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Citation for published version:

Haszeldine, RS 2016, 'Can CCS and NET enable the continued use of fossil carbon fuels after CoP21?' Oxford Review of Economic Policy, vol 32, no. 2, pp. 304-322. DOI: 10.1093/oxrep/grw013

Digital Object Identifier (DOI):

[10.1093/oxrep/grw013](https://doi.org/10.1093/oxrep/grw013)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Oxford Review of Economic Policy

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Can CCS and NET enable the continued use of fossil carbon fuels after CoP21?

Stuart Haszeldine*

Abstract: Carbon capture and storage (CCS) does not generate energy. CCS applied to fossil and modern bio-carbon fuels and feedstocks removes environmentally damaging CO₂ emissions. CoP21 stipulated a maximum 2°C–1.5°C global warming from 2050 in perpetuity. Both CCS and negative emission technology (NET) are now required to manage the carbon stock in earth's atmosphere and oceans. All components of CCS are operationally proven secure at the industrial scale. Fifteen CCS projects operate globally; seven are under construction. CCS systems increase electricity prices, to about £100/MWhr. CCS on industry is cheaper and storage costs minimal (£5–20/tonne). CCS reduces whole economy costs of carbon transition by 2.5 times. Policies of capex subsidy, oversupplied emissions certificates, weak carbon pricing, and weak emissions standards have all failed to develop large cost CCS mega-projects. New carbon certificates could link the extraction of carbon to an obligation to store a percentage of emissions. Certificates connect CCS and NET pathways to secure carbon storage for the public good.

Keywords: technology, infrastructure, public goods, net-zero carbon, climate, atmosphere protection, CoP21, low-carbon, electricity, industry, heat, CO₂ emissions,

JEL classification: O3, O5, Q4, Q3, H4, D5, D4, A1

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Haszeldine is supported by EPSRC, NERC, Scottish Government, Scottish Enterprise, and the University of Edinburgh. Scottish Carbon Capture & Storage (SCCS) staffing and sponsorship is by Scottish Funding Council, and a consortium of power and hydrocarbon companies.

I. Introduction: what is CCS?

The use of energy stored in fossil fuels and carbon feedstock has been the basis of great human wealth since the European industrial revolution, and cannot rapidly be replaced. Combustion or conversion of the energy held stored in fossil and bio-hydrogen and carbon will continue to be a central plank of energy and products provision to 2030 and likely well beyond 2050 (IEA, 2015). Carbon capture and storage (CCS) equipment fitted on to power plant or concentrated industrial point sources offers a technological method by which the energy and commercial value from fossil fuel energy and carbon feedstocks (including limestone and biomass) can continue to be used with greatly

decreased impact from emissions of greenhouse gases (Haszeldine, 2009). CoP21¹ agreed a ‘net-zero’ carbon economy from 2050. CCS has two roles, first to reduce emissions and second to re-capture already emitted carbon dioxide (CO₂). In the first role, CCS is applied as effective engineering on to point sources of concentrated CO₂. Here CCS is not restricted simply to electricity generation, but has impact in reducing emissions across the entire economy to include electricity, heat, industry, manufacturing, and transport. The construction of CCS is very slow (Scott *et al.*, 2013). In its second role, to achieve ‘net-zero’, negative emission technologies (NET) are required in addition to CCS. These technologies are currently much less effective and are consequently more expensive. Thus fossil carbon can be recycled, via re-capture from air, to geological storage or product utilization. That can offset small but very numerous decentralized emissions, such as transport fuel; or partly offset industries which include many dispersed processes, such as refineries, or emissions escaping from CCS plant. NET can use equipment engineered as stand-alone Direct Air Capture; or as an adjunct to biomass industries (biochar, ethanol, ammonia); or CCS on thermal conversion (BECCS).

This paper discusses the styles and options of CCS now and into the immediate future. This is a context in which to explore some of the much greater challenges for carbon budgets after CoP21 and then, lastly, examine several of the economic and policy options which have attempted to develop and deploy CCS. The paper also suggests a new carbon certificate option to include NET.

II. What are CCS capture technologies?

The application of CCS is frequently thought of as being restricted to electricity. However it is clear that, to achieve 90 per cent or greater net-zero decarbonization, CCS could become widespread. This can reduce emissions from electricity generation powered by gas or by coal, from heat, or from industrial emissions and process emissions. These are existing CCS systems, which create improvement by serial build, with cost-reductions by learning and efficiency improvements by innovation. Many NET, which are still at laboratory or first small pilot stage, also require CCS.

There are three leading methods of CO₂ separation from combustion gases at a fossil fuel power station. Boot-Handford *et al.* (2014) provide a thorough review in detail of the diversity of capture methods established and under development. A suite of videos and basic information is available at ZEP (2015a).

¹ The 2015 United Nations Climate Change Conference held in Paris from 30 November to 12 December 2015.

- (i) *Post-combustion capture* from the hot gases after burning the fuel. This is conceptually the simplest, and the longest established, method of CO₂ capture. Chemical solvents (nitroso-amines) selectively adsorb CO₂ from the nitrogen and minor water, sulphur, and oxygen in flue gases. The solvent is heated in a different part of the plant, to drive off pure CO₂ and recycle the solvent. This is already commercially applied to coal and to gas power plant by Cansolv. That has an energy penalty on power plant output of 18–25 per cent. Gradual improvement can be expected, but it is likely that new technologies currently in pilot testing will replace these solvents once commercially guaranteed. That could be within 10 years, and reduce energy and cost penalties to less than 10 per cent.
- (ii) *Oxycombustion* burns the fuel in oxygen, which has previously been separated from air. The products are CO₂ and water, which are easily separated by cooling to condense the water. Oxygen separation from air is a well proven mature process. Oxycombustion can be applied to gas, powdered coal, or biomass, and can be operated more flexibly, for variable power output, than traditional coal. This has never yet been built commercially, but has been the subject of the UK White Rose project and Future Gen in the USA.
- (iii) *Pre-combustion capture*, operates by gasifying a solid feedstock at 800°C (lignite, coal, refinery wastes, or biomass)—known as IGCC (Integrated Gasification Combined Cycle)—or by direct feed of syngas from underground gasification, or direct feed of natural gas. The fuel is chemically transformed to CH₄, H₂, and CO suitable for combustion, or for use as industrial chemical reagents in refineries. A variety of outputs are saleable: CO₂ for enhanced oil recovery (EOR), feedstock H₂, CH₄ for urea or high-value chemicals, and even electricity. These processes are very well established in refining with long-established expertise in USA, China, and South Africa. CO₂ capture integration needs 3–15 times size scale-up. Efficiency losses can be only 10 per cent.

III. Examples of CCS projects

Multiple styles of CCS exist, and brief descriptions are given of successful capture-to-storage operations. It is noticeable that most of these are fitted to low-cost industry capture, and are run by single lead developers—who are often oil companies with extensive expertise in gas handling. CCS costs in these cases are 50–30 per cent the cost of electricity CCS, making such ‘industry’ projects ideal learning vehicles. Low-cost entry points depend on local regional circumstances and can then act as nucleus projects for add-on CCS to rapidly reduce cost/tonne CO₂.

(i) Gas sweetening off(on)shore: Sleipner, In Salah, Snøhvit

These three sites are grouped because they provide the longest track-record of deliberate industrial scale CO₂ injection for the purpose of climate mitigation. The need to ‘sweeten’ methane gas accumulations is common, increasing, and worldwide. These types of projects reduce CO₂ emissions at minimal extra cost, and are templates for what should be a mandated practice. From 1996 to 2010, these sites stored 16 Mt CO₂, and now total about 24 Mt CO₂ stored. These sites are linked by the source of CO₂—being natural associated gas mixed with the extracted hydrocarbon. They are also linked by the simplicity of the projects: in each case the consortium owning and operating the hydrocarbon field has elected to store CO₂ in a site geographically close to the commercial field. That reduces the business complexity of a project, and reduces the infrastructure and monitoring costs. The technological ease and feasible cost of operation of CO₂ injection offshore is shown first by Cavanagh and Ringrose (2014), making a comparison with the established injection of 160 Bcf/yr methane at Åsgard North Sea gasfield, being the equivalent of 8 Mt/yr CO₂. Second, Haszeldine (2015) shows that methane injection offshore in Magnus and Ula occurs at a similar scale and produces additional oil profitably. The required price is \$70/tCO₂ (£47) at \$80 oil, rising to around \$100 (£67) with a lesser oil price.

