Progressive supply-side policy under the Paris Agreement to enhance geological carbon storage

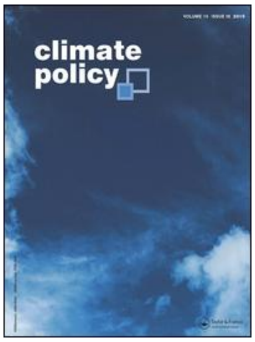
Citation for published version:
Zakkour, PD, Heidug, W, Howard, A, Stuart Haszeldine, R, Allen, MR & Hone, D 2020, 'Progressive supply-side policy under the Paris Agreement to enhance geological carbon storage', *Climate Policy*, pp. 1-15. https://doi.org/10.1080/14693062.2020.1803039

Digital Object Identifier (DOI):
10.1080/14693062.2020.1803039

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Climate Policy



Climate Policy

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tcpo20

Progressive supply-side policy under the Paris Agreement to enhance geological carbon storage

Paul D. Zakkour , Wolfgang Heidug , Andrew Howard , R. Stuart Haszeldine , Myles R. Allen & David Hone

CLIMATE POLICY
https://doi.org/10.1080/14693062.2020.1803039

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

Progressive supply-side policy under the Paris Agreement to enhance geological carbon storage

Paul D. Zakkour [a], Wolfgang Heidug[b], Andrew Howard [c], R. Stuart Haszeldine [d], Myles R. Allen [e] and David Hone[f]

[a]Carbon Counts, Frankfurt am Main, Germany; [b]King Abdullah Petroleum Studies and Research Center, Riyadh, Saudi Arabia; [c]Koru Climate, Bonn, Germany; [d]School of Geosciences, University of Edinburgh, Grant Institute, Edinburgh, UK; [e]Environmental Change Institute, School of Geography and the Environment, University of Oxford, Oxford, UK; [f]Shell International Ltd., Shell Centre, London, UK

ABSTRACT

As the Paris Agreement moves towards implementation, we explore opportunities it presents to move part of the climate change mitigation challenge upstream into supply-side climate policy. Supply-side climate policies have been sparsely employed to date, although interest is growing in approaches that can curtail and end fossil fuel production. Rather than focussing on fully eliminating fossil fuel production, we set out an alternative supply-side approach that involves fossil fuel producers taking progressive action to reduce and eliminate the climate impacts of their products. Our proposal uses the Paris Agreement's framework for finance and international cooperation to establish supply-side climate action that supplements demand-side climate policies, and thereby enhance climate ambition. The concepts presented rely on large-scale geosequestration technologies that can deposit carbon into geological reservoirs at rates progressively aligned to those at which carbon is being extracted by fossil fuel producers. Convergence of extraction and deposition rates is a necessary condition for achieving net-zero CO_2 emissions while still enabling some essential uses of fossil carbon. We propose an evolutionary approach to policy development, starting as a technology-support mechanism using results-based finance before transitioning into systematic measures under, firstly, Article 6 of the Paris Agreement, and, ultimately, decarbonised fuel standards. Collectively these could incentivise fossil fuel resource holders to manage both outflows and inflows of carbon in the geosphere, and in doing so, create, foster, accelerate and maintain an urgently needed market for geological CO_2 storage.

Key policy insights

- Balancing rates of carbon extraction from the geosphere (e.g. fossil fuel production) and rates of carbon deposition in stable geological reservoirs can achieve net-zero emissions alongside efforts to reduce emission flows to the atmosphere.
- Framing the climate mitigation challenge around carbon stock management on the supply-side of fossil fuel markets offers new ways to enhance climate ambition by mobilizing the financial and technical resources of fossil fuel producers in deploying carbon capture and storage.
- International cooperation under the Paris Agreement offers a powerful opportunity to establish tradeable units that support establishment of a liquid market in verified carbon storage.

ARTICLE HISTORY
Received 30 January 2020
Accepted 24 July 2020

KEYWORDS
Paris Agreement; climate finance; Article 6 mechanisms; supply-side climate policy; storage crediting; stock-based carbon accounting

CONTACT Paul D. Zakkour paul.zakkour@carbon-counts.com Carbon Counts, Feuerbachstrasse 38, 60325 Frankfurt am Main, Germany
This article has been republished with minor changes. These changes do not impact the academic content of the article.

