in construction (6Mt capacity) and expected to come on-line by the end of the decade, and five plants are in advanced development phase (11 Mt). This compares to 400Mt deployed in the 2DS by 2025, and 900Mt in the B2DS. Even if all plants currently in development come into operation, the total capture would only be close 70Mt (GCCSI, 2017).

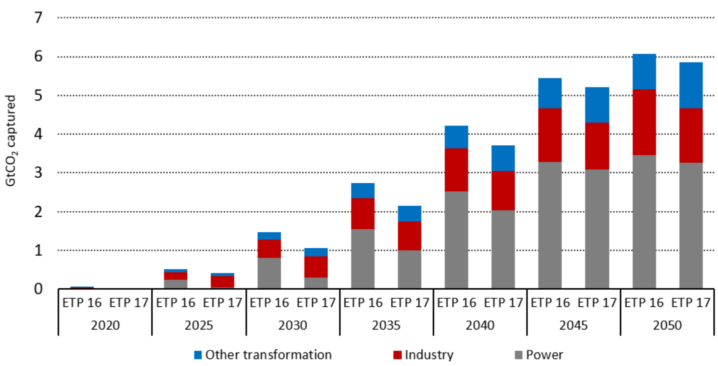
Figure 16: Share of operating and development phase CCS projects



Source: CDP adapted from Global CCS Institute, 2017

Due to implementation challenges the number of projects coming on stream over the past two years has seen significant slowing. This has driven a downward revision of IEA's CCS deployment in 2DS between their 2016 and 2017 estimates. The agency estimated the cumulative (2020 – 2050) CO_2 captured to be approximately 11% lower in ETP 2017 vs 2016. The main difference between the two estimates is concentrated between now and 2040, and given the lack of progress in the early years a steeper ramp up will be required in later years. The power sector in particular has experienced a visible reduction, with 2030 capture rates being one third of the ones previously estimated, while capture rates in the industry remain broadly flat in the two estimates.

Figure 17: IEA's downward revision of CCS estimates



Source: CDP adapted from IEA 2017

The main challenges to implementation lie in the uncertain policy framework, financing constraints, and limited development of storage and transport infrastructure, which we discuss below. Low carbon and commodities prices pose further headwinds to development (refer to Economics section for more details).

Financing

The lack of financing is arguably the most critical challenge, with both limited bankability and uncertainty around government funding programs. As with many first-of-a-kind technologies, commercial banks find it hard to debt-finance, due to a combination of uncertainties around risk allocation, limited availability of large scale commercial operation precedents and the lack of established commercial contractual forms.

Government financial programs have therefore been crucial in enabling project development, and more than half of the large-scale CCS currently operating or under construction have benefited from grant funding. However, the large size of initial equity required, together with government budget constraints and limited flexibility of design programs often pose critical challenges to these initiatives. (see Box 2: Peterhead and White Rose, below).

Policy uncertainty

The policy context surrounding CCS has undergone significant volatility over the last decade making long term planning and decision-making challenging. The positive momentum seen until 2009 faded following the Copenhagen summit and the implementation of austerity programs from governments affected by the global financial crisis. This combined with a lack of consistent policy has contributed to increased uncertainty. Between 2010 and 2016 more than 20 large scale CCS projects were cancelled globally as early CCS deployment proved to be more complex, expensive and politically challenging than anticipated (IEA, 2016).

Box 2: Peterhead and White Rose

Just days before the Paris COP21 summit, the UK government pulled out of its commitment to fund a £1 billion CCS project. In the running for this funding was a large-scale CCS project based in Peterhead backed by Shell and SSE. The withdrawal of this funding came after George Osborne’s autumn review and comprehensive spending review which saw additional cuts to renewables and household energy efficiency spends. The National Audit Office stated that this decision could destroy the possibility of CCS contributing meaningfully to the decarbonization of the UK and cause a significant increase in the cost of meeting the United Kingdom’s 2050 emissions reduction target (NAO, 2016).
Also in the running for this grant funding was a large-scale CCS project backed by Drax and the White Rose consortium based at the UK’s largest power in North Yorkshire. However, prior to the government announcement the primary funder Drax withdrew its investment in the project because of a “drastically different” financial and regulatory environment. These two case studies demonstrate the significant impact policy uncertainty has had on the deployment of CCS at scale.

Against the volatile policy backdrop there are numerous technology-specific policy challenges. These include uncertainties around long-term storage related liabilities. It is often unclear when there is a transfer of responsibility with regards to the CO_2 stored in geological formations. After a specific timeframe has elapsed (20 years in the EU) the site operator should be able to transfer responsibility for stored CO_2 to the relevant authorities. However, it is often unclear when and how this transfer occurs, and there are historic examples where regulators have not accepted this transfer of responsibilities (CCCEP, 2015).

Also, there have been no policy mechanisms developed to commercially insulate CO_2 capture from CO_2 storage and vice versa. This amplifies the counterparty risk exposure of CCS investments across the value chain, with underperformance in a specific phase threatening the commercial viability of the whole operation. Such a policy mechanism might involve awarding plants with the ability to keep operating if there is an outage further up the value chain to avoid venting CO_2 into the atmosphere. The IEA among others promotes the possibility of governments creating publicly backed intermediaries to reduce price and quantity risk.

There are then political concerns around international boundaries of storage facilities, which often do not fit neatly into national boundaries. Even in situations where international directives provide a consistent legislative framework (e.g. EU), there may be discrepancies in public opinion surrounding off and on-shore storage in different countries creating political tension.

- **Transport and storage infrastructure**

The availability of transport and storage infrastructure has the potential to significantly limit the deployment of CCS at scale. If CCS is to have a meaningful impact on emissions, the current geological storage capacity required by existing and planned projects would need to increase several thousand times. While studies have shown that global storage potential is more than adequate to accommodate ambitious growth scenarios for CCS, significant investment and evaluation is required to convert this theoretical storage potential into realized storage. This kind of evaluation can take up to 15 years and according to the IEA may cost much more than what has historically been estimated (IEA, 2016).

CCS infrastructure, by contrast, is relatively well understood but requires significant upfront capex which needs to be shared amongst potential users. Pressurized pipelines for gas transportation have been servicing the fossil fuel industry for over a century. However, taking a networked approach to the planning and investment in new pipelines may be crucial in ensuring the economic viability of future CCS projects. According to the Energy Technologies Institute, linking and oversizing pipeline infrastructure to accommodate future projects around a cluster of users (industrial installations and energy generators) could reduce pipeline cost by 64% (ETI, 2014). These kind of cost savings however require significant upfront investment and introduce greater risks around potentially stranded assets. Without government funding, it is unlikely that this networked approach would be rolled out as it is not commercially viable.

Lastly, geological differences and availability of storage may represent an important constrain to CCS development in specific locations. Access to storage coupled with the need for a networked transport systems, mean different parts of the world will have different capacities for deployment.

What would a world without CCS look like?

The IPCC Climate Change (2014) estimates that, without CCS, the cost of achieving 450ppm CO_2 equivalent by 2100 could be 138% more costly compared to scenarios that include CCS, and that only a minority of climate model runs could successfully produce a 450ppm scenario in the absence of CCS. The IEA (2016) estimates USD 3.5trn as the minimum incremental investment in scenarios without CCS, based on a requirement of 1,900 GW of renewable power capacity by 2050 over and above the one required by the 2DS scenario.

Below we have run a simplified scenario analysis to try and get a view of a world without CCS. This sensitivity is not based on IAMs and does not aim to have scientific validity, but it is rather an illustration of outcomes based on certain policy and technological choices. The analysis uses the IEA 2017 B2DS as the base case.

The analysis is highly simplified in that it assumes that one variable in the model can change with all other staying the same, and there are no constraints to expanding a given technology. Important caveats are also the fact that the simulation:

1. Ignores incremental energy and emission efficiencies that would derive from such a significant expansion in any technology
2. Ignores drags on energy/emissions intensity that may derive from local saturation in a technology
3. Assumes CCS capture 100% of emissions while in reality this is closer to 85-90%

Also note that the investment required is simply calculated as a proportion of the extra capacity required in any given technology, using IEA investment estimates as a base. This ignores any potential effect from increased/reduced economies of scale, learning curve effects of technology and any supply/demand dynamics of raw materials.

In the power sector, we excluded CCS from the technology mix, and worked out basic alternative routes that lever on other technologies to obtain the same electricity output and the same carbon emissions. These routes are:

- Substitute entirely with gas and early retirement of coal ("Gas")
- Substitute entirely with renewables ("Rnw")
- Substitute entirely with nuclear ("Nuc")
- Substitute with one third each of the above (gas, renewables, nuclear) ("Mix")

In the industrial sectors, we consider:

- The power sector "offsetting" CCS-related industrial emissions
- Steep adoption of low-carbon processes and technologies – using the cement sector as an example by estimating the go-to clinker ratio required to replace CCS abatement

Beyond these two options, there are alternative capture technologies available such as afforestation and soil sequestration however these have not been covered in the scope of our analysis due to the complexity of estimating capture potential at a global scale.

Below we present the key findings of our sensitivity:

- **Gas/coal switch:** In the power sector, replacing CCS with an earlier gas/coal switch looks unrealistic, with coal needing to be phased out immediately to make emissions balance with a B2DS scenario. In addition, this scenario also creates a stream of emissions from gas which will be too high beyond-2060 and will need drastic abatement at that point. However, this scenario presents the lowest cumulative investment.

- **Renewables:** Expanding renewables to plug the power gap left by CCS looks more promising, with a relatively contained capacity increase (12%) against the cumulative B2DS capacity and zero incremental emissions. Main hurdles are the steep capacity ramp-up already required by the B2DS (i.e. 155 years of current generation in the period 2015-2060) and an investment approximately 15% larger than the one assumed in the B2DS CCS scenario. This equates to a total investment in renewable energy that is more than double what is required under the reference scenario and is the most expensive option.

- **Nuclear:** Expanding nuclear has the benefit of a lower investment compared to renewables. However, the incremental capacity required looks challenging, with the cumulative extra generation over and above the B2DS representing 43 times the 2015 global generation. Also, in this scenario almost quarter of the 2015-2060 power generation would be generated by nuclear (compared to 11% in 2015), with would raise clear risk management and political challenges.

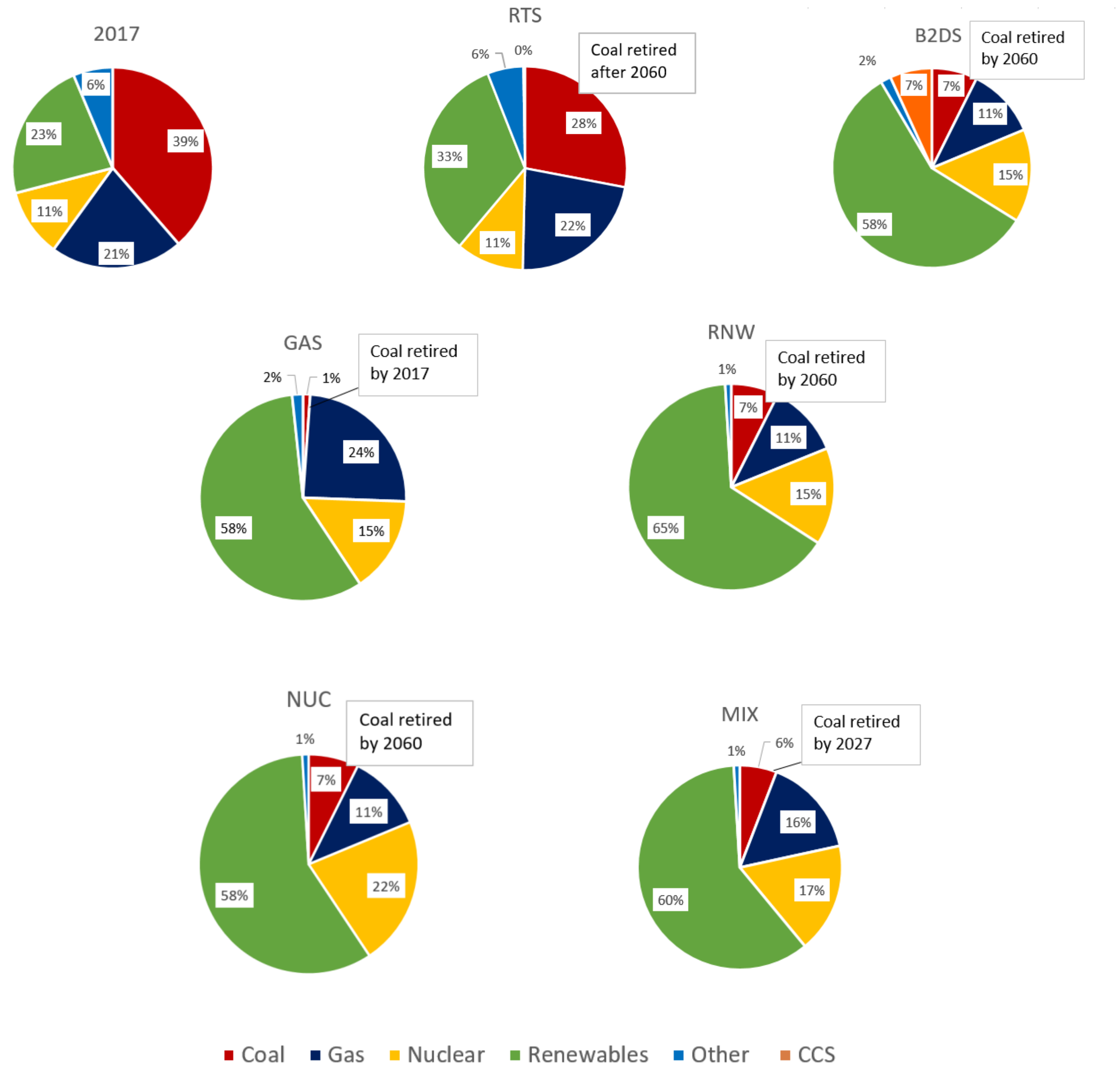
- **Mix:** A combination of the three technologies in equal parts still looks ambitious: coal needs to be retired by 2027, and the switch to gas would imply a larger requirement for gas beyond 2060 which would need abatement at that point. Renewables needs to generate 4% cumulative incremental power compared to an already ambitious B2DS. Nuclear generates 17% of cumulative power between 2015-60. The total investment required for the combined scenario is around 75% of what is estimated in CCS in the B2DS.

- **Industry (power sector offsets industrial emissions):** we explored two scenarios, one where we assume that CCS is a success in the power sector (B2DS CCS targets are met) but not in industry. The second where CCS fails in both power and industrial sectors. In both scenarios, coal is retired in 2017. In the first scenario gas is retired by 2037, in the second scenario by 2032. If we split the power generation gap left by coal/gas retirement equally between nuclear and renewables, nuclear capacity increases by 1/3 in scenario 1 and more than 40% in scenario 2 against their respective reference capacities (i.e. B2DS and MIX). Renewable capacity would need to increase by 8% and 10% respectively, although from already stretched levels.

- **Cement (technological change abates emissions):** in our sensitivity, we have used granulated blast furnace slag (GGBFS, based on a bio-product from the production of iron) to abate process emissions as it presents the highest emission abatement potential. In practice, abatement is likely to rely on a combination of technologies (e.g. from other feedstock such as fly ash, pozzolans, limestone, to further energy efficiencies, etc.) depending on availability of feedstock, plant location, energy efficiency base rates, etc. In our scenario, we estimate that to keep the trajectory of the B2DS emission, the clinker ratio would need to drop from its current global average of 0.65 to somewhere between 0.45 and 0.5. This compares to the 0.59 in the IEA B2DS in 2060. Approximately 40% of 2021-60 cement production would need to be replaced with low emitting feedstock. Using other technologies would require even lower go-to clinker ratios. Clinker ratios this low however may not be applicable for all cement applications depending on different regulatory and structural requirements. Also, blast furnace slag will be less available in a B2DS due to the decreased conventional steelmaking. This gives an idea of the dramatic change in processes that such a scenario would require.

Figure 18: Energy mix under different scenarios

2017, RTS and B2DS respectively refer to current, reference scenario and beyond 2 degrees scenarios as per the IEA, 2017. GAS, RNW, NUC and MIX refer to the alternative scenarios discussed above.



Source: CDP, 2017

Table 1: Results of scenarios

	RTS	B2DS	GAS	RNW	NUC	MIX
Coal (ex-CCS) retirement year	>2060	2060	2017	2060	2060	2027
Investment required *	213	3,794	1,597	4,307	2,080	2,774
Incremental GWh vs B2DS in yrs of current generation (per tech)	N/A	N/A	41.9	20.5	43.4	11.7

Note: *For CCS in RTS B2DS and replacement technology for the other scenarios
Source: CDP, 2017

CCS at risk as a low carbon solution

Despite its theoretical appeal and conceptual simplicity, the adoption of CCS as one of the key abatement technologies carries significant risks and raises important questions over its role in decarbonization frameworks. As discussed previously there is an increasing gap between CCS being built into IAM's that support scenario analysis and current policy. Some studies suggest it is impossible to reach 1.5 degree with a 50% likelihood without significant negative emissions (Anderson and Peters, 2016) and only few scenarios have explored mitigation without negative emission in 2 degree scenarios (e.g. Greenpeace, 2015).

The absence of carbon capture/negative emissions from climate policy discussions and the lack of investment over recent years is therefore particularly concerning. The very fact that majority of IAMs include CCS in their abatement strategies reduces the incentives for immediate abatement action, even when these would come at lower cost, such as in the cases of further energy efficiencies, or promoting low carbon-behaviors. Combined with low carbon prices, this also allows corporates to continue to plan and invest in practices that in one or two decades may not be economic anymore, should CCS fail. The lack of commercial incentives therefore not only delays CCS development, but it also creates a dangerous distortion, whereby corporates devolve to third parties (governments, research centers, foundations) the responsibility to develop technologies that are critical to make business-as-usual operating models viable in the mid-term. Should the technology not be deployed or not be available, we would either be locked into high-temperature pathways or be forced to take sweeping actions across multiple sectors.

The risk of this happening should be hedged more credibly. This can be done by better defining and quantifying these risks, decreasing IAMs reliance on CCS, making CCS part of a wider array of capturing technologies, and ultimately pushing further ahead with existing mitigation strategies.

At the same time the discussion on CCS should become central to policy at both a national and international level. If CCS is going to have a meaningful impact on carbon abatement, a sound policy framework is required to reduce the risk profile, create certainty to allow for long term planning and generate incentives to attract private investment. In the absence of an appropriately valued carbon price, alternative technology-specific policies could play this role.

Market based mechanisms including subsides or feed-in tariffs have shown promise in their application to promote investment in renewables. These policy mechanisms correct market externalities and target private investment in carbon abatement. Alternatively, price support mechanisms could be explored such as long-term price contracts, or contracts which agree payments for units of carbon stored. Experiences of applying these kinds of policies to renewables have shown that long term price support mechanisms can remain cost effective for governments through auction based contracts (Global CCS institute, 2017).

Ultimately when observing historic examples of where policy has effectively supported new technologies, the policy framework applied was not a single mechanism but rather a combination of interventions designed to support technologies through different phases of the innovation process. This is especially relevant for CCS given the systemic nature of the technology and the coordination required to deploy it cost effectively. Therefore, governments would need to not only provide the right financial incentives through technology specific support but also play a coordination role and take a position on CCS as a broader industrial strategy.

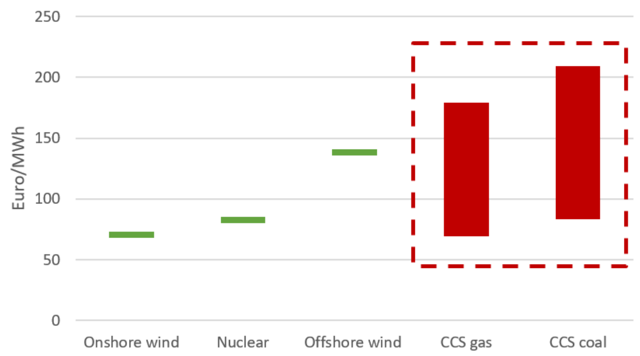
Appendix

CCS economics

CCS is a highly capital-intensive technology which significantly increases operating costs of the associated plant. Cost of carbon avoided and levelized cost of electricity/production (LCOE/LCOP) are among the most widely used metrics to compare economics between competing technologies, although defining normalized unit-prices for CCS is not straightforward, given the limited availability of full-scale CCS plants, the complexity of the process (capture, transport, storage phases have different economics) and the multiple technologies to which it could be applied.

LCOE/LOCP is the cost per unit of electricity (or other output) averaged over the lifetime of a project, including capex, opex and decommissioning costs. Despite its limitations (e.g. ignores time effects of production and matching to demand profiles), it is useful when comparing costs per unit of production across technologies. According to a literature review of a number of sources, gas CCS has an estimated LCOP of € 69-179/MWh which compares to € 83-209/MWh for CCS coal (CCS Cost Reduction Taskforce 2013 and IPCC 2014).

Figure 19: Competitiveness of CCS using LCOP

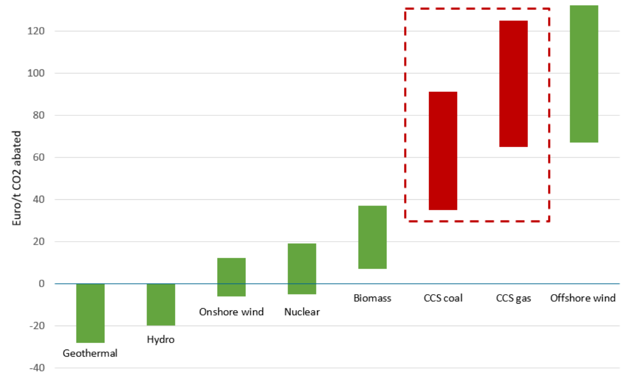


Source: CDP adapted from CCCEP, 2015

Typically, around 75% of total capex is associated with the capturing phase, making the level of investment largely dependent on the extent to which the CO_2 capture requires a departure from the conventional energy or industrial process (CCCEP, 2015). Processes which already include elements of carbon capturing (such as natural gas processing and fertiliser production) will require lower investments compared to other applications such as coal powered generation, natural gas combined cycles (NGCC), steel and cement production.

Cost of carbon avoided is determined as the difference between the levelized costs of a power/industrial plant with and without CCS, and comparing it to the abatement cost of other technologies. It is estimated at € 47-51/tCO_2 for CCS on steel production, € 35-91/tCO_2 for CCS coal, € 65-125/tCO_2 for CCS gas and € 7-15/tCO_2 for fertiliser production (CCS CRT 2013 and IPCC 2014). This compares to EU ETS allowances currently below € 10.

Figure 18: Competitiveness of CCS using avoided cost of carbon



Source: CDP adapted from CCCEP, 2015

The initial investment for a small to medium sized plant (1Mt CO_2 captured p.a.) would typically start from USD 1 billion and it would generally increase its running cost compared to its non-CCS reference, making the technology not competitive against non-CCS technologies and most renewables power generation. Large-scale CCS deployment has therefore only emerged where some form of revenue-stream can be secured. Currently CO_2 utilization is limited to EOR (enhanced oil recovery) in the oil & gas sector, and to some specific chemical processes, which we describe in further detail below.

Revenue streams from CCS

While exploration into routes of commercialization for captured carbon dioxide have been ongoing since the 1850's, currently EOR remains the most promising option for CO_2 utilization at scale. EOR however has attracted much debate as to whether it actually delivers the net emissions reductions intended. For each ton of carbon stored there will be some associated carbon emitted as a result of the consumption of extracted oil. However, most estimates demonstrate that even if EOR results in net positive emissions, when applied to conventional crude oil, it will be displacing the extraction of more emission intensive oils resulting in a net reduction in CO_2 emissions at a system level.

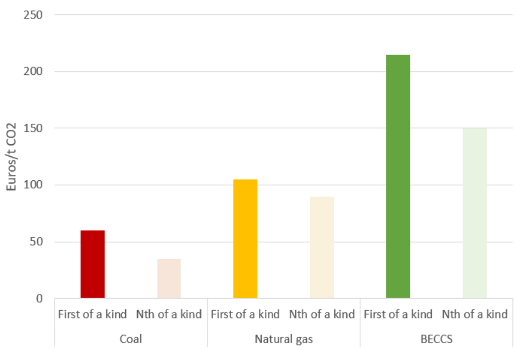
Currently 76% of live CCS projects rely on EOR for revenue generation and most of these are based in the United States. These projects have been important in demonstrating the business case for CCS technologies and the range of prices which carbon dioxide can yield. Retailed carbon dioxide prices tend to fluctuate with oil prices, in 2011 for example they ranged 40 – 45 USD/ton. The influence of the oil price and the undisclosed nature of most EOR contracts makes forecasting carbon dioxide prices year on year difficult. Estimates suggest that carbon prices have not been sufficient to cover the whole range of capture, transport and storage costs (Godec, 2011).

Carbon dioxide also has a number of utilization pathways in the chemicals industry, however, these processes are less mature and are often inefficient and uncompetitive. Captured CO_2 can replace fossil fuels as a source of carbon in the production of petrochemicals (IEA, 2017). It can also be reacted with other modules to produce carbonates and polymers with a diverse range of applications. Captured CO_2 can also be used in the production of urea. While this process is relatively mature, urea production sites often already have a pure carbon dioxide stream available from the production of ammonia. Finally captured CO_2 can be converted into transport fuels. In all these cases, the energy penalty required for conversion is high and therefore only results in a net emission reduction if renewable energy is available. It is also important to note that in many of these cases some portion of the captured CO_2 is returned to the atmosphere during the life of the chemical product.

The role of carbon pricing

Given the significant commitment required for CCS deployment at scale, and the limited opportunities available to make the technology commercial, the creation of economic incentives through policy instruments is crucial in driving investment. Current carbon price mechanisms have failed to create the right incentive due to weak price signals. A number of studies have estimated the carbon price required to make CCS energy processes competitive with conventional technologies. For a first-of-a-kind technology this has been estimated to be around € 60 for coal, € 105 for gas (ETI, 2014) and € 215 for BECCS (Akgul et al, 2014). This sensitivity is dependent on several factors including energy prices, location of plants, transportation requirements, maturity of the technology and the nature of the operations, but it gives a sense of how far these levels are from current prices.

Figure 20: Range of carbon pricing necessary to incentivize investment in low carbon technologies



Source: CDP adapted from ETI, 2014 and Akgul et. Al, 2014

Carbon pricing is on paper the main lever to make the technology commercial, however the timing for allowances to achieve the required price levels is highly uncertain. Carbon utilization has potential, but demand levels outside of EOR are currently limited to around 200 $MtCO_2$/year (Aresta et al, 2013), small compared to the scale of sequestration amounts required (900Mt of capture required by 2025 in B2DS). EOR has potential for further expansion, but the process itself is relatively mature and can be applied only in specific circumstances. So it is hard to see how it can transform CCS breakeven levels, even before considering its issues related to net emissions. Lastly, it is reasonable to expect a progressive cost reduction in CCS from a learning curve, however the rate of decline will be largely dependent on the rate of deployment and in any case it may be slower than seen with other technologies due to the complexity and diversified nature of CCS technologies. Under these circumstances it is therefore not obvious that CCS technologies can become competitive in the near/mid-term.

Technology

Since the pioneering Sleipner CCS project in Norway was opened in 1996, carbon capture technologies have continued to evolve and our knowledge regarding the science of long term storage has become more and more sophisticated. Today, technologies for capturing waste CO_2 from energy and industrial processes can be divided into four primary categories which are applied depending on the specific context of capture. Each category has a different level of maturity and different ranges of application.

Process/ technology	Description	Application/example
Post combustion capture (PCC)	CO_2 is captured from a blend of gases after the energy or industrial process is complete. Most post combustion capture processes involve the extraction of CO_2 using amine-based solvents. This process of capture is very mature relative to other technologies.	The first PCC based commercial scale power plant at Boundary Dam Unit 3 commenced operation in 2014. At full capacity it is capable of capturing up to 1 Mtpa of CO_2.
Pre combustion capture	CO_2 is captured through a process of gasification in which fuels are processed with oxygen or steam to produce syngas. The carbon monoxide contained within the syngas is in turn reacted with steam to produce hydrogen and CO_2. This CO_2 can then be separated leaving a raw syngas which can be used as an energy feedstock.	The Kemper County IGCC project, also in the United States, will also apply Selexol gasification technology.
Oxy-fuel combustion	CO_2 is captured by a process of combusting fuel with pure oxygen rather than air. This produces a flue gas comprised of CO_2 and water vapour which can be dehydrated to produce a high purity CO_2 stream.	Oxy-fuel technology has been successfully tested on a relatively small scale. Such projects include a 30 MW retrofit oxy-fuel pilot project operating in Callide in Australia between 2012 and 2015 and a 30 MW pilot project at Schwarze Pumpe in Germany operating from 2008 to 2014.
Inherent separation	A number of energy and industrial processes produce a pure stream of CO_2 as an inherent part of the process. These streams can be captured rather than be emitted directly into the atmosphere.	Synthetic fuel production and gas processing are examples of processes in which inherent separation is feasible. The Rectisol pre combustion capture process has been applied at scale at the Dakota Gasification facility in the United States.

Significant progress has been made by technology producers to improve the performance of these technologies and processes and explore novel technologies. Since the first application of amine-based solvents for post combustion processes for example, the energy burden has been reduced by some 50%. CO_2 capture by oxy-fuel combustion has also undergone considerable advances over the last ten years with all aspects of the technology investigated on a wide range of experimental scales and using robust modelling tools. While the technology was initially applied in power generation its application in large scale industrial sectors such as cement, steel and oil refining also has potential. In addition to scaling up existing technologies, a range of novel technologies have emerged including CO_2 separation at low temperature by solids adsorbents and polymeric membranes for post-combustion, chemical looping combustion for solid fuels and post-combustion calcium looping systems.

A significant enabler driving progress on these technologies has been the development of capture test centres which have emerged over the last decade. The Technology Center Mongstad (TCM) in Norway, the National Carbon Capture Centre (NCCC) in Alabama and the Shand Carbon Capture Test Facility in Saskatchewan are playing a significant role in developing post-combustion based capture.

Case studies

There are currently 17 live CCS projects globally, with an additional 20 in planning phase, 3 of which are expected to come online within the next 12 months. Together these live projects capture approximately 31.2Mt of CO_2 per annum (Global CCS Institute database). Most of the pioneering projects are based on inherent separation and therefore do not require much disruption or investment in modifying existing energy or industrial processes. Today, however we are seeing an emergence of more complex projects involving oxy-fuel and pre-combustion capture systems, but these are still quite rare and generally operate on a small scale. The bulk of existing projects are based in the US and are based on Enhanced Oil Recovery (EOR).

Steel: Al Reyadah CCS Project

The Al Reyadah project captures CO_2 from the Emirate Steel Factory for the purpose of EOR. The project was developed as a joint venture between Masdar and the Abu Dhabi National Oil Company (ADNOC). The CO_2 is captured using a combination of dehydration and compression processes and transported 43km from the factory to a ADNOC operated oil field. The project has been operational since 2016 representing the Middle East's first commercial scale CCS facility and it will capture approximately 0.8 Mt of CO_2 per annum (IEA, 2017).

Chemicals: Coffeyville Resources Gasification Plant

The Coffeyville gasification project captures CO_2 from the Coffeyville Resources' nitrogen fertiliser plant in Southeast Kansas. Nitrogen fertiliser production involves the gasification of petroleum coke to make synthetic natural gas. This process produces CO_2 which is captured and sequestered using pre combustion techniques, reducing CO_2 emissions by 1Mt per annum. The CO_2 captured is then transported by pipeline to Chaparral, an independent oil and natural gas production and exploitation company and applied for EOR on its oil fields at its North Burbank Unit in Osage County, Oklahoma. This project has been operational since 2013.

Power generation and chemicals: BASF and Linde Pilot Post Combustion Project

In 2016 BASF and Linde successfully completed a pilot project involving the capture of CO_2 from flue gas at a coal fired power plant at the National Carbon Capture Centre (NCCC) in Alabama. The project achieved a 90% capture rate, extracting CO_2 at a purity level of over 99.9%. The project applied BASF's amine based solvent and process

BECCS: Illinois Industrial Project

The Illinois Industrial BECCS project began operations in early 2017 representing the first global large scale BECCS project. The project captures CO_2 from the distillation of corn into bioethanol which is then dehydrated and compressed before being injected into Mount Simon bedrock. The project was funded by the US Department of Energy and will receive CO_2 storage credits of 20 USD per ton of CO_2. As a pioneering BECCs project it has been significant in demonstrating the favourable economics of BECCs under the right circumstances as it has required relatively less investment than other CCS projects associated with power generation. This is largely due to the lack of transportation costs and prior investment in geological research in the area.

Chemicals: Air Product Steam Methane Reformer Plant

Air Products was tasked by the Industrial Carbon Capture and Sequestration Program (ICCS) to create a system to capture CO_2 from two steam methane reformers in Port Arthur, Texas. In August 2011, construction of a steam methane reformer plant with carbon capture began and by January 2013 it was operational. Roughly 1Mt of CO_2 annually will be captured and distributed via the pipeline for injection into Denbury Onshore's enhanced oil recovery projects in Texas. The project cost approximately USD 384 million to develop, 66% of which was funded by the US Department of Energy.

Policy

As seen above, policy support is crucial in enabling CCS to play a meaningful role in carbon mitigation. Governments globally have explored and implemented three kinds of policy mechanisms in a variety of forms. These policy categories are explored further below.

Policy type	Commentary
Market based mechanisms designed to manage climate change broadly	While there are a growing number of carbon pricing schemes emerging globally, many of these are relatively immature and provide a diluted price signal which is not strong enough to support CCS deployment at scale. The EU Emissions Trading Scheme for example, has suffered from severely depressed carbon prices of below € 20/tCO_2 for the past five years. Studies have demonstrated that prices would need to increase to € 60/tCO_2 to stimulate investment in coal CCS plants and € 105/tCO_2 for gas fired CCS plants (see section 'CCS economics' in the Appendix for more information on economics) (CCS CRT, 2013). The only case study where carbon pricing has been successful is the Norwegian carbon tax for offshore oil and gas production which drove investment into the pioneering Sleipner project due to a strong pricing signal.
Financial incentives targeting CCS specifically	The provision of direct financial support has been significant in allowing many CCS projects to become operational. More than half the large-scale CCS projects that are currently operational or in development phase have been backed by capital grant funding. However, there is a growing pool of examples of where government funding has been withdrawn from projects due to budget cuts, unrealistic program deadlines and lack of support in the operational phase. In fact less than 10% of committed government funding was actually invested in CCS projects on the ground between 2007 and 2014. The FutureGen 2.0 project for example was cancelled after the Department of Energy concluded that it could not meet the 30 September 2015 deadline to spend USD 1 billion in grant funding (IEA, 2016),
Regulation of CCS operations relating to legal and safety considerations	CCS requires a number of specific regulations primarily to ensure appropriate storage procedures and clearly define the long-term responsibilities associated with permeant storage. Many of these parameters however remain to be clearly regulated creating risk and uncertainty.

The EU Directive for example is unclear about when there is a transfer of responsibility with regards to the CO_2 stored in geological formations. After 20 years the site operator should be able to transfer responsibility for stored CO_2 to the competent authority however this is not clearly defined. There are historic examples from similar cases relating to environmental management where regulators have not accepted this transfer of responsibilities.
Another legislative challenge exists around storage facilities which very rarely fit neatly into national boundaries particularly in Europe. While the EU Directive provides a consistent legislative framework, there may be discrepancies in public opinion surrounding off and on-shore storage in different countries creating political tension.

Alternative sequestration technologies

Some studies indicate that the global economy will need to generate between 500 and 800 Gt of negative CO_2 emissions by 2100 in order to achieve 2DS and 1.5DS respectively (Geden, O and Shafen, S, 2016). While BECCS represents one technology available for achieving negative emissions there are a number of other forms of geoengineering which can provide similar emissions relief.

- **Afforestation** involves the replanting of trees on marginal crop lands in order to sequester carbon from the atmosphere into biomass. While this natural form of geoengineering shows promise, there are some concerns within the scientific community that greater forest coverage of the globe would cause an increase solar absorption offsetting the temperature stabilizing effects of carbon sequestration.

- **Ocean fertilization** involves the targeted addition of iron into the oceans to encourage otherwise depleted algal growth. These algae then absorb CO_2 from the atmosphere which is sequestered into the seabed when the algae die. The effectiveness of this method however is questionable as trials have shown varied results.

- **Ocean liming** involves the addition of calcium oxide powder to the oceans to increase the pH as more alkaline water absorbs more carbon from the atmosphere. While this process could also aid in reducing ocean acidification, the production of carbon oxide powder is carbon intensive reducing the net impact of this process on emissions.

- **Soil management** could play a significant role in carbon sequestration due to the high carbon storage capacity of soils. If the management of all currently cultivated lands moved to regenerative agriculture practices more than 40% of annual carbon emissions could be captured. These practices however can be expensive and often return no direct financial benefit to the farmer.

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