In 1994 Norway signalled a tax on offshore CO₂ emissions of €50/t CO₂ (£37). This led to an immediate response from Statoil, fitting gas separation scrubbing on to condensate produced from Sleipner West, which contains about 9 per cent natural CO₂. A semi-detached link platform was built adjacent to the main production facility, to house the amine separation unit, and an additional borehole was drilled to inject 99 per cent pure CO₂ into the Utsira sand at 1km depth adjacent to the platform. This has injected about 1 MtCO₂/yr without any abnormal incident since 1996 (Eiken *et al.*, 2011). The CO₂ injection costs are £12/tonne. A similar project exists at In Salah, Algeria, where 3.8 MtCO₂ from associated gas was injected from 2004 to 2011 for \$6/tCO₂ (Ringrose *et al.*, 2013). And offshore at the Snøhvit field in the Barents Sea some 2 Mt CO₂ has been re-injected at less cost than the Norway emissions tax of €50/t CO₂ (£37).

(ii) CCS on coal power post-combustion: Boundary Dam

Boundary Dam is a good example of strong project leadership, integrated management, and globally shared learning. Sask Power is the provincial dominant electricity supplier in Saskatchewan, and owns a 100–300-year supply of lignite adjacent to the power plant. Federal standards on power plant operational emissions performance and cumulative emissions are now in force (IEA-GHG, 2015). That created a strategic decision to invest in CCS and protect the local, reliable, low-cost fossil carbon from becoming a stranded asset. This project is a seminal example of a retrofit on to an existing coal/lignite combustion plant. Boundary Dam boiler unit BD3 of five was re-powered during a 42-month programme (including winter downtime), by renewing the

130MW steam boiler, and at the same time installing amine CCS from Cansolv at a cost of \$Can600m (Bassi *et al.*, 2015). The 1 Mt/yrCO₂ is sold by pipeline to nearby enhanced oil recovery at 30km distance and sulphuric acid and fly ash are also sold. The project over-ran cost from \$Can1.2m to \$Can1.4m and was 3 months late in final delivery. Operation from late 2014 was initially erratic, due to equipment suppliers failing to meet guarantees, but in late 2015 capture was operating as designed, with a very low overall 13 per cent efficiency penalty (IEA-GHG, 2015). The project received \$Can240m of Federal support (about 20 per cent of capital cost), with no subsidy for operational costs. If borrowing rates were 5.9 per cent (internal borrowing), then the electricity price would be €142/MWhr (£104/MWhr) (Boyd, in Bassi *et al.*, 2015). Note that many reports of Boundary Dam costs are inaccurate, because they combine the cost of boiler replacement and CCS fitting, whereas the CCS component was only half the total capex spend. These costs are all substantially less than in the UK, which can be explained by: (i) lower operating costs onshore in Canada; (ii) much more stringent UK safety and operating reliability construction requirements; and (iii) experienced Canadian management creating a cost-control system suitable for an engineering mega-project and to liaise with multiple contractors. A very comprehensive report (IEA-GHG, 2015) details pathways to cost reductions on the next boiler units, BD4 and BD5, to be retrofitted with CCS between 2027 and 2025. Sask Power persistently claims that these costs can be reduced by 30 per cent for a follow-on CCS construction at Boundary Dam—suggesting that a CCS electricity price of €95/MWhr (£70) is feasible in Saskatchewan.

(iii) CCS on gas power post-combustion: Peterhead (Goldeneye)

Gas fuel in 2011 supplied 22 per cent of European electricity, and is forecast to rise in all scenarios. The Peterhead project was planned to be the world's first on a gas-fuelled power plant, and would be particularly important in Europe, to demonstrate CCS on power plant which could flex output around variable renewable energies. One-third of Peterhead with CCS would supply 400MW net power and send 1MtCO₂/yr offshore to storage in the depleted Goldeneye gasfield. Re-use of the legacy 100km offshore pipeline, reconditioning offshore boreholes for CO₂ injection, and re-purposing the existing offshore unstaffed platform should all have resulted in substantial savings of capital costs (but did not). The storage site was exceptionally well known because Shell had operated the gas extraction, and was resilient against leakage with three layers of sealing rock. Using Cansolv amine separation, and multiple integrations in the system design, the efficiency penalty would have been just 11–16 per cent (Assaf *et al.*, 2014). A capital grant of about £400m was available in the UK commercialization competition, believed to cover about 50 per cent of capital, together with operational costs from the 'contract for difference' feed-in-tariff in the UK electricity market covering the full additional costs of capture operations for a 10–15 year project life, at around £320m/yr. The generic learning would be made available globally. The process of competition

application was protracted, from December 2011 to December 2015, with an anticipated 3-year construction. Multiple additional performance safeguards in the engineering specifications were required by government during the contract bidding, and substantial risk on finance, project performance, and liability had to be retained by the developers. Partly because of these over-design features, the cost of CCS electricity became greatly elevated, said to exceed £170/MWhr. Ironically, the high costs, partly required as a result of government specifications and risk aversion, were then used by government to define the project as uncompetitive and expensive, resulting in unilateral cancellation on 25 November 2015, about 4 weeks before final Front End Engineering and Design (FEED) bids were to be submitted.

(iv) Refinery hydrogen: vacuum swing, Port Arthur

A fourth method of carbon capture is often forgotten, but is well suited to separation of process gases in industry. Vacuum swing—changing the adsorption of gas molecules into a physical material by changing the pressure—is operating routinely and unobtrusively in the Valero refinery plant in Texas. Air Products is the world's largest industrial gas separator of hydrogen. This plant uses two vacuum swing adsorption units. The project captures at 97 per cent purity more than 90 per cent of the CO₂ from the product stream of two commercial-scale steam methane reformers that would otherwise be emitted into the atmosphere. The plant is much smaller in size than the Cansolv-style amine equipment, and the power requirement is modest: 28 MWe steam and operational electricity. For this exact type of operation, the upscale potential is 56 Mt CO₂/yr in USA, and it can enable large parts of hydrocarbon or chemical plant emissions to be captured. Operations captured 1Mt/yr by 26 June 2014 (DoE, 2014). The CO₂ is sold and is transported by a 159km pipe to the Hastings field CO₂-EOR, where additional oil of 1.6–3 Mbbl/yr is produced by Denbury. This is a good example of a USA operation where federal and/or state grants or tax breaks are awarded to help neutralize the additional costs of CO₂ capture and storage, by connecting them to the profitable benefits of very large-scale use of CO₂ by EOR.

(v) Iron and steel: retrofitting, or changing the process

Process industries as a group account for about 25 per cent of global CO₂ emissions. Iron and steel refining and manufacture are responsible for about 6 per cent of global CO₂ emissions. To show how established methods are very difficult to retrofit on process industries, whereas new methods are more effective, this section contrasts two methods of making iron and steel.

China produces about half of the newly made iron globally, emitting about 1.5Bnt CO₂ in 2012. An example of an established process, and the difficulty of reducing emissions

is the east China Caofeidian steel plant (GCCSI, 2015a), sited on the coast about 200km south-east of Beijing. This produces about 16 MtCO₂/yr from 8 Mt/yr steel production. Capture of CO₂ from several stages of the process needs installation of amine retrofit equipment at different parts of the plant. Multiple types of capture equipment would be needed, because CO₂ arises at different localities in the process at very different temperatures and concentrations between 15 and 30 vol per cent CO₂. The CCS project needs income, potentially from selling its captured CO₂ for local EOR in the Jidong Oilfield onshore of Bohai Bay. But this CO₂-EOR market needs to be created. The break-even price for purchase of CO₂ for EOR to fund capture at the steel works would be around \$50/tonne. In summary, a retrofit could be achieved, but is complex and costly, requiring synchronous development of, and fitting and operating of, complex processes in the plant, combined with a step change upwards in the user market for CO₂ which would need to be secure for several decades ahead.

Alternatively, the Emirates Steel plant at Abu Dhabi shows how a wish to decarbonize, combined with the ability to invest, can drive a complete switch from an established process. An abundant local supply of natural gas exists, at very low cost, with decades of future availability. That will enable Emirates Steel to refine steel from iron ore at its Mussafah steel works in a way entirely different from traditional blast furnaces. The methane gas is used as a reagent to reduce iron ore, while the methane is oxidized to CO₂. That makes for easy separation, in just one step, of 95 per cent pure CO₂, with minimal energy penalty, by condensing water vapour. The project was first publicized in 2007, and aims to capture 800,000 tCO₂/yr, at a cost of £80m in construction, cited as \$123m costs in 2015. Again in this project, selling CO₂ for EOR is a method of paying for the cost and operations. The CO₂ will be piped about 40km, to a group of established large oilfields, which create multiple decades of demand. The project is scheduled to start up in mid-2016.

(vi) Negative carbon: air capture

Assessments of future global temperature and climate by IPCC (2015) climate models show that most predictions require ‘negative emissions’ to maintain global climate within 2°C warming. After the Paris CoP21, aspirations of a 1.5°C warming limit are expected to make more urgent the requirement for withdrawal of already emitted CO₂ from the atmosphere. Either of these 1.5 or 2°C warming scenarios will require ‘net-zero’ emissions from 2050, so that the carbon stock emitted into atmosphere does not increase. There are three leading methods for negative emissions: (i) engineered recapture from air—which requires CCS if the carbon is stored rather than re-emitted by CCUS (carbon capture, use, and storage); (ii) surface carbon stock increase—afforestation or soil re-carbonization (biochar); and (iii) biomass combustion or gasification with CCS. The methods with permanent geological storage ((i) and (iii)) require less maintenance to guarantee storage integrity (Haszeldine and Scott, 2014; Scott *et al.*, 2015).

Air capture is an emerging technology suite, often linked to climate engineering. There are numerous rival methods, with major claims for their effectiveness, with claimed (but not verified) costs of \$27–136/tCO₂. Capture methods include mineral capture by water of crystallization, adsorption into resins, or hydroxyl cation exchange cycles. All suffer from the need to contact immense quantities of atmospheric air, in order to extract from extremely dilute concentrations. All suffer from the need to find methods to regenerate the capture material with minimal energy input. And none has tackled the problem of how to securely store the captured CO₂. Based on prior research by the US Navy, some projects are attempting to synthesize artificial hydrocarbon fuels. In 2016 ClimeWorks expect to commercially offer CO₂ from air, converted to hydrocarbons by established Fischer Tropsch synthesis, at a cost of €1.50/litre without tax, which is similar to fossil-derived fuel including tax. If further research can develop these processes to reduce costs, then a ‘circular economy’ could re-use the existing carbon stock and displace the continuing extraction of additional fossil carbon from underground. At present, fossil carbon remains at extremely low cost for the energy contained, and air capture still has a long way to go on cost reduction and size scale-up.

Many engineers believe and calculate that air capture is extremely expensive, especially compared to capture from concentrated streams of CO₂ at power plants or in industry (Ranjan and Herzog, 2011; Brandani, 2012). A review of technologies remains sceptical about true system costs, placing them at \$250–\$1,200/tCO₂ captured, for energy alone, with an additional capital cost to build of \$600/tCO₂ (Ranjan and Herzog, 2011). There is much scope for innovation and research to improve the technology of air capture and very greatly reduce costs. After that, work will be needed to understand how the captured CO₂ can be stored. And if that is by geological-style CCS, then there also needs to be factored in the energy and money costs of pressurization for transport of CO₂, pipeline costs, and demonstrating a secure injection site where CO₂ can be monitored.

(vii) Biomass CCS methods, Decatur Illinois

Biomass has been included in recent IPCC models, as a means of burning fuel and generating heat without releasing fossil carbon. The implicit concept is that an important new set of activities will develop. Energy crops will be grown, harvested, and transported to power plant sites where the biomass will be thermally converted to energy by combustion. However biomass with no CCS applied is considered to be carbon-positive, i.e. emitting more CO₂ in the decades-long life-cycle needed to replace biomass carbon which has been rapidly burned without consideration of the time needed for re-growth. (IEA-GHG 2014, Figure 4; Smith *et al.*, 2016). It appears that biomass use without CCS is counter-productive in emissions.

Big issues for biomass are: the competition for land use with ecosystems and with food; water supply, and soil nutrient depletion; authentication of provenance; the technology and cost of CO₂ capture. The harvesting, transport, energy conversion, and capture methods vary greatly, as biomass feedstocks are extremely complex. For post-combustion capture the costs are stated to be similar to those from fossil fuel combustion, but this has not yet been applied at large scale. By contrast, gasification of biomass produces a much cleaner flue gas, which makes separation reliable at lower cost. However, these technologies are not yet reliably scaled up to the demands placed upon their commercial reliability and cost in an electricity supply market.

Much easier, and lower cost, capture from biomass can occur when conversion is not combustion, but fermentation for ethanol production, or anaerobic digestion of non-wood biomass. The ethanol plant operated by Archer Daniels at Decatur, Illinois is a good example of successful industry CCS from bio-ethanol manufacture. The Illinois Basin—Decatur Project is supported by the US Department of Energy (DoE), and during 3 years has captured and injected 1 MtCO₂ on-site for storage into a deep saline sandstone (NETL, 2012). A follow-on project, Illinois ICCS, will cost \$207m, about half supported by DoE, and will scale up to double daily injection rates of 0.9 MtCO₂/yr (Gollakota and McDonald, 2014).

IV. What net-zero carbon means

This section explains that the required actions from policy on decarbonization are becoming much more onerous through time. In 1979 the first conference on world climate took place, with a goal to limit the rate of CO₂ release into the atmosphere. But it was not until 2015 at CoP21 in Paris that a joint global agreement of 195 countries made a commitment to keep global warming ‘well below’ 2°C forever into the future, and to pursue attempts to limit temperature increase to 1.5°C. The agreement is voluntary, but nations are asked to report their progress each 5 years, to assess changes or progress. The actions have no established means of delivery. The commitment on temperature means that the rate of CO₂ emissions is not important. A ‘net-zero’ balance of emitted CO₂ and stored CO₂ is required. Either hydrocarbon extraction must stop, or CCS and NET are required for a cost-effective steady-state global climate.

This means that a very important difference in 2015 is that the science focus of the CoP21 agreement has changed from reducing the rate of CO₂ release, to a finite limit on the total stock of carbon held in the atmosphere. That is because it is now clear that the rate of release of ‘carbon’ as CO₂ into the atmosphere is extremely rapid on a climate timescale, whereas the natural processes of removal of ‘carbon’ are relatively slow—including for example rock and soil weathering, dissolution into ocean surface waters,

and incorporation into biomass. This total carbon stock includes all of fossil fuel carbon, land-use, and soil carbon, and also includes deforestation carbon.

This concept can be described as ‘net-zero’, where one tonne of carbon released is balanced by one tonne of carbon from the atmosphere sequestered, re-captured, or stored (Allen *et al.*, 2009). Thus the goal in 2050 is no longer to reach a reduced rate of CO₂ emissions from fossil fuel use (Figure 1), but to balance emissions from fossil fuel, carbon feedstock, and biomass utilization, by CO₂ capture and geological storage; re-capture and utilization or storage; or storage into soil, weathered minerals, or ocean. This balance has to be continued into the indefinite future.

Utilization of CO₂ is being, and will be, claimed as a commercially viable alternative to expensive storage. However these are economic constructs to create saleable products from a capture plant, these are not viable sequestration mechanisms for the required environmental timescales (Scott *et al.*, 2015). A very few utilization methods may be able to store CO₂, e.g. EOR, biochar and soil carbon, mineral weathering, or magnesia cement. Many other methods (forestry, horticulture, plastics, fertilizer) need to be excluded from financial or policy rewards for sequestration, unless carbon storage can be clearly guaranteed for centuries.

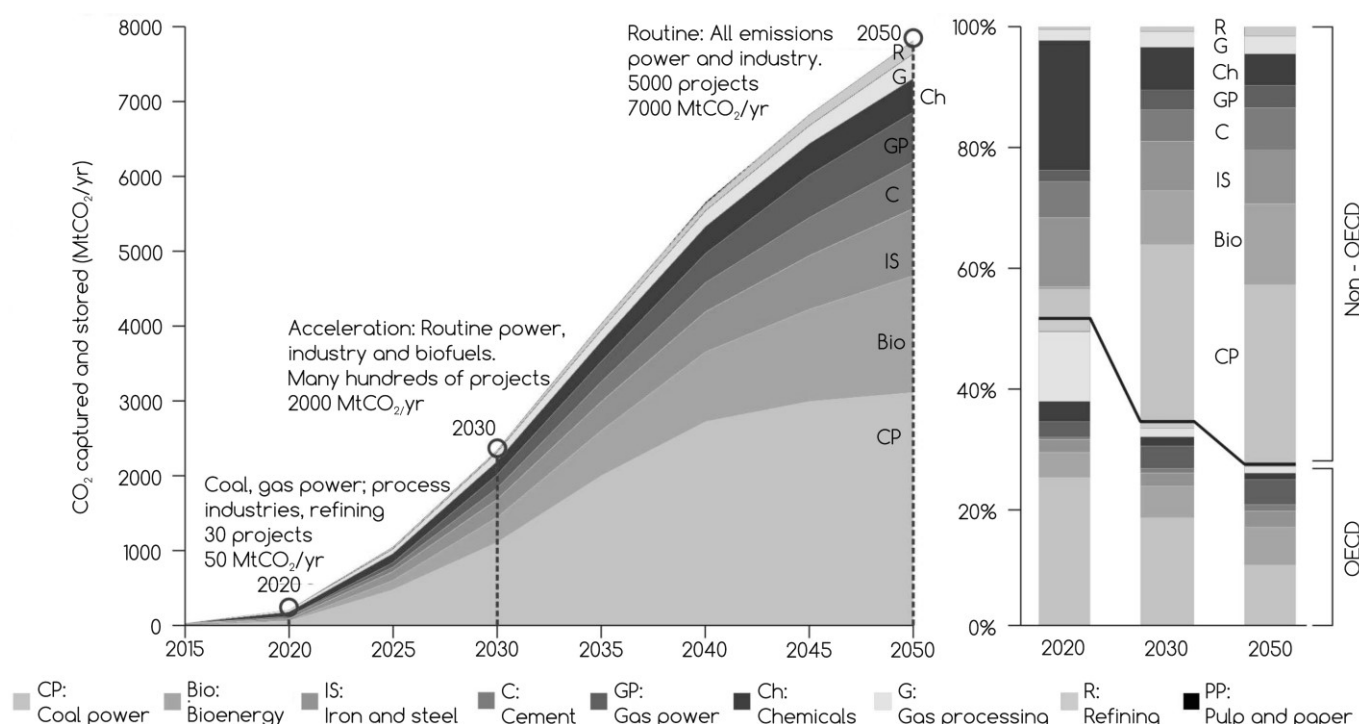
The bad news is that an immediate and continuing challenge for political science, policy analysis, and practical economics, is how to develop, scale up, deploy, and mandate innovative actions such that technologies, taxes, and transactions become embedded as net-zero carbon, without damage to established economies. The good news is that multiple high-level analyses since 1979 claim that the cost of this carbon transition is just 2 per cent of global GDP. Or to make a European analogy, the UK national electricity system can be decarbonized for an increased bill per household of less than one-fifth of a middle-class household spend on Christmas.

For CO₂ storage to be effective in a net-zero balance, the timescales of storage need to be very long in human time (many hundreds to tens of thousands of years) and security of storage needs to be highly predictable (e.g. less than 1 per cent return to atmosphere in 1,000 years). These CCS and NET stores, security, and economic hierarchy effects are semi-quantified by Haszeldine and Scott (2014) and Scott *et al.*, (2015), and many of the NET limits to land-use, biophysical impacts, and high-level economics are modelled by Smith *et al.* (2016). The capacity limits to storage, and the biophysical limits to resources mean that neither CCS nor NET are open-ended actions. The amount of commercial fossil carbon reserves to 2050 may be possible to balance by CCS, NET, and storage, but that leaves a zero carbon budget thereafter. Consequently, a smart transition will immediately and in parallel decrease the rate of utilization of fossil and biomass carbon emissions, while investigating the anticipated storage availability to balance emissions for decades to hundreds of years ahead. Either extraction of fossil fuels plummets, or carbon capture and re-capture technologies are used. This could be

Journal: Oxford Review of Economic Policy 2016
Title: Can CCS and NET enable the continued use of fossil carbon fuels after CoP21?
Cite as DOI 10.1093/oxrep/grw013

the start of the end for the extractive fossil fuel energy era. But lobbying by established business interests is likely, from all historical precedents, to delay the transition.

Figure 1: Goals for the capture and storage of CO₂ by industry, 2015–50



Source: Re-drafted from IEA (2013).

Figure 1, redrawn from the IEA CCS Roadmap (IEA, 2013), shows an increased rate per year of CO₂ capture and the split between energy and industry technologies. According to the IEA, CCS by 2050 is expected to contribute about 13–20 per cent of CO₂ reduction actions globally, along with fuel use efficiency, switching from coal to gas, renewable electricity generation, and nuclear power. The 2050 capture and storage rate is projected to be about 7,500 Mt CO₂/yr; in 2015 it is 40Mt CO₂/yr (GCCSI, 2015b).

V. Policy to deploy CCS—some success, mostly failure

Fossil fuels are the best source of stored energy available to humans and so have been, and are, exploited as the basis of most energy needs. CCS, by contrast, is not a technology group which supplies energy—it consumes energy and costs more. The purpose of CCS is as a route which could enable fossil fuels to continue being used, but without the disbenefits of emissions. What then can drive the installation of CCS? Examining past and current policy actions on CCS from the USA, EU, and UK shows that none has been effective, and new radical policy innovation is suggested. The challenge then, is to design government actions, such as markets, taxes, and financial

incentives, which both create innovation in CCS and NET technology, and simultaneously act to incentivize construction of projects at large commercial sizes, while also keeping energy prices low for citizens and (allegedly) avoiding technology choices by government. These are incompatible aims, and require compromises for 'second best' solutions, and/or acceptance of multiple market failures. These are not new effects, Grubb and Ulph (2002) discussed very similar issues in the interaction of technology, energy, and environment. Their central conclusions are still important to the present situation with CCS: environmental policy alone does not necessarily lead to major relevant innovation, technology policy is also needed; commitment by both government and business is essential; innovation of large changes takes a long time and requires learning-by-doing to inform businesses.

(i) Europe: emission certificates and trading

Famously in 2005, Europe created Emission Allowances, as certificates within a cap-and-trade system covering 45 per cent of EU emissions. These are permissions to pollute, given tonne by tonne of CO₂ discharged. Initial allocations of emission certificates were distributed across European states; these allocations systematically become smaller over the years, and 40 per cent are now auctioned. Consequently a market is created where emitters of CO₂ become short of certificates and progressively need to purchase permits, at an ever-increasing price. A crossover will occur when the price of purchase is greater than the cost of equipping with capture, transport, and storage of CO₂.

This is a purist economic solution. It is technologically neutral, and will discover a least-cost route from the options available. The EU emissions trading system (EU-ETS) is regarded as a success, with 2020 emissions being 21 per cent less than 2005, and 2030 emissions expected to be 43 per cent less. The problem is that introducing a new technology like CCS needs all of deployment, plus development, plus innovation. The pure EU-ETS instrument is too general across the economy, and is insufficiently priced to produce and sustain development and innovation in large-scale technologies which will take decades to develop. Consequently deployment has not occurred, because construction of the first CCS projects is both big and expensive, requiring a high price per tonne of carbon. One concentrated big project cannot be funded from the dispersed receipts of economy-wide emissions permits—these receipts need to be aggregated together. CCS projects take 5–10 years to plan and permit, hence these also require prolonged support through multiple government cycles. This means that CCS is more difficult than established decarbonization options which can be built at smaller size (cheaper per project) and operate immediately.

Both photovoltaic (PV) solar and NO_x scrubbing required 20–50 years to reach acceptable market prices. To incentivize CCS as a new technology which is only slowly

emerging and developing, actions specific to that technology are needed. If the EU-ETS market functions correctly, then CCS will not be built before a critical emissions price is reached, with foresight of highly probable sustained prices into the future. That does not provide adequate signals to drive private-sector investment into a new industry and drive cost reduction by serial construction for 10 or 20 years. Consequently there have been appropriate levels of European tea and biscuits, coffee and croissants, but zero effective steel and concrete.

In 2009 it was recognized that the EU-ETS alone would not work. It would be necessary to invest in development, deployment, and innovation of CCS technologies outside the power and industrial products markets, while enabling the lower-carbon CCS power and products to be sold into the market. A second attempt at this was to allocate European Energy Programme for Recovery (EPR) funds—economic restructuring grants—as capital to pay for construction costs of electricity plant. Six CCS projects were part-funded around Europe; however, these required additional funds from the power companies and from member states. The power companies found that receiving *farming* renewable energy incentives was more lucrative, and the member states simply found cheaper priorities. Even if capex had been pulled together, the opex costs of a CCS operation to bridge the price gap between established dirty products, and new cleaner products requires £400–600m per year for a 400MW power plant. Only the UK (see below) has adequately considered payments for running costs to CCS. A third European attempt was made using the New Entrants Reserve (NER 300), i.e. the dormant allowances of the EU-ETS. This plan gathered together unallocated European emissions allowances to enable a donation of a fixed quantity of dormant allowances to CCS power projects. Since those allowances would not be needed (as CCS does not emit CO₂) they would be sold by the CCS project to provide capital and operational funds. Even with this subsidy, additional funding guarantees were required from member states (ensuring cooperation). But the market price of European Allowances collapsed because the number of European Allowances released into the EU-ETS was over-supplied during the economic recession. So rather than an NER 300 award being €1 billion with highly priced European Allowances, it became €200m, as a consequence of lower priced European Allowances. As a final coup, the renewables industries successfully lobbied to gain access to the NER 300 fund; and managed to gain co-funding to win 80 per cent of the finance. No CCS projects were built.

In a fourth attempt, the business-led ZEP (2015b) has created an ‘Executable Plan’, which aims to help CCS emerge with ‘strong political direction, the right funding mechanisms and a robust investment environment’. This points out that the benefits to Europe of including CCS are estimated at €2–4 trillion up to 2050 for the energy sector alone, and that the core industries of cement, steel, and, especially, chemicals require CCS to escape punitive costs under EU-ETS. The plan decouples capture from transport and storage, so that a market-maker can purchase CO₂ from power and industry owners, and resell to regional transport and storage operators. This removes the risk of a capture

operator being liable for storage. The anchor projects to establish regional hubs will be funded through the EU Innovation Fund (similar to, but with 25 per cent more allowances than, the NER 300), which will pay capex and opex.

At best, these actions could create two or three CCS projects across Europe by 2020. There is no ring-fenced programme to develop and pull through reduced cost capture or CCS technology—CCS must continually compete for funds with rival low-carbon energy technologies. Recent history shows that renewables in Europe are altogether more ‘popular’ than CCS, so winning each and every funding contest is unlikely to succeed. That contrasts with the much more structured and systematic internationalization of Airbus, for example, where EU governments provide 33 per cent of funds through low-interest 17-year loans. And contrasts again with the USA DoE, where a three-phase plan of 10–20 years is supported by billions of dollars of government funding to ensure that multiple CCS technologies are invented, pulled through, trialled, and commercialized. European development of CCS is very unlikely to succeed by these methods.

(ii) USA: legally enforced emissions performance, plus technology development

The USA has chosen an entirely different method on its pathway towards decarbonization. In contrast to Europe, the USA is hampered by a deep and perennial schism in its political leadership. The concept of global change, warming, and sea-level rise driven by human activity has been continually and deeply resisted by many Republican politicians. In the USA system this has often meant that the President and elected members have had opposed agendas, with no agreement to act. Faced with that in the past on power plant sulphur emissions, or on motor fleet emissions, the USA has taken a legal route by creating and enforcing product standards. Both of those environmental clean-ups have been successful, although requiring tens of years for the changes to penetrate the industrial fleet. From 1970 to 2014, emissions of six air pollutants have dropped by 69 per cent, against a tripling of GDP and doubling of energy use.

For CO₂ emissions, the US President is taking executive action, using a legal route through the Clean Air Act. This ‘Clean Power Plan’ enables the USA to protect its citizens against excess CO₂ in the atmosphere. CO₂ in excess is labelled a pollutant, unlike the European position. This is producing a contest between legislators and incumbent industrialists. There is an attempt to mandate carbon capture and storage on power plants legalistically, in forms which will resist recidivist push-back. The instrument invoked to do that is an Emissions Performance Standard (EPS) on power plant which has to be met from summer 2020, but the means is not specified. The EPS is complex in its detail, administered by the Environment Protection Agency, with targets negotiated state by state. The EPS is imposed on new coal power plant, and if successful will be extended to new gas power plant. When the method is adequately established on

new power plant, the Clean Air Act enables EPS standards to be applied to existing coal or gas power plant, thus enforcing retrofits. This aims to reduce emissions from power plant by 32 per cent below 2005 levels, by 2030.

To ensure that CCS technology is available in the USA, in contrast to Europe, the US DoE has allocated multiple billions of dollars (currently about \$500m/yr) since starting with \$10m in 2000, to support a coherent suite of work to support CCS on power plant and on industry until at least 2025. This is a multi-year programme of research, development, and deployment, which develops co-funding between industry, university, and government. It plans systematically to innovate, develop, and establish the technology of carbon capture at reduced costs, and also to create working examples of full-chain developments, from capture through transport to subsurface storage. Judged by numbers of research propositions, by publications, and by current and imminent operational commercial-size projects which have stored 11 Mt CO₂, this DoE strategy is creating wide and deep capacity for innovation and development across the USA. To pull those innovations into commercial developments, now requires a pathway and pipeline of commercially developed projects. That will be created by the commercial desirability of building new power plant which can meet EPS regulations. A failsafe measure of enacting this strategy now is taking advantage of the unanticipated access to lower carbon shale gas fuels which have become available in the USA since 2000. Emissions reductions are already being achieved, initially by commercially driven fuel switching from coal to cheaper gas. However at least five commercial CCS projects are expected to operate by 2020, meaning that USA innovation support and deployment is successfully on track.

(iii) UK: competition, markets, and carbon pricing

The UK recognized in the 1990s that climate change is a long, slow challenge which threatens global disruption, and so requires a serious long-term response. The Climate Act 2008 has been passed, binding the Secretary of State for Energy and Climate Change to decarbonize 80 per cent from 1990 emissions across the whole economy, by 2050. That number was based on a report published by the Royal Commission on Environmental Pollution (2000), which derived a connection between 550 ppm CO₂ emissions and 2°C warming from the IPCC's second report.

The UK also wishes to decarbonize at a low and effective cost and will start with electricity. This will be achieved by creating a market setting where government can encourage multiple styles of decarbonization, which mutually compete to produce lower-carbon electricity at a low price. CCS has eventually to bid into that market of nuclear, gas, and renewable power suppliers. Industry decarbonization received minimal attention until 2013.

Instead of operating a technology development programme, the UK decided to move directly to full-scale CCS power plant. A CCS competition was created, where developers would work closely with government and submit bids to receive a share of £1 billion capex support, plus a premium electricity price as opex support for 10 or 15 years. This system acts as a type of feed-in tariff, so could support CCS power plant construction and operation. But it requires continual and complex interaction with government. The original justification (2003–10) for such large-scale government investment was that the UK could be a first-mover and gain a pre-eminent position as a vendor of CCS equipment and design services globally, including to China. Since 2005 and up to late 2015, three cycles of CCS bidding have now run. The first CCS project was volunteered to the government by BP—the Peterhead to Miller project, which failed to gain a government decision on funding; the second and third CCS projects offered to government have been under the £1 billion competition rules. About 17 different CCS projects have been proposed, four have undertaken detailed and expensive FEED evaluations of engineering design and costing. All have failed to win government approval. The expressed reasons have revolved around high cost, business complexity, and allocation of risk liability. It is now, perhaps, more clear that although CCS science research and invention is strong in the UK, CCS technology development does not have a large or well-connected support system such as that in the USA, China, or Canada. A commercial pay-off for UK manufacturing and design has become very much less than first proposed. About £500m has been expended, 70 per cent by commercial companies. Ironically, that could have funded the first commercial CCS project.

Although a competition for procurement process may be a solution applicable to an established technology in a functioning electricity market, this does not work for emerging CCS in solving what is a technology innovation, development, and demonstration programme. It is as much a mismatch of skills and pace, as is a Formula 1 racing driver in a 24-wheel truck. The competition process suffers from multiple difficulties. First, the development of early projects is in close cooperation with government, which makes these vulnerable to requests to add additional safety or extra high-quality back-up, i.e. over-engineering. Exactly as with the Longannet CCS project in the UK, if 15 per cent cost is added to each step, then it is inevitable that the total project can cost 80 per cent more than necessary (Haszeldine, 2012, Figure 3). Second, the low-emission gains, which are attractive for a power plant developer, are not matched by the skills, risk, and long-duration liability for a transport and storage operator, or for a government. Third, the protracted process of bidding and engineering design, extending over many years, makes these projects subject to changes in companies, or external events, leading to cancellation. Fourth, close links to government create exposure to short-term and long-term changes in government policy and attitude, leading to changes of confidence and sentiment. Fifth, it is hard to produce economies of learning—through project development pipelines, or serial builds, or to offer developers multiple projects—because projects proceed one at a time. Sixth, UK

government planning by Treasury extends a maximum 5 years ahead, with major and fundamental review points intervening. Each review point is a hazard.

The above comments were written before 25 November 2015, which was the date of the government 5-year spending review. The Treasury abruptly, and without warning, withdrew the election manifesto commitment of just 3 months before for a ‘ring-fenced’ £1 billion capex prize. The two competition bidding groups, White Rose and Peterhead Goldeneye, were left with losses estimated to be £50m each. At the time of writing, the medium-term outcome is unclear. The initial reaction is that ‘political risk’ in the UK outweighs all others, and that lack of trust makes it impossible for major investment in low-carbon energy to engage with the UK, without very explicit and guaranteed contracts in advance. At the root of all this is the UK treatment of CCS as an energy provision technology which can be procured as a single high-cost item, in price competition against multiple lower-cost modules of better-improved low-carbon energy provision. That will always be unwinnable. By contrast, in this article, it is proposed that CCS has a much wider and deeper application to a net-zero carbon economy—deployment could be valued not as energy, but through environment and development sustainability, or citizens’ health, as in the USA.

(iv) A new economic method: zero charge certification of carbon storage, to balance extraction

Two types of major problems underpin all of the above actions and their varying successes and failures. First, radical and deep carbon emissions reduction by 90 per cent requires actions wider than those of the electricity industry alone—the EU-ETS covers only half of carbon emissions, and certificates for industrial processes are often waived. Unless extraction of fossil and bio-carbon is completely halted, then limiting warming to 2°C–1.5°C in perpetuity requires that extraction is balanced by storage across all these sectors (Allen *et al.*, 2009), and extends into NET as well. Second, most nations do not have the finance to subsidize large technology development, and will take on only minimal risk liability. How can investment be driven to develop improved capture and storage, without government expense? Additionally, an investor’s horizon in a large capital cost investment or venture is 20–30 years, whereas the timescale for an elected official or whole government is less than 5 years. And in the UK, ‘no government can bind its successor’ except by law, which is spectacularly unhelpful for investors.

As stated by Grubb and Ulph (2002), it is necessary to join together markets, policies, government, and business for many years to remove and store CO₂ in sufficient quantities to limit environmental damage. CO₂ emissions need to be stopped, or allowed and balanced with certainty by storage, across the whole economy—not just electricity. A mechanism is needed which directly acts to achieve the desired objective, which is to ensure that CO₂ produced becomes CO₂ stored. At some point, all emissions need to be

balanced or overbalanced by storage of carbon. That point is expected to be around 2050. How can carbon storage be enacted by multiple individual nations, in such a rapid timescale, while also engaging business and funders, and remaining resilient against future changes?

There is a disconnect between organizations which produce carbon (coal, oil, gas, biofuel companies), and those who use carbon (industry, business, travel, citizens). The present system tries to penalize carbon users, but releases carbon producers from any responsibility for the clean-up of their product wastes—which are routinely discharged into the common global atmosphere. All citizens suffer a detriment to the public good. This does not happen in other energy or environmental sectors—the polluter pays. Why should carbon energy be different?

The proposal is to link extraction to storage. The skills and the commercial interests of carbon extractors coincide well with those of carbon storage. Under present regimes, attainment of emissions standards or purchase of emissions certificates can be seen as ‘compliance’ issues. The linkage of extraction to storage is intended to imply that storage becomes as much of a central core business interest as carbon extraction is now. To achieve net-zero from 2050, it is necessary to create a link between CCS reducing emission rates, and the future need for NET, to reduce the stock of emitted carbon. Addressing emissions and re-capture through the currency of carbon will enable a pathway to be navigated along a national or global carbon budget to 2050 and beyond; this can be a durable multi-decade system with governments and businesses in partnership. The linkage does not conflict with existing systems of EU-ETS cap-and-trade, or with emissions performance. A no-value certificate focuses on the outcome, not on creating trading between dealers or governments.

The core concept (Figure 2) is the creation of a certificate of carbon extraction which has no monetary face value, but carries an obligation to store part or all of the carbon extracted (Allen *et al.*, 2015). Each tonne of fossil or bio-carbon production is allocated a certificate by its originating government. If carbon is imported (coal, oil, gas biomass), then the receiving government unilaterally allocates a certificate to that carbon with liability held by the importer. That means that certificates can arise in different jurisdictions, and are not dependent on a united global movement. The certificate is not an import tariff, as there is no monetary value; it is an audit of environmental security. The users of the carbon are not liable for storage of resulting CO₂, that liability is retained by the original extractor, or by the importer. The government of the state where the carbon is used—as combustion, fuel, heat, process, or manufactured products—imposes a storage obligation on to the certificate holder. That obligation will start small, maybe just 0.25 per cent of state annual carbon (e.g. storing 1.2Mt annually of 500Mt UK CO₂ in 2020), but is intended to rise to become in line with the storage rate required to meet the global net-zero carbon budget (e.g. storing 500Mt/yr of UK CO₂ by 2050). It is important that the increase of storage is understood, impartial, and resilient against

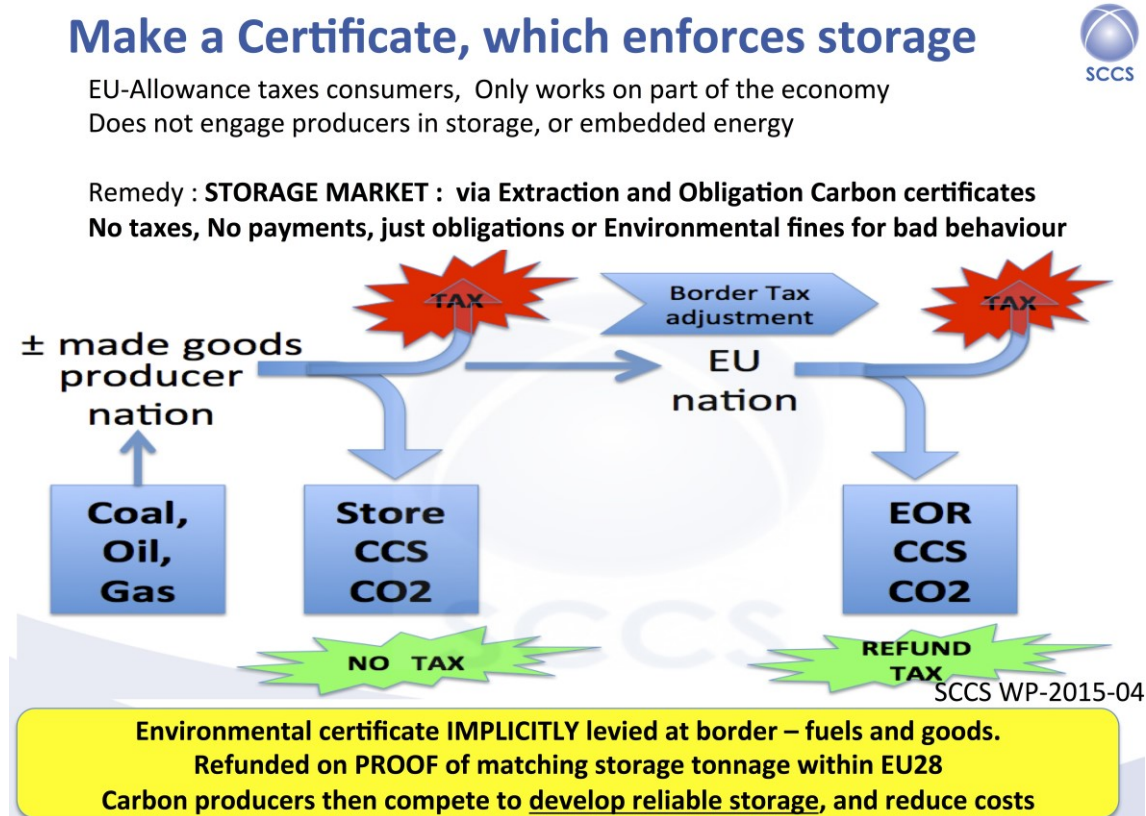
government and policy changes (Otto *et al.*, 2015). Thus the trajectory will be modified by feedback from globally agreed values of climate measurements established from moving multi-year averages, so that the time of arrival at net-zero is determined by all global actions—if less carbon is extracted and converted, or if global heat retention and temperature warming is less than expected, then less CO₂ storage is needed.

The region of storage can be defined by a state, but must be reliably verifiable. For the UK, storage can be within the European Union. This may create a border adjustment at national boundaries within the EU. But that is again an environmental remedy, and so is not a business tariff barrier. The ability to make bilateral contracts transferring CO₂ across borders is already established.

The storage obligation certificate creates new business. Predictable multi-decade timescales avoid disruption to businesses, and create opportunity for innovation into reliable marketplaces. Services to store CO₂ are created by new companies. The extractors or importers do not need to store their own precise CO₂ tonnage, but can pay a services company to store an equivalent tonnage. To that extent, there is a market—carbon extractors or importers are incentivized to seek out the least-cost, reliable provider of secure long-term storage. If a certificate holder defaults on their obligation to store CO₂, then the state can identify those certificates, and levy a penalty fine sufficient to pay a third-party services supplier to undertake the verified storage. The certificate system links simply with NET. If CCS is applied only to electricity generation from carbon fuels, then economy-wide decarbonization is not possible. Instead, to discharge a certificate obligation for storage, it is permitted to store CO₂ re-captured from NET. This still achieves the net-zero balanced budget.

Why not use money and taxation? No face value means no money, means no carbon traders. Certificates are a lever to enforce storage, which are directly linked to the desired outcome, and so are impossible to escape from. This is much better than tax because we know from North Sea oil history since 1971 that the UK Treasury has placed immense taxes on oil production, but has kept the money. A trivial amount of money has been transferred to fund carbon storage. Forty-two billion barrels of oil have been produced, which has emitted about 18 billion tonnes of CO₂. Approximately none of that CO₂ has been removed and stored by the UK. Taxation manifestly does not incentivize storage, as politicians and the Treasury can intervene. But net-zero climate needs storage to operate and to balance extraction.

Figure 2: Conceptual flow of carbon extraction import and storage certificate



Notes: This tags each tonne of carbon extracted within the EU, or imported into the EU, and awards a certificate. The certificate has no value or cost, but carries an obligation to store emitted carbon. The percentage of emitted carbon starts small, but through each year rises in line with environmental need, to store progressively more of the extracted carbon. Using NET re-capture and storage of CO₂ is equally valid, so certificates are resilient and durable as a measure of net-zero balance for both CCS and NET. This creates certainty of storage, to limit carbon stock in the atmosphere and biosphere and achieve net-zero CO₂ emissions by 2050. This also creates a market for storage providers, who develop transport and storage operations, competitively and reliably, at least cost.

VI. Summary and conclusion

CCS is not an energy-generation technology; it is an environmental mitigation technology. CCS applies to greenhouse gas emissions across many sectors of the economy. Electricity generation is frequently considered, but also heat, process industries, transport, biomass, and the negative emissions technologies (NET). There are many styles of CCS.

Journal: Oxford Review of Economic Policy 2016
Title: Can CCS and NET enable the continued use of fossil carbon fuels after CoP21?
Cite as DOI 10.1093/oxrep/grw013

Pervasive application of CCS enables the lowest-cost transition to a low-carbon economy. The Paris CoP21 committed to a 2°C–1.5°C average warming limit in perpetuity. This means that either fossil and biomass carbon extraction is halted, or CCS is applied to achieve a net-zero balance of extraction to capture or re-capture and long duration ($>10^4$ year) storage. Short-term (10^2 year) carbon capture and utilization does not store carbon.

All components of CCS exist and are proven operationally. Innovation is needed to overcome business and finance blockages. CO₂ can be captured and stored at low cost from ignored industrial and business sources. International collaborations and oil company developers are essential. Capture processes have great potential for efficiency innovation leading to step-change cost reduction. Only the USA, Canada, and China are developing new technology, with systematic decadal programmes. A crucial aspect to low-cost delivery is the creation of an infrastructure system, which can transport CO₂ effectively at lower cost, and at tens of millions of tonnes per year flow rates.