1. Introduction

Economic theory suggests that pricing of greenhouse gas (GHG) emissions is an effective and efficient way to address the negative externalities of climate change (Baumol & Oates, 1971). Climate change policymaking has therefore tended to adopt the cardinal principle of 'polluter' (or emitter) 'pays' and the continued pursuit of new ways to price GHGs emitted to the atmosphere by fossil fuel users. Much of the international debate since adoption of the Paris Agreement has focussed on how its Article 6 mechanisms – through which Parties may cooperate to achieve or exceed their stated climate mitigation contributions – can support the wider deployment of carbon pricing and carbon markets (carbon taxes and emissions trading systems or 'ETSs'; e.g. Hawkins, 2016; Keohane et al., 2017; Marcu, 2016; World Bank, 2016). Yet even the most ardent political advocates conclude that carbon pricing by itself may not be sufficient to induce change at the pace and scale required for the Paris Agreement targets to be met, and may need to be complemented by a mix of other well-designed policies (Carbon Pricing Leadership Coalition, 2017). Within the broad ambit of options (e.g. Goulder & Parry, 2008; Somanathan et al., 2014) – a full review of which is beyond the scope of this paper – the supply-side of fossil fuel markets has been the 'road less taken' by climate policymakers (Green & Denniss, 2018; Lazarus & van Asselt, 2018).

Establishment of the 'carbon budget' concept a decade or so ago (Allen et al., 2009a; Matthews et al., 2009; Meinshausen et al., 2009; Zickfeld et al., 2009) did, however, propel stock-based, supply-side thinking to the fore of climate policy dialogue. A straightforward comparison of the remaining carbon budget consistent with the Paris Agreement 1.5°C or 2°C warming limitation goal (about 400–800 $GtCO_2$ with a possible range of 325–1180 $GtCO_2$; IPCC, 2014, 2018; Millar et al., 2017) with the Earth's extractable geological fossil fuel carbon stock (some 11,000 $GtCO_2$; Jakob & Hilaire, 2015) highlights the stark choices and challenges for climate mitigation, especially for countries and companies highly dependent on fossil fuel extraction and use. Although inherent uncertainty and upward revisions of the carbon budget over recent years (Millar et al., 2017) has raised questions over its political utility (Geden, 2018; Peters, 2018), stock-based thinking still offers value in accurately framing the climate mitigation challenge. Revelation of an impending global carbon stock imbalance was certainly effective in precipitating a wave of supply-side climate activism that continues to this day under refrains such as 'unburnable carbon' and 'stranded assets' and 'keep it in the ground' and 'fossil fuel divestment' campaigns (e.g. Ayling & Gunnigham, 2015; Carbon Tracker Initiative, 2011; Gaulin & Le Billon, 2020; McKibben, 2012). All these actions exclusively target the curtailing and ultimate end of fossil fuel production to avoid overshooting the remaining carbon budget. Recent scholarly literature on supply-side climate policy also tends to frame options in the same way (e.g. Lazarus & van Asselt, 2018; Piggot et al., 2018). A consequence of this singular focus, however, is that the choices and outcomes for supply-side action have been set in binary terms: either fossil fuels must be phased out or runaway climate change will occur because fossil fuel producers will be driven away from mainstream climate action; essentially the playing out of Sinn's 'green paradox' (Sinn, 2012).

A supply-side option that has, to the best of our knowledge, received far less attention is the application of an 'extended producer responsibility' approach to fossil carbon producers (that is, a policy approach where producers accept significant responsibility – financial and/or physical – for the treatment or disposal of post-consumer products; OECD, 2001). Under such a framework, the deployment of large scale carbon capture and storage (CCS) and negative emission technologies (NETs) offers possibilities through which to engage supply-side actors in ambitious efforts to reduce the climate impacts of the fossil fuels (and/or cement) they produce.[1]

Most supply-side policy advocates are wary of CCS, however, driven by concerns over high costs, fossil fuel subsidies, carbon lock-in, perpetuation of fossil fuels, governance and public perception (e.g. Bellamy, 2018; Honegger & Reiner, 2017; Markusson, 2012; Stephens, 2014). Widespread reliance on NETs to meet climate mitigation goals also poses concerns about technical feasibility, risk of failure (Anderson & Peters, 2016; Fuss et al., 2014) and the possible deterrence or deferral of ambitious emission reduction efforts (Markusson et al., 2018; McLaren et al., 2019). Other recent research has, conversely, reaffirmed the necessity of CCS and NETs in reducing and balancing (or 'offsetting') recalcitrant fossil CO_2 emission sources[2] in pursuit of the Paris Agreement's net-zero emissions goal (e.g. Haszeldine et al., 2018; Peters & Sognnæs, 2019). Analysis such as the IPCC's P1 pathway (IPCC, 2018) and the accompanying low energy demand (LED) scenario (Grubler et al., 2018) has shown that warming limitation goals could possibly be met without using NETs, so long as rapid, unknown, extreme and enduring technological, social and behