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A Review of the Role of Fossil Fuel-Based Carbon Capture and Storage in the Energy System

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1. Introduction

Carbon capture and storage (CCS) is a climate change mitigation system with potential applications for decarbonising industrial processes, electricity generation, hydrogen production and providing carbon dioxide removals (CDR¹). The focus of this report is the role of CCS in the energy sector, particularly in relation to 2030 climate change targets.

While CCS for CDR² features in the majority of GHG emissions pathways compatible with the 1.5°C goal of the UN Paris Agreement on Climate Change [1, 2], and it is expected to have a significant role in mitigating emissions from heavy industries, its role in low carbon energy is less clear. Expectations for the role of CCS in electricity generation in international, European and UK energy pathways have decreased – which is likely due to slow deployment of coal and gas CCS, coupled with faster progress in renewables, energy storage and demand-side technologies [4]. Most (81% of global capacity) CCS deployment to date has been for enhanced oil recovery (EOR)[6]. Notionally, its use in EOR should provide expertise and bring down costs as the technology transfers into carbon mitigation, but progress on this has been slow over the past decade [4]. If CCS is to have a meaningful role in mitigation, deployment would need to accelerate markedly. Emphasis on CCS has notably shifted to industrial applications and fossil fuel-based hydrogen production.

Overall, the role fossil fuel-based CCS can and should have in energy system decarbonisation is unclear. Global carbon budgets are increasingly constrained with substantial progress in energy sector decarbonisation required by 2030 [1, 8, 9], while significant levels of CCS are not expected until 2030 at the earliest. It is still unclear what the preferred option for decarbonising heating, long-distance transport (including aviation and shipping) and feedstock hydrogen in industrial processes will be, and CCS related products are still considered as options. However, the extent to which fossil fuel-based CCS can be a part of low carbon energy systems will also depend on the level of residual emissions from hydrogen and electricity production and fuel supply [10, 11] allowable in future carbon budgets. Delays in CCS roll out also

¹ Carbon Dioxide Removal (CDR) approaches are also referred to as greenhouse gas removal (GGR) and as negative emissions technologies (NETs).

² For example, through bioenergy CCS (BECCS) and direct air capture (DAC) systems.

mean that developments elsewhere are salient. CCS applications for transport, power and heating services may depend upon how it performs relative to other low carbon generators (renewables and nuclear), demand management and the electrification of transport and heating. Consequently, policy makers would be expected to have low, or zero, fossil fuel CCS energy scenarios for climate change targets to reflect these uncertainties.

This report provides an overview of CCS development to date and its expected role in future decarbonisation, considering the global context but with a focus on the UK. The focus of this report is primarily on the near-term deployment of CCS in energy systems. Section 2 of the report reviews the expectations for CCS in current energy and climate scenarios. In Section 3 the progress to date is assessed, and in Section 4 key issues for future deployment of CCS are considered.

2. The Role of CCS in Scenarios and Policy

CCS features prominently in many energy and climate change scenarios and strategies for meeting climate change mitigation targets. This includes the Intergovernmental Panel on Climate Change (IPPC), European Commission, International Energy Agency (IEA) and the UK Committee on Climate Change (CCC). It is, however, apparent that the current trend of CCS deployment worldwide has yet to reach the pace of development necessary for these scenarios to be realised.

The mitigation potential of CCS for fossil fuel power generation in the energy sector features in many IPCC emissions pathways and future IEA energy scenarios. In the case of the IPCC, there are also 1.5°C pathways with no fossil fuel CCS or BECCS, which rely instead on social, business and technological innovations that lead to lower energy demand (LED - low energy demand scenarios). Under the LED scenarios, afforestation is the only CDR alternative, and nuclear is also considered [13].

For those emissions pathways with high reliance on CCS in the energy sector, however, there is inconsistency between the CCS projects currently in the pipeline and interim and these long-term expectations. Furthermore, existing CCS facilities for fossil fuel power generation are dominated by coal, despite projections for natural gas to replace coal-fired power generation in many archetypal pathways even with CCS. This section reviews the expectations for CCS in key energy and climate change scenarios and strategies. In the next section, this is then contrasted with the current status of CCS development.

IPCC - Special Report on Global Warming of 1.5°C

The **Intergovernmental Panel on Climate Change** (IPCC) in its special report on global warming of 1.5°C published in 2018 [14] shows that reliance on CCS to meet climate targets varies depending on the emissions pathways. Three out of four archetypal

model pathways feature fossil fuel CCS. Within the CCS featured pathways there is a range between a limited role scenario (cumulative 348 GtCO₂ stored by 2100, of which BECCS is 151 GtCO₂) to a more extensive role scenario (cumulative 1,218 GtCO₂ stored by 2100, of which BECCS is 1,191 GtCO₂). Under these emissions pathways, CCS reduces CO₂ emissions from natural gas-based and, to a lesser extent, from coal-based power generation. The role of CCS combined with bioenergy production (BECCS) plays an even bigger part in most of the 1.5 °C emissions pathways with its potential to remove CO₂ from the atmosphere and thus delivering net negative emissions [1]. There are IPCC 1.5°C pathways (the LED scenarios) that do not include CCS or BECCS at all, which involve radically and immediately reducing energy demand, with CDR achieved through afforestation.

The IPCC illustrative pathways also show that the share of renewables for electricity generation in 2050 increases at different levels (63%-81%) across all the pathways. Inversely, for three out of the four IPCC model scenarios, the shares of coal, oil and gas as primary energy sources are expected to decline by 2050 relative to 2010 for all the model pathways. In relation to this, while the deployment of CCS on natural gas and coal power stations varies widely across IPCC pathways, in most cases the deployment of natural gas CCS is greater than coal CCS.

International Energy Agency Scenarios

The IEA Sustainable Development Scenario (SDS) lays out a major transformation of the global energy system it considers consistent with supporting the achievement of the Sustainable Development Goals (SDGs); affordable and clean energy access (SDG7), climate action (SDG13) and air quality (SDG3). The IEA SDS analysis includes a pathway without any CDR technology (global mean temperature rise below 1.8°C at a 66% probability), and one with CDR (consistent with a global mean temperature rise of 1.5 °C with a 50% chance - requiring around 300 Gt of CDR, which is less than the median level of CDR in the IPCC 1.5 °C scenarios) [15]. The contribution of CCS to energy-related CO₂ emissions reductions in the SDS is 9%, compared to 37% from efficiency improvements and 32% from renewables.

In the SDS, the role of CCS in the power sector is more limited compared to previous IEA scenarios (i.e. the 450 Scenario³). The current SDS relies more on renewable energy in the power sector with 8,100 TWh of electricity generation from wind and solar PV compared to 3,900 TWh from nuclear and CCS; in contrast, the former IEA 450 Scenario projected 3,600 TWh of electricity from wind and solar PV and 7,100 TWh from nuclear and CCUS. This reflects a change in expectations on the deployment of fossil fuel CCS power generation relative to renewables for delivering decarbonisation in IEA analysis.

³ The 450 Scenario refers to the CO₂ concentration of 450 ppm consistent with a 50% chance of limiting global temperature rise below 2°C

In the IEA SDS, the power sector is expected to reach a decarbonisation rate of 90% by 2050. Under this scenario, CCS (and nuclear energy) supplement the role of renewable energy, increasing the share of low-carbon electricity generation to 84% by 2040. CCS combined with coal and gas power contributes to 5% of the electricity generation mix by 2040 in contrast to a 67% share from renewable sources and 11% from nuclear. In terms of energy generation, 1,909 TWh of electricity are produced from coal- (994 TWh) and natural gas- (915 TWh) based power CCS in contrast to 26,065 TWh of electricity generation from renewables in the latest IEA pathways.

European Commission: The European Green Deal

In response to the European Green Deal and the targets of the Paris Agreement, the European Union has committed to achieving climate-neutrality by 2050 and reducing emissions by 55%⁴ from a 1990 baseline by 2030. The proposed transition to climate neutrality includes investments and directives on CCS, smart infrastructure and innovative technology, smart grids, hydrogen networks and energy storage. Regarding CCS, the 2009 EU CCS Directive provides a framework on the geological storage of carbon dioxide regulates mainly the CO₂ storage phase. It also includes some provisions related to the CO₂ capture and transport phases with the intention to facilitate the integration of the CCS supply.

The European Commission [16] has stated a key role of CCS deployment to meet the EU's long-term GHG emissions reduction target by 2050. The Commission expects CCS to become one of the few technology options to cut direct emissions at scale from industrial processes and serve as a low-carbon technology when combined with fossil fuel-based generation to provide flexibility to energy systems, with increasing variable renewable sources [16]. However, it also indicates that the role of CCS has diminished with the faster deployment of renewable energy and other technologies to reduce emissions from industrial processes [16]. Despite this, CCS is still considered necessary to capture and store the CO₂ from carbon-intensive industries; in the transition of fossil fuel-derived hydrogen production and for the deployment of bioenergy with CCS at scale to achieve negative emissions. The European Commission's Hydrogen Strategy as a whole however emphasises electrolysis derived hydrogen (targeting 40 GW of electrolysis capacity by 2030) [17].

The European Union via the EU Innovation Fund (circa 10 billion euros), and using revenues from around 450 allowances of the EU Emissions Trading Scheme, is financing innovation projects including renewable energies, CCS, energy storage and industrial low-carbon processes [18]

UK - Committee on Climate Change

⁴ Recently voted on by the European Parliament and may increase to 60% by 2030 against 1990 baseline

The Committee on Climate Change (CCC) has advised the UK Government to reduce GHG emissions reduction to 'net-zero' by 2050 under the UK's obligations to the Paris Agreement. The CCC in their Net Zero report [19] introduced new scenarios to illustrate options on how to reduce emissions from current levels. The CCC indicates that current UK policies are insufficient to meet even the previous 80% of emissions by 2050 target and that efforts in climate policy need to ramp-up [20].

In statements made to date, the CCC considers CCS systems essential to deliver net-zero GHG emissions by contributing to the projected increase supply of low-carbon electricity, hydrogen production, and the requirement of GHG removal through BECCS systems [21]. The CCC has *Core*, *Further Ambition* and *Speculative* scenarios. The *Core* scenario represents findings on low-cost low-regret options, the *Further Ambition* scenario involves more challenging and costly options than those in the *Core* scenario, and the *Speculative* scenario includes options considered to be at low-level of technology readiness, higher cost and with barriers to public acceptability. The extent to which CCS contributes to the net-zero target, however, varies within the scenarios and involves an aggregate annual capture and storage between 75-175 MtCO₂ in 2050 and a major CO₂ transport and storage infrastructure servicing at least five clusters [19].

Under the *Further Ambition* Scenario, CCS has a larger role across industry, greenhouse gas removals (i.e. BECCS), hydrogen production and power generation, with up to 175 MtCO₂ captured and stored in 2050. In the power sector, CCS integration with gas-fired or biomass power plants would be required to supply some flexible electricity generation and complement the remaining 5% share needed to fully decarbonize the electricity supply in 2050. Under this scenario, 57 MtCO₂ /year and 46 MtCO₂/year would respectively be captured and stored from fossil-based electricity generation with CCS and fossil fuel-derived hydrogen production with CCS. This scenario also assumes higher CO₂ capture rates of 95% [19] than the conventional 90% capture rate usually assumed in the literature for power-CCS plants. Technology options and economic challenges of higher CO₂ capture rates are further discussed later in this report.

The CCC also finds that CCS progress has stalled in the UK due to slow movement on UK policy for CCS deployment. Although CCS has recently begun to be discussed as a priority again slow progress leaves the UK with currently no CCS facilities in operation or construction at this time [20]. In these scenarios, a minimum of two CCS clusters are expected to operate by 2030 capturing at least 10 MtCO₂ per year. This is on the basis of the government leading infrastructure deployment, with long-term contracts for carbon capture and encouraging investment. These scenarios also include the development of hydrogen, mainly through natural gas reforming, assumed to operate at scale by 2030 in industrial CCS clusters, as well as policy frameworks across energy generation, industry, and greenhouse gas removals. The CCC highlights in particular that the UK should take advantage of the significant potential in regional CCS storage capacity, estimated in 78 Gt and equivalent to over 150 MtCO₂ stored per year [19].

In an illustrative generation mix of the power system in 2050, the share of electricity generation through natural gas power stations with CCS could reach up to 23% in the mix, although this could be partially replaced by nuclear power and alternative renewable technologies. The main supply of electricity would derive from variable renewables with a minimum 59% share. Additionally, electricity from BECCS (6%), nuclear (11%) and others sources (i.e. existing bioenergy and hydropower, and hydrogen or ammonia to provide back-up) would complement the generation mix [20].

The UK Government and the Department for Business, Energy & Industrial Strategy (BEIS):

As part of the UK Government, the Department for Business and Industrial Strategy (BEIS) considers that CCS technology has a significant role to play in meeting the net-zero target. CCS is expected to contribute to the decarbonisation of the power and industry sectors, produce fossil-based hydrogen and achieve large-scale commercial greenhouse gas removal [22]. Specifically, in the power sector, CCS is expected to capture and store the 45 MtCO₂ emissions per year from existing natural gas CCGT⁵ based electricity generation, assuming a 95% CO₂ capture rate. Emissions from these systems are currently equivalent to 12% of UK emissions [22]. In the production of fossil fuel based-hydrogen via natural gas reforming or biomass gasification CCS would capture CO₂ as a by-product.

The UK Government considers CCS infrastructure likely to be delivered for the net-zero target with a substantial CO₂ storage capacity (78 billion tonnes of CO₂) using reservoirs deep underground off the UK coastline [22]. To this end, research investment competitions for greenhouse gas removals and development plans for six industrial CCS have been supported. The Government has also invested over £130 million in R&D and innovation with the aim of reducing CCS costs. They are supporting innovative technologies such as those developed by C-Capture (i.e. pilot testing of non-amine capture technology at Drax power station); Carbon Clean Solutions on novel carbon capture solvent and the Allam cycle technology, used by NET Power, capable of 100% capture rate at costs similar to an unabated CCGT [23].

Since the Clean Growth Strategy [23], the government committed to deploy CCS at scale during the 2030s subject to costs coming down sufficiently and to invest up to £800 million in developing CCS infrastructure to support the decarbonisation of our power and industrial sectors [21].⁶ Recently enhanced ambition to begin construction of two CCS hubs in the mid-2020s and a further two created by 2030 has been announced [24]. The role of CCS is, however, considered essential by BEIS to reduce the costs of meeting the 2050 target contributing to lower emissions across industry, power, heating and transport sector [23].

⁵ Combined Cycle Gas Turbine

⁶ See BEIS (2020) <https://www.gov.uk/government/news/beis-in-the-budget>

In scenarios with a significant role for CCS, deployment is required through the 2020s, with the delivery of major projects by 2030 at the latest (particularly in UK scenarios). In the case of the IEA projections for the role of CCS in the energy sector have been downgraded. In the UK changing expectations in the role of CCS in energy are manifest in the National Grid Future Energy Scenarios, wherein in 2015 CCS coal and natural gas power generation is significant in scenarios [25] but absent in the 2020 scenarios [26]. The role of CCS in National Grid scenarios 2020 is exclusively in combination with bioenergy and for hydrogen production for heat and transport [26]. This reflects a shift in the expectations for fossil fuel CCS from the power sector to hydrogen and a greater emphasis on CCS for CDR and industry. In the next section, the current status of CCS worldwide is reviewed. The delays in CCS deployment discussed may in part explain this shift. Table 1 provides a review of the role of CCS in key scenarios reviewed.

Table 1: Summary of the role of CCS on energy and climate change scenarios and strategies for the IPCC, IEA and UK Committee on Climate Change

Report	Emissions reduction by 2050	Characteristic of CCS contribution/participation
IPCC 1.5°C Global Warming report	91%-97% CO ₂ emissions reduction by 2050 (relative to 2010) across the four illustrative 1.5°C model pathways. 78%-89% reduction in Kyoto GHG emissions by 2050 (relative to 2010) across the four illustrative model pathways	CCS (including BECCS) contribution to CO ₂ emissions reduction leads to cumulative CO ₂ stored until 2100 spanning (four illustrative model pathways) between: The lowest share, zero GtCO₂ for low-energy demand-LED scenarios to 348 GtCO₂ stored in a sustainability-focused scenario of which BECCS 151 GtCO ₂ , to 686 GtCO₂ stored in a middle-of-the-road scenario of which BECCS 414 GtCO ₂ , to the highest share 1218 GtCO₂ for the resource and energy-intensive scenario of which BECCS 1191 GtCO ₂ .
IEA - World Energy Outlook 2019	In the Sustainable Development Scenarios (SDS): The emissions trajectory of SDS decline by 730 Mt on average each year compared with a 400 Mt annual decline in the 450 Scenario.	2776 Mt of CO₂, from the energy-related GHG emissions, are captured and stored through CCS by 2050. CCUS contributes 9% of the energy-related CO ₂ emissions reductions. Across all sectors, around 0.7 Gt of CO ₂ emissions are captured each year by 2030; this rises to almost 2.8 Gt in 2050 where CCS is equally split between power and industry. Under the SDS in the power sector , CCUS is applied to over 320 GW of coal- and gas-fired power generation capacity by 2040, with 20 GW per year from late 2020's to 2040. 1323 MtCO₂ are captured and stored through CCS in the power sector
CCC – UK Net Zero Report (2019a, 2019b)	In the Further Ambition Scenario (required to get to net-zero GHG emissions): 96% reduction in all GHG emissions by 2050 compared to 1990 levels, remaining in 35 MtCO ₂ e in 2050 CO ₂ emissions slightly below net-zero Remaining emissions from agriculture and aviation.	In the UK , CCS captures and stores an aggregated annual 175 MtCO ₂ in 2050 (from zero MtCO ₂ in 2017). CCS to integrate with hydrogen, electrification and resource efficiency, the portfolio of options for emissions reduction: CCS in electricity generation: 57 Mt CO ₂ captured and stored through fossil power generation with CCS. Decarbonised gas via CCS and hydrogen contributes with 5% for full (100%) electricity decarbonisation in 2050 and remaining emissions are of 3 Mt CO ₂ e CCS in Hydrogen production: 46 Mt CO ₂ captured and stored through fossil hydrogen production with CCS CCS in Industry: 24 Mt CO ₂ captured and stored BECCS: 44 MtCO ₂ captured and stored. Bioenergy combined with CCS to produce electricity, biofuels for aviation and in buildings off the gas grid

3. The Current Status of CCS

The CCS concept, for long-term sequestration of CO₂, has been successfully demonstrated on a technical basis since 1996, however, scaling up deployment and applications outside of the chemical sector and oil and gas processing beyond EOR as a business model has been slow. The Global CCS Institute (GCCSI) notes that in 2010 ~10 Mt of CO₂/year CCS capacity was operational, with a further 150 Mt CO₂/year in some form of development, yet by 2020 only 39 Mt CO₂/year was in operation⁷, with ~75 Mt CO₂/year capacity in some form of development (see Figure 4 of GCCSI [6]). This represents a decade of very limited progress in terms of CCS project development. Projects in development fell to as low as ~30 Mt CO₂/year in 2017 [27] reflecting various cancellations in early and advanced development projects. The IEA's 2019 scenarios for meeting SDGs considers 840 Mt CO₂/year of CO₂ capture (of which 81 Mt CO₂/year is BECCS and 189 Mt CO₂/year is used rather than stored) overall by 2030 [4], implying deployment averaging 80 Mt CO₂/year capacity per year over the coming decade. This is roughly equivalent to adding 25 projects globally each year with a capacity similar to the proposed Scotland CCS cluster (3-4 Mt CO₂/year) with the additional difficulty of the long deployment timelines for CCS projects. This will require overcoming the financial and risk barriers to the technology observed so far.

Carbon capture technology for use in the energy industry (primarily oil extraction) has been in place since the 1970s, with research into applications for long term sequestration accelerating through the 1980s (e.g. with the start of the MIT Carbon Capture and Sequestration Technologies programme in 1989). The role of CCS expressly for environmental goals was demonstrated in the 1996 Sleipner gas project [28], but clearer expectations around the role of CCS in climate policy became increasingly apparent around 2008. The UK Committee on Climate Change 'Building a Low Carbon Economy' in 2008 recommended CCS as an option for power generation (with coal and gas) and likely essential for some industrial applications [29]. This informed a policy process to develop CCS, firstly for coal power stations, pursuing deployment by the early 2020s [30]. A key international indicator for CCS expectations in this period was the G8 (Group of Eight) commitment to launch 20 large scale CCS projects by 2010 with broad deployment (19 to 43 large projects) of operational CCS by 2020 [31]. The IEA's CCS Roadmap in 2009 set a goal of 100 projects globally capturing 300 Mt CO₂/year by 2020 [4]. Deployment progressed slowly in relation to this, with only five projects developed by 2012. However, by 2014 the first commercial CCS power station at Boundary Dam in Canada was completed. In the UK two R&D competitions to develop demonstration projects in the UK between 2008 and 2015 produced significant research outputs on CCS application but ultimately did not lead to a demonstration project. The failure of the UK competitions

⁷ Accounting for mothballed operations at Petra Nova and Lost Cabin facilities in 2020.

was primarily attributed to uncertainty around the economic feasibility of CCS, with a £1 billion state investment into CCS ultimately not materialising at the end of the second competition process [32]. The ownership structure (i.e. responsibility for the 'full chain' of CCS processes) expected of project developers is also considered a factor [33]. Additionally, a key driver of this initial round of investment in UK CCS was to mitigate carbon from coal power generation, which is now no longer a significant part of the UK electricity mix.

To date globally, 28 CCS plants are developed to the operational stage (although 2 are currently suspended), five of them with integrated dedicated geological storage and the remaining 22 using the CO₂ captured for enhanced oil/gas recovery (EOR/EGR) applications [6].

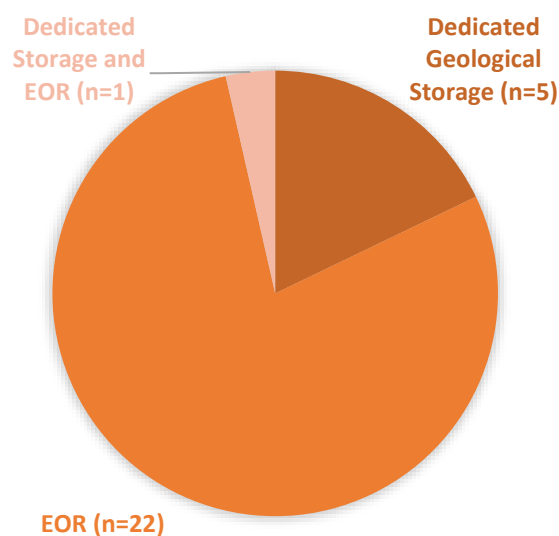


Figure 1: Operational CCS Projects by type of CO₂ storage. Based on the Global CCS Institute. *The Global Status of CCS: 2020*. (2020)

The CO₂-EOR process entails the injection of CO₂ in an oil reservoir, working as a solvent to swell and mobilise the oil previously trapped in rock's spaces and with the final purpose of increasing oil production in a well. The CO₂ is permanently trapped in the space that originally held the oil [27]. The global capture capacity of the operational CCS plants stands around 37 Mt CO₂/year, where approximately just 19% (~7 Mt CO₂/year) is used for the sole purpose of CO₂ emissions avoidance through dedicated CO₂ storage and the rest applied for EOR processes.

The GCCSI [6] also reports that two large-scale CCS facilities are under construction with an aggregated CO₂ capture capacity between 1.91 Mt CO₂/year and end-use applications in EOR. The expected start date of operation of these projects is in the late 2020s. An additional 37 projects are in the pipeline, 13 of which are in advanced

development using a dedicated front end engineering design (FEED)⁸ approach and comprising a mix of dedicated storage (seven), EOR (four) and under evaluation (two). From the 21 CCS projects in early development, the majority (16) are planning to have CO₂ dedicated geological storage.

The natural gas processing industry embeds the highest number of CCS plants (11 facilities in operation) using industrial separation to capture the CO₂ and the majority with EOR application eight). These industries can capture the CO₂ at relatively low costs due to its high concentration in the gas streams [27]. Other industry sectors with projects integrating CCS, whether for emissions mitigation or as an inherent stage of the production process, are the power generation sector (one), fertiliser production (four), hydrogen production for oil refining (three), synthetic natural gas production (one), ethanol production (three) and iron and steel production (one)[6]. The emphasis on using EOR applications for existing CCS plants is because the majority of these facilities are located in the US where onshore EOR is a long-established process, with many miles of existing CO₂ pipelines. Furthermore, in the absence of strict regulations and cost on CO₂ emissions, there is little incentive to develop CCS for mitigation. Hence, EOR is so far one of the economically feasible ways to capture and store CO₂ while extracting more oil. It is therefore notable that at this stage CCS planned deployment remains dominated by EOR – which has a minor role in expected CCS scenarios by 2030 (see Section 2).

CCS deployment in Europe and the UK

Among the 28 operational large-scale CCS facilities worldwide, two are located in Norway (Sleipner: 1 Mt CO₂/year and Snøhvit: 0.7 Mt CO₂/year) capturing and storing 1.7 Mt CO₂/year of CO₂ from the natural gas processing industry in dedicated storage sites [6][4]. In addition to the two operating CCS projects, the Longship CCS project in Norway is projected to commence operation by 2024 and capture up to 0.8 Mt CO₂/year of CO₂ from the Norcem's cement factory and the Fortum waste-to-energy plant facility [34]. The CO₂ transportation and off-shore storage will be managed by the Northern Lights consortium through an open-access infrastructure using existing oil and gas infrastructure. In addition to the CO₂ captured from the capture plants in Norway, Northern Lights is expected to serve as transportation and storage for other capture sites across Europe [34].

Despite a regulatory framework for CCS being in place through the 2009 CCS Directive, CCS deployment in Europe outside of Norway has not yet materialised. Compared to other regions like North America with 12 CCS large-scale facilities in operation, the integration of CCS to current power and industry sectors in Europe has been much slower.

⁸ **Front End Engineering Design** is an approach used to control project expenses and thoroughly plan a project before a fix bid quote is submitted. It is conducted after completion of Conceptual Design or Feasibility Study, and before the Engineering, Procurement and Construction.

Progress on CCS deployment in Europe is however projected to accelerate in the mid and later 2020's with as many as 10 large scale CCS projects (six in the UK, two in the Netherlands, one in Norway and one in Ireland) being proposed. Most of these projects are to function as part of CCS hubs and clusters in industrial installations and using shared infrastructure for the CO₂ transportation and storage network to reduce costs of the CCS supply chain. This, however, represents the current best case, with the UK Government so far only committed to 'at least two' industrial hubs by 2030.

The operation of the planned CCS facilities is expected to capture up to 26.7 Mt CO₂/year; 22.7 Mt are planned for injection in dedicated geological storage sites, with 4Mt captured from Drax (in conjunction with bioenergy) under evaluation [6]. The total CO₂ storage capacity available in Europe is estimated by the GCCSI to be 300 Gt [6].

In relation to funding and policy aspects, 10 billion euros are expected to be available for the Innovation Fund, the largest European fund financing CCS, as part of the portfolio of low-carbon technologies and processes. CCS is also part of the current European Commission strategy to achieve climate neutrality by 2050, with contributions spanning between 52 to 606 MtCO₂/ year in 2050 across scenarios. It is anticipated to have a more limited capacity in the power sector, instead, its proposed role is more relevant as an industrial decarbonisation alternative and for hydrogen production.

Within the UK, there are five clusters which have received funding to develop cluster plans under the first stage of the Industrial Decarbonisation Challenge Fund; bids to the second stage deployment plans have been submitted and are expected to commence early 2021. The *Net Zero Teesside* project is one of the initial CCS clusters under development estimating to capture up to 6 Mt CO₂/year of CO₂ emissions from a new commercial-scale natural gas power plant, that has completed the Stage 2 Consultation stage of the 'Development Consent Order' process, and also from other existing industrial processes. This cluster is expected to start operation by 2030. Furthermore, the Zero Carbon Humber cluster, also under development, is planned to capture CO₂ up to 10 Mt CO₂/year when fully operational from a BECCS plant (Drax biomass-power station) and from the production of hydrogen to fuel the industry sector. The Acorn Full Scale CCS project plans to function as a major fossil fuel based-hydrogen production pathway with a CCS transport and storage hub located at St Fergus in Scotland. The project was awarded the first carbon dioxide appraisal and storage licence by the Oil and Gas Authority in the UK and has stated it could commence operation in 2025. The *Net Zero Teesside* and *Acorn* projects could use the Northern Lights open-access infrastructure as an alternative CO₂ transportation and storage option. The other two clusters receiving funding from the Industrial Decarbonisation Challenge Fund (stage 1) are the HyNet North West industrial cluster for hydrogen production and the South Wales Industrial Cluster.

CCS in the power sector

The abatement of fossil CO₂ emissions through CCS deployment in the power sector remains limited, with currently two large-scale CCS facilities incorporated into coal-fired power plants, both in North America. Together, these facilities have a combined capture capacity of 2.4 Mt CO₂/year and use the CO₂ captured for EOR. This deployment is considered to be significantly off-track to meet climate change targets [4]; compared for example to the target of 310 Mt CO₂/year for power generation alone in 2030 by the IEA's Sustainable Development Scenario [15]. This would require an increase in CCS capacity in the power sector of approximately 129 times the existing capture capacity from the two existing power plants with CCS integration.

The first large-scale CCS facility in the power sector consisted of the integration of a CCS system in the Unit 3 of the *Boundary Dam* coal-fired power plant in Canada. It started operation in 2014 with a capture capacity of 1 Mt CO₂/year, resulting in a cumulative 3.4 Mt CO₂ captured up to July 2020. The capture method is the Shell Cansolv post-combustion CO₂ capture technology with a target capture rate of 90% [35]. The CO₂ is compressed and transported to Weyburn oil field for EOR and a smaller portion is stored in a dedicated saline aquifer (Aquistore project) to monitor and evaluate the safety and permanency of the deep underground CO₂ storage. The capital cost of the plant was reported to be 600 million Canadian dollars (~455 million USD) [36] and a capture cost of USD 100 per tonne CO₂.

Several conditions enabled the deployment of Boundary Dam CCS, including the opportunity to sell the CO₂ captured for EOR; grant supports, subsidy provision by government, and the prospect of low-cost CO₂ transport and storage [27]. The key driver, however, was the environmental regulation introduced by the Canadian government to meet emissions performance standards consistent with natural gas generation, therefore the only options were to retrofit (addition of a CCS unit to an existing power plant instead of adding it to a new plant) with CCS, switch to natural gas or decommission the plant [37].

Petra Nova Carbon Capture is the second commercial coal-fired power plant with CCS integration, located in Texas, USA. It started to operate in 2017 with a capture capacity of 1.4 Mt CO₂/year. It has accumulated 3.4 Mt of CO₂ captured and stored for EOR during the third phase (demonstration and monitoring) of the project between 2017-2019 [27]. The facility is however currently offline due to low oil prices [6, 38]. The capital cost of the project was USD 334 million and the levelised capture cost for this plant reduced to USD 65 per tonne CO₂, compared to Boundary Dam (although modifying existing infrastructure may have contributed to cost savings). The capture method used is an advanced amine-based CO₂ absorption technology (KM-CDR Process) [39].

The rationale behind the deployment of the plant was also different from Boundary Dam, as Petra Nova was constructed as an enhanced oil recovery project and received a significant grant (USD 190 million) from the US Government Clean Coal Power Initiative Program [36]. Furthermore, it has received emissions credits. Operation of CCS at the plant has however been reportedly affected by low oil prices [38].

As such, at this point, CCS deployment in sectors that it is primarily envisaged for (particularly in Europe) – natural gas power CCS, fossil fuel hydrogen production, industrial capture outside of oil and gas sector and carbon dioxide removals – is currently minimal or non-existent. Therefore, while technological aspects for capture technologies, transport and storage have been demonstrated, integrated systems delivering CCS services for key decarbonisation activities remain a future prospect. In the next section, the future potential for fossil fuel CCS in the energy system is reviewed. It suggests a limited role for CCS in energy system decarbonisation over the coming decade (2020-2030), but renewed policy priorities to establish CCS processes by 2030.

4. The Future Potential of CCS

Despite its representation across most model pathways for meeting climate change goals, research evidence collated in Rogelj et al [2] identifies uncertainty around the future deployment of CCS given the slow pace of deployment and lack of incentives, policies and regulation for CCS implementation compared to what is expected to be delivered by CCS infrastructure. Given the prominence of CCS in most mitigation pathways and its current limited improvement, the large-scale deployment of CCS as an option depends on the further development of the technology for permanent CO₂ (as opposed to EOR) in the near term.

This section considers some of the issues CCS faces in meeting the expectations identified in the energy and climate scenarios it features in (Section 2), specifically around emissions, technical attributes, regulation, and cost and complexity.

BOX 1: Technical Attributes of CCS

Among the stages comprising CCS, the CO₂ capture is the most energy-intensive and costly, imposing a considerable energy penalty to the process [3]. Energy penalty is a common metric applied to the power generation sector that compares the performance (efficiency) of a plant with CCS compared to a similar one without it [5]. It can be interpreted as the additional energy input (fuel) required to maintain a power's plant output at the same level, or the loss of power output for a constant energy input [7].

There are various types of CO₂ capture technology, featuring inherent advantages and limitations, and at different stages of development; post-combustion, oxyfuel combustion and pre-combustion.

In the **post-combustion capture technology**, the CO₂ is separated and captured, from the flue gases (nitrogen, water, CO₂, and other impurities) after the fuel combustion in a power plant or industrial process. The main advantage of this technology is the feasibility for retrofits of existing industrial plants without further large equipment investments and low impact on the process operation [3].

The main energy input is required in the form of low pressure steam for the solvent regeneration process, imposing a significant efficiency penalty. Part of the steam generated to produce electricity in the power plant is diverted for the amine solvent regeneration, thus imposing an energy penalty between 15-28% for pulverised coal power plants and 15-16% for natural gas combined cycle plants with integrated post-combustion capture [5].

In **oxyfuel combustion capture**, fuel (coal, gas, or biomass) is burned in a mixture of oxygen and recycled CO₂ (to control the temperature inside the boiler) producing a gas mainly formed of CO₂ and water vapour. The CO₂ is separated afterwards by a condensation process [3].

The major advantage of this is simple and low-cost CO₂/H₂O separation. It also has the potential of retrofitting for existing power plants. The energy penalty (around 19%) is imposed by the energy-intensive air separation process [12]. Therefore the development of more efficient air separation systems might also enhance the overall process efficiency [3].

The **pre-combustion capture technology** entails a reaction between coal, natural gas or biomass and air, oxygen and/or steam to produce a syngas comprised mainly by CO, H₂, CH₄ and CO₂. The syngas reacts with steam in a water-gas shift reactor to produce CO₂ and more H₂. The CO₂ is later separated using physical or chemical absorption methods, resulting in two separate gas streams: a pure CO₂ gas and hydrogen-rich fuel.

Because pre-combustion capture involves steam reforming or gasification process, this route has limitations on the operating flexibility as gasification is a more complex and novel technology than combustion. The capital costs are higher forcing full load operation to produce syngas. The operating condition of the pre-combustion technology varies to post-combustion because in pre-combustion the syngas is at higher pressures (2-7 MPa) and high CO₂ concentration content, therefore the compression and desorption requirements are not so demanding, resulting in lower efficiency penalties [3]. Energy penalties range between 5-20% for Integrated Gas Combined Cycle (IGCC) power plants combined with pre-combustion capture CCS.

Emissions

Mitigating climate change in line with the goal of staying well below 2°C of warming depends on a timely transition to low carbon energy [40]. In contexts such as the UK, legislative targets require net-zero greenhouse gas emissions by 2050, which for the energy system means almost zero CO₂ emissions [19]. It is not only what is achieved by an endpoint target (such as 2050), but the extent to which cumulative CO₂ emissions – the primary driver of long term climate change [40] – are limited over time that ultimately matters. The emissions associated with a given future technology and its contribution to mitigation at a given time are therefore of particular importance. The remaining global carbon budgets published by the IPCC imply immediate and sustained reductions in emissions, with a reduction in global CO₂ of ~45% against a 2010 baseline required by 2030 for a chance of 1.5°C [14]. The EU is considering a mitigation target of over 55% relative to 1990 by 2030 and the UK recently updated its 2030 target to 68% cut in emissions by 2030 against the 1990 baseline [41], entailing significant additional progress on heating and transport by 2025 [21]. Analysis by Anderson et al suggests that mitigation rates in countries such as the UK should be even greater (~10% per annum, up from recent historical trend of 3% per annum), decarbonising energy systems by 2035 to 2040 [8]. By all measures, significant progress in energy system decarbonisation is required over the coming decade particularly in developed nations such as within Europe.

Within many of the pathways proposed for reaching these targets, CCS has various roles in industrial decarbonisation, power sector decarbonisation and CDR (see Section 2). CCS offers a means of capturing ongoing emissions of CO₂ from existing industrial processes such as iron & steel and cement, providing an option to decarbonise these typically hard to abate emissions. Hydrogen via electrolysis also offers an alternative to CCS based decarbonisation of steel production. The IEA World Energy Outlook 2019 reports that CCS together with energy and material efficiency supports the decarbonisation of heavy industries, such as cement, iron and steel production, and the refining sub-sector of oil and gas extraction [15]. In the IEA SDS, CCS contributes to 21% of savings in energy-related CO₂ emissions in industry [15]. They also note that the current pipeline of projects, however, is far short of what is required under this scenario to abate emissions from key industrial sectors of the economy [15]. Carbon dioxide removal with CCS is central to national net-zero targets in the UK [19]. In the case of energy provision through fossil fuel CCS, however, there are apparent limitations to the role that it may be able to play within highly constrained future carbon budgets.

In the case of natural gas CCS power stations, there are residual emissions that would contribute to direct territorial CO₂ emissions of at least 39 kgCO₂e/MWh (assuming a 90% CO₂ capture rate) [42]. Upstream emissions of greenhouse gases (notably methane) associated with extraction, processing and transport increase with CCS

application due to increased energy use for capture and reduced efficiency meaning life cycle emissions of at least 123 kgCO₂/MWh [10].⁹

Steam methane reforming (SMR) and autothermal reforming (ATR) processes of transforming natural gas feedstock into hydrogen also entail greenhouse gas emissions in production and across the supply chain. The UK CCC estimates emissions savings on a whole life basis of 65% to 85% when switching from natural gas to hydrogen from fossil fuel CCS for home heating [11]. Producing fossil fuel-based hydrogen with CCS is estimated to produce 50 gCO₂/kWh to 188 gCO₂/kWh (process and supply emissions) [11]. Similarly, a report by Navigant reports a range of 51 gCO₂/kWh to 63 gCO₂/kWh for producing CCS derived hydrogen [43]. As such whether fossil fuel-based hydrogen is sufficiently low carbon – from UK Net Zero and relative to global remaining carbon budgets – to have a major role in energy provision is an important consideration.

With these considerations in mind, the IEAGHG note that scenarios for a constrained global carbon budget, especially for 1.5°C and high probability well below 2 °C cumulative budgets, have limited fossil fuel CCS energy production [42]. The UK CCC similarly concludes that hydrogen utilisation should be prioritised for niche functions and where derived from fossil fuel conversion would not have a widespread role in low carbon scenarios [11].

These emissions considerations assume a 90% to 95% CO₂ capture rate, which as discussed below, could in principle be increased (however with increased upstream emissions through increased fuel use). There may also be wider environmental impacts (as is the case with any scale-up of a technology) not captured in a global warming potential (CO₂e) focused assessment. However, the lack of sufficient data on natural gas CCS power station capture rates, CCS hydrogen production operations, or any CCS energy application with >90% capture rate, means that it is prudent to await these results before applying high capture rates to these emissions factors.

Potential higher capture rates (99%)

In power generation plants with CCS, the CO₂ capture rate has been historically fixed at 85% - 90% due to associated captures costs of flue gas streams with low CO₂ concentration (below mol-20%). The two large-scale power plants with CCS retrofit used this capture rate as target (*Boundary Dam* and *Petra Nova*) and IAMs used a 90% capture rate in their assessments, assuming 10% of residual emissions.

Recent studies by the IEAGHG [10] looking at the feasibility of reaching near zero emissions in fossil-CCS concluded that in theory there are no technical barriers to

⁹ The data presented in table 9 of IEAGHG (2019) 'Towards zero emissions CCS in power plants using higher capture rates or biomass' provides this breakdown based on the best performing emissions data for natural gas fired turbines.

increasing the capture rate across the three main capture technologies. However, trade-offs should be considered as costs (total plant cost and levelised costs of electricity) are expected to increase, in some cases modestly, depending on the capture technology. Additionally, the plant's performance is expected to decline (i.e. higher energy penalties) and the indirect emissions from fossil fuel use increase. Alternatives to increasing the CO₂ capture rate above 90% and the implications of higher capture rates on costs and plant's performance are presented in more detail below for each of the three main carbon capture technologies. While optimisation for CO₂ capture at a CCS facility presents opportunities to mitigate direct emissions, it also has implications for indirect emissions and validation against actual performance is still required [10].

For **post-combustion capture**, pathways for reaching higher CO₂ capture rates are through increasing the effectiveness of the CO₂ separation process or co-firing with biomass, which could result in relatively lower costs depending on the biomass type. The increase in costs will also depend on the type of power plant. In ultra-supercritical coal (USC) power-CCS plant with 99.7% CO₂ capture, the levelised cost of electricity (LCOE) can increase by 8% and the CO₂ avoided cost (CAC) by 6%. Further, co-firing with 10% of biomass in the same plant could increase, instead, the LCOE by just 2% and the CAC by 1.4%. In a CCGT-CCS plant, a 99% of CO₂ capture increases the LCOE by 6.6% and CAC by 7.8% [10]. Concerning the net plant efficiency, a 99% capture rate decreases the net plant efficiency by 5% in a USC power plant configuration and by 4.5% in a CCGT plant. The cofiring of biomass (10%) would avoid a further reduction in the plant's efficiency for a USC coal-CCS plant and a neutral CO₂ emission intensity with a 90% capture rate.

Pathways to increase the CO₂ capture rate in **oxy-combustion capture process** are achieved via a reduction in the inert gases of the CO₂ stream by using oxygen with higher purity and/or reducing the air leakage to the boiler [10]. CO₂ can also be recovered by passing the vent gases from CO₂ purification to a membrane separation unit [44]. From a performance and costs perspective, increasing the capture rate from 90% to 98% could reduce the plant's net electrical efficiency by -1% and increase the total plant costs (TPC) by 2% and the LCOE by 3%, while reducing the cost of CO₂ avoidance by -4%.

For **pre-combustion capture**, increasing the capture rate to 98.6% in a coal-based Integrated Gasification Combined Cycle power plant leads to a 2% reduction in the plant's electrical efficiency, and higher total plant costs by 4% and LCOE by 4.2%. These figures almost doubled the efficiency penalty and costs increase, compared to oxy-combustion capture, however, the CO₂ avoidance costs also decrease by around 3.6% [44]. Reducing the CO₂-slip emissions in the flue gas could be attained by improving the carbon conversion (water-gas shift reaction conditions) and the CO₂ separation process. As in other processes that increase the gross fuel input into the power plant to account for energy penalties of the capture stage, doing so has

consequences for environmental and human health impacts through the coal supply chain.

Table 2 collates performance data reported by the IEAGHG [10, 44] on the implication of higher CO₂ capture rates and/or biomass cofiring to reach near 100% CO₂ direct emissions reduction in comparison to standard CCS integration with 90% capture rate:

Table 2. Implications of higher CO₂ capture rates on plant net efficiency, LCOE and CAC

Capture technology	Characteristics	Change in plant efficiency	Change in TPC	Change in LCOE	Change in CAC
Post-combustion capture [10]	USC-power plant (99% capture rate)	↓ 5%	↑ 6.6%	↑ 8%	↑ 6%
	10% biomass cofiring (90% capture rate)	0%	↑ 1.9%	↑ 2%	↑ 1.4%
	NGCC power plant (99% capture rate)	↓ 4.5%	↑ 6.5%	↑ 6.6%	↑ 8%
Oxy-combustion capture [44]	SC-power plant (98% capture rate)	↓ 1.1%	↑ 2.2%	↑ 3%	↓ 4%
Pre-combustion capture [44]	Coal-IGCC plant (98.6% capture rate)	↓ 2.4%	↑ 4.1%	↑ 4.2%	↓ 3.6%

Overall, increasing the capture rate in oxy-fuel combustion and pre-combustion CCS would marginally increase costs and reduce the plant's efficiency, also the CO₂ abatement costs could decrease for both capture technologies. More detrimental results are observed for post-combustion capture plants using coal or natural gas and better results for biomass cofiring keeping the same 90% capture rate. Numbers are more favourable for oxy-combustion capture because of a relatively simpler and low-cost CO₂ separation process. IEAGHG [10] also highlight that these findings need validation through demonstration in real-life operation across the different CO₂ capture routes and, that indirect emissions from the coal and/or natural gas power-CCS plant supply chains should be minimised in parallel to direct emissions in order to decrease total lifecycle emissions.

Global CO₂ storage capacity

CO₂ storage starts with the injection of the captured CO₂ into deep underground geological reservoirs, such as deep saline formations and depleted oil and gas reservoirs, for permanent storage. The porous rock layer is overlaid by an impermeable layer of rocks that seals the reservoir and prevents the upward migration of CO₂ and escape into the atmosphere.

The estimations of global CO₂ storage capacity vary hugely and have many uncertainties. These estimates indicate that capacity is potentially sufficiently large to meet the global demand for CO₂ storage [4, 5] [45]. Global estimates of storage capacity sit between 8,000 Gt and 55,000 Gt CO₂ [4] whereas 600-2,000 Gt of cumulative CO₂ are expected to be stored by 2100 to keep CO₂ concentrations

between 400-500 ppm [4] for global climate targets. A larger storage potential capacity exists for onshore reservoirs (6,000 Gt to 42,000 Gt) compared to offshore (2,000 Gt to 13,000 Gt) and the regions with largest capacities are in Eurasia, North America and Africa [4]. For context, annual global emissions of CO₂ for energy were at around 35 GtCO₂ in 2019 [46].

Emissions pathways consistent with 1.5 °C (with no or limited overshoot) indicate that CCS could produce up to 1,200 GtCO₂ for storage. On the other hand, IPCC 2005 estimates a technical potential of at least about 2,000 GtCO₂ of storage capacity in geological formations [47]. In general, the storage capacity of all these global estimates is larger than the cumulative CO₂ stored via CCS in 1.5°C pathways over this century.

This storage capacity varies within regions, with USA, China and West Europe accounting for almost half of the global CO₂ storage capacity under 1.5°C and 2°C scenarios. For the top five regions that include USA, China, Western Europe, India and Russia, the storage demand fits within the regional storage capacity except for Russia, where the CO₂ storage required for this region exceeds the estimated capacity for a 2°C scenario with 66% probability [45].

Overall, there is broad agreement on the match, at a global level, between the demand of CO₂ storage and the technical potential capacity of CO₂ storage in geological formations, at least for CO₂ storage operation until the year 2050 (IPCC [14] and GCCSI [6]). Under the IEA Sustainable Development Scenario, the demand of CO₂ storage required (220 Gt CO₂) between 2020-2070 could be met by the lower end of the estimated CO₂ storage capacity (8,000 Gt).

To attain a large annual CO₂ storage rate, the IEAGHG estimates that approximately 30-60 storage sites need to be characterised and deployed annually until 2050, with these numbers expected by the GCCSI to double when including negative emissions storage [27].

For certain regions, such as, in China, Japan and South Korea, the source-sink matching is more uncertain and could be potentially limited, compared to other regions where regional storage supply is more developed, i.e. North America, Europe and Brazil [5]. Furthermore, by 2100, there is more uncertainty on the real CO₂ storage capacity for different regions.

Detailed assessment and careful selection of the storage sites is considered essential to guarantee the safety and permanency of the CO₂ stored and to reduce risks of potential CO₂ leakage to the atmosphere or groundwater [4].

The costs associated with CO₂ storage are lower compared to the capture process, however, is considered an essential factor to CCS deployment in the coming decades [4]. CO₂ storage costs range between negative costs (approximately -30 USD/t CO₂) for EOR applications, to costs ranging between 10 USD/t CO₂ with 60% of the onshore storage capacity, to even higher costs for offshore storage, 60% of offshore capacity

is available at costs below 60 USD/t CO₂. The cheapest options among the different reservoirs are the depleted oil and gas sites [4].

The development of CCS industrial clusters that pools the transport and storage demands to share the infrastructure is expected to contribute to reducing transport and storage costs [4].

Risks over CO₂ leakage and long-term geological stability

The leakage of CO₂ refers to the unintended escape of the fluid from the storage site.

One of the barriers identified to large-scale CCS deployment has been the risk associated with the safety of the CCS infrastructure, particularly during CO₂ transportation and storage [5, 48]. For instance, CO₂ leakage and over-pressurisation are common concerns underscored in public acceptance analysis [49].

Practical experience gained through the operation of many industrial-scale CCS projects in the oil and gas industry; in addition to pilot-scale research projects have provided further knowledge on the physical and chemical phenomena affecting the stability of a storage site. Advanced monitoring tools and modelling capability is also available to assess with more precision the behaviour of the CO₂ plume in the storage site [28]. These advances have provided a better understanding and common agreement on the safety of long-term storage and the low probability of CO₂ leakage if the storage sites are characterised, monitored and managed in an adequate manner [48].

On the other hand, the stability of a geological storage site can be managed through its local pressurisation, limiting the CO₂ injection into the well to prevent wellbore fracturing. Additionally, to oversee regional pressurisation of the storage sites, management strategies for pressure and waste brine disposal should be considered [5]. The absence of these strategies to control the reservoir pressurisation imposes limits to the CO₂ storage capacity, as pressures in the reservoirs need to be maintained under certain values to avoid induce fractures or reactivate faults in the sealing caprock [5].

With regard to storage integrity, the IPCC SRCCS considered that “for well-selected, designed geological storage sites the vast majority of the injected CO₂ will gradually be immobilised by various trapping mechanisms and in that case be retained for millions of years. Because of the trapping mechanisms identified storage would become more successful over longer time frames” [47]. This body of research concluded that CO₂ storage is by and large a safe operation if storage sites are properly selected, characterised and managed, thus reinforcing the message in the IPCC SRCCS [47, 48].

Regulatory frameworks to monitor and oversee the safety of CCS infrastructure

A robust legal and regulatory framework is important to ensure appropriate site selection and safe operation of geological CO₂ storage sites. This already exists in

many countries, with the UK having launched a licencing process.¹⁰ Project developers and public authorities have to address public concerns through effective stakeholder engagement [4].

To address and minimise the risks associated to CO₂ leakage during long-term storage, as well as the geological stability of the storage site, it is important that liabilities are allocated and managed among the stakeholders of the CCS supply chain.

Risks should be distinguished depending on their potential impacts, whether it is a local environmental and safety issue or a global “climate-related leakage risks [28]. Policymakers and project developers have agreed that practical, well-defined legislation and a strong global regulatory framework are necessary for CCS to reach its potential.

Programmes of Monitoring, Measurement, and Verification (MMV) are considered essential to ensure that CO₂ storage meets operational, regulatory and community expectations, using the experience of the oil, gas, and groundwater industries [5, 27].

Cost and Complexity

The financing of CCS projects has been an ongoing issue causing delays to project development. Most carbon capture projects developed to date have revenue from the utilisation of CO₂ in EOR, particularly in North America. For example, the Petra Nova CCS project's reliance on revenue from EOR is highlighted by its recent mothballing since the fall in oil prices in 2020 [38]. The development of Sleipner CCS projects in 1996 and Boundary Dam to CCS in 2014 can be attributed to tax and regulatory regimes in Norway and Canada [37] respectively that made CCS economically beneficial for the ongoing operation of the facility.

This is in part a reflection of the scale, complexity, and consolidated nature of CCS projects, which face similar challenges to nuclear in terms of deployment. For example, the capture, transport and storage aspects of CCS have been described as quite distinct, but co-reliant businesses which multiply the risks to a potentially unmanageable degree if a single developer responsible for the whole ‘chain’ is not in place to handle this [33, 50]. This has been an observed problem in the UK where the attribution of long term CO₂ storage liabilities to the private sector and ownership of the full-chain of CCS processes are seen as a barrier to development [33]. Research by Wilson et al [51] suggests that these ‘lumpy’ characteristics of technologies such as CCS can in part explain why more modular technologies such as solar photovoltaics, wind energy and battery storage have deployed at a faster rate. De-risking CCS sufficiently to facilitate the required capital investment into CCS infrastructure appears to be a core challenge that requires long term state intervention in some form (if EOR is not part of the business model). This seems particularly acute for ‘transport and

¹⁰ See <https://www.ogauthority.co.uk/licensing-consents/carbon-storage/>

storage' (T&S) operators for whom there are high up front capital costs with expected multi-decadal operating lifetimes [50, 52].

In relation to costs, the UK CCC estimated that in 2050 using CCS combined to mid-merit electricity generation would have CO₂ abatement costs ranging between 115-120 £/tCO₂ and generation costs around 108 £/MWh. However, if CCS would have to be part of firm low carbon power in gas-fired power plants abatement, costs would be lower 48 £/tCO₂ and generation costs around 70-80 £/MWh [19]. Although costs are expected to be higher for CCS as a mid-merit generation technology, this is considered to be the preferred alternative so renewables have higher priority over CCS and power-CCS would precede over unabated fossil-based power generation.

Support for new CCS will likely need to subsidise ongoing revenue for CCS enabled products (electricity, hydrogen, or carbon removal) or offer long term avoided costs (e.g. a carbon tax) to make industrial process capture attractive. The current Contracts for Difference (CfD) mechanism (essentially a guaranteed minimum price for electricity sold over a period of time), capacity and/or flexibility payments for electricity grid services (e.g. frequency response, black start, and inertia). CCS power generation in the UK is now not expected until 2030 and the form and scale of public subsidy is not clear. In the meantime, costs associated with technologies such as offshore wind have seen their levels of required support (as viewed through UK CfD payments) fall from over £100/MWh to less than £40/MWh. While capacity factors for offshore wind have improved, they do not provide dispatchable power equivalent to existing power stations. Capacity or other grid service payments may be needed to compete with low marginal costs per unit of electricity from renewables while valuing potential dispatch, inertia, and flexibility benefits of CCS power stations relative to renewables. Here too CCS may face increasing competition from energy storage and demand response offerings over the coming decade. The European Zero Emissions Platform review for the industry identified a likely need for state support for transportation and storage aspects of the CCS industry akin to electricity and water network investments [52]. This is a key issue as new CCS projects in the UK for long term geological storage are unlikely to progress until the policy and investment for T&S are agreed. A delay in agreeing to this will postpone the deployment of CCS further.

5. Summary

Highly constrained global carbon budgets for meeting the goals of the Paris Agreement require significant progress in energy sector decarbonisation by 2030, particularly in developed economies [8]. This is increasingly being reflected in national policies to increase the rate of decarbonisation in relation to 2030 as well as setting longer term targets. While the longer-term application of CCS in industrial processes and for carbon dioxide removal retains a significant role in climate scenarios, this is not necessarily the case for fossil fuel-based CCS in the energy sector (see Section 2). CCS deployment in the energy system for power, heat and transport decarbonisation has to-date been largely non-existent, with significant deployment now not expected

until 2030. As such the role of natural gas- and coal-based CCS for power generation has been downgraded in future energy pathway scenarios. In contexts such as Europe, with supra-national and national targets to cut emissions by over 50% against 1990 levels by 2030 – through which the energy sector would change significantly - CCS deployment is likely now too slow (see Section 3). Focus recently has in part shifted to the role of CCS with fossil fuel-based hydrogen as an alternative vector. There are at present disparities in the extent to which CCS is featured in future hydrogen pathways, relative to electrolysis based hydrogen and electricification alternatives. The European Commission [17] assume limited if any role for CCS in hydrogen provision, while in the UK its application varies across scenarios considerably [19, 26]. This reflects concern about residual emissions from capture and fuel supply stages of the CCS hydrogen life cycle in the context of constrained carbon budgets, and that commercial applications of this technology are still forthcoming (see Section 4). The technical feasibility of higher CO₂ capture rates (>95%) and application of capture throughout the fuel supply chain may address these issues, but until this can be demonstrated and costs are clarified it is prudent to have energy pathways without fossil fuel CCS in policy scenarios for meeting climate change goals.

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