Environmental policies have not deployed any CCS. Wide spectrum economic actions have not deployed any CCS. Targeted actions are needed, linked directly to the desired result, which is net-zero carbon. Feed-in tariffs work, but at huge state expense. Emissions standards work at business expense, but may not innovate. A new proposal is made for carbon extraction certificates with an obligation for CO₂ storage. These are directly coupled to the outcome, and enables connection of CCS and NET, tied to climate commitments. Fifteen large CCS projects exist globally, eight are in construction; at least 3,500 plus NET are needed by 2050. That speed is unprecedented.

References

- Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., and Meinshausen, N. (2009), 'Warming Caused by Cumulative Carbon Emissions Towards the Trillionth Tonne', *Nature*, 458, 1163–6, doi:10.1038/nature08019.
- Allen, M., Haszeldine, R. S., Hepburn, C., le Quéré, C., and Millar, R. (2015), 'Certificates for CCS at Reduced Public Cost: Securing the UK's Energy and Climate Future, Energy Bill 2015', Scottish Carbon Capture and Storage Working Paper 2015-04, available at www.sccs.org.uk
- Assaf, R., Claessen, M., and Spence, B. (2014), 'Making Gas CCS a Reality', Abu Dhabi International Petroleum Exhibition and Conference, Society of Petroleum Engineers SPE-172108-MS.
- Bassi, S., Boyd, R., Buckle, S., Fennell, P., Mac Dowell, N., Makuch, Z., and Staffell, I. (2015), 'Bridging the Gap: Improving the Economic and Policy Framework for Carbon Capture and Storage in the European Union', Grantham Institute, www.lse.ac.uk.
- Boot-Handford, M. E., Abanades, J. C., Anthony, E. J., Blunt, M. J., Brandani, S., Mac Dowell, N., Fernández, J. R., Ferrari, M.-C., Gross, R., Hallett, J. P., Haszeldine, R. S., Heptonstall, P., Lyngfelt, A., Makuch, Z., Mangano, E., Porter, R. T. J., Pourkashanian, M., Rochelle, G. T., Shah, N., Yao, J. G., and Fennell, P. S. (2014), 'Carbon Capture and Storage Update', *Energy and Environmental Science*, 7, 130–89, doi: 10.1039/C3EE42350F.
- Brandani, S. (2012), 'Carbon Dioxide Capture from Air: A Simple Analysis', *Energy and Environment*, 23, 319–28.
- Cavanagh, A. J., and Ringrose, P. (2014), 'Improving oil recovery and enabling CCS: a comparison of offshore gas-recycling in Europe to CCUS in North America', *Energy Procedia*, 63, 7677–84.
- DoE (2014), 'Energy Department Project Captures and Stores more than One Million Metric Tons of CO₂', Port Arthur, US Department of Energy, available at <http://energy.gov/articles/energy-department-project-captures-and-stores-more-one-million-metric-tons-co2>
- Eiken, O., Ringrose, P., Hermanrud, C., Nazarian, B., Torp, T. A., Høier, L. (2011), 'Lessons Learned from 14 Years of CCS Operations: Sleipner, In Salah and Snøhvit', 10th International Conference on Greenhouse Gas Control Technologies, *Energy Procedia*, 4, 5541–8, doi:10.1016/j.egypro.2011.02.541.
- GCCSI (2015a), 'Applying Carbon Capture and Storage to a Chinese Steel Plant', available at www.globalccsinstitute.com
- GCCSI (2015b), 'The Global Status of CCS: 2015, Summary Report', available at www.globalccsinstitute.com
- Gollakota, S., and McDonald, S. (2014), 'Commercial-scale CCS Project in Decatur, Illinois—Construction Status and Operational Plans for Demonstration', *Energy Procedia*, 63, 5986–93.

- Grubb, M., and Ulph, D. (2002), 'Energy, the Environment and Innovation', *Oxford Review of Economic Policy*, **18**(1), 92-106
- Haszeldine, R. S. (2009), 'Carbon Capture and Storage: How Green Can Black Be?', *Science*, **325**, 1647–52, doi: 10.1126/science.1172246.
- Haszeldine, R. S. (2012), 'UK Carbon Capture and Storage, Where Is It?', *Energy and Environment*, **23**, 437–50.
- Haszeldine, R. S. (2015), 'Introduction', in *CO₂ Storage and Enhanced Oil Recovery in the North Sea: Securing a Low-carbon Future for the UK Scottish Carbon Capture and Storage*, available at <http://www.sccs.org.uk/images/expertise/reports/co2-eor-jip/SCCS-CO2-EOR-JIP-Report-SUMMARY.pdf>
- Haszeldine, R. S., and Scott, V. (2014), 'Storing Carbon for Geologically Long Timescales to Engineer Climate', *Issues in Environmental Science and Technology*, **38**, Royal Society of Chemistry.
- IEA (2013), 'Technology Roadmap, Carbon Capture and Storage 2013', available at www.iea.org
- IEA (2015), *Energy Technology Perspectives*, available at www.iea.org
- IEA-GHG (2014), Biomass and CCS - Guidance for accounting for negative emissions', IEA-GHG Technical Report 2014–05, available at www.ieaghg.org
- IEA-GHG (2015), 'Integrated Carbon Capture and Storage Project at SaskPower's Boundary Dam Power Station', Report 2015-06, available at www.ieaghg.org
- IPCC (2015), 'Climate Change 2014', Synthesis Report AR5, available at www.ipcc.ch/report/ar5/syr/
- NETL (2012), 'Decatur Biomass CCS Project', available at <https://www.netl.doe.gov/File%20Library/Events/2012/CO2%20Capture%20Meeting/S-McDonald-ADM-Illinois-CCS.pdf>
- Otto, F. E. L., Frame, D. J., Otto, A., and Allen, M. R. (2015), 'Embracing Uncertainty in Climate Change Policy', *Nature Climate Change*, **5**, 917–21.
- Ranjan, M., and Herzog, H. J. (2011), 'Feasibility of Air Capture', *Energy Procedia*, **4**, 2869–76.
- Ringrose, P. S., Mathieson, A. S, Wright, I. W, Selama, F., Hansen, O., Bissell, R., Saouka, N., and Midgley, J. (2013), 'The In Salah CO₂ Storage Project: Lessons Learned and Knowledge Transfer', 11th International Conference on Greenhouse Gas Control Technologies, *Energy Procedia*, **37**, 6226–36.
- Royal Commission on Environmental Pollution (2000), *22nd Report: Energy—The Changing Climate*, London, HMSO, available at <http://www.rcep.org.uk/>
- Scott, V., Gilfillan, S., Markusson, N., Chalmers, H., and Haszeldine, R. S. (2013), 'Last Chance for Carbon Capture and Storage', *Nature Climate Change*, **3**, 105–11, doi:10.1038/nclimate1695
- Scott V., Haszeldine, R. S., Tett, S. F. B., and Oschlies, A. (2015), 'Fossil Fuels in a Trillion Tonne World', *Nature Climate Change*, **5**, doi: 10.1038/NCLIMATE2578
- Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson,

Journal: Oxford Review of Economic Policy 2016
Title: Can CCS and NET enable the continued use of fossil carbon fuels after CoP21?
Cite as DOI 10.1093/oxrep/grw013

R. B., Cowie, A., Kriegler, E., van Vuuren, D. P., Rogelj, J., Ciais, J. P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grubler, A., Heidug, W. K., Jonas, M., Jones, C. D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J. R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., and Yongsung, C. (2016), 'Biophysical and Economic Limits to Negative CO₂ Emissions', *Nature Climate Change*, **6**, 42–50.

ZEP (2015a), 'Carbon Dioxide Capture and Storage', available at <http://www.zeroemissionsplatform.eu/carbon-capture-and-storage.html>

ZEP (2015b), 'Executable Plan for CCS in Europe', available at www.zeroemissionsplatform.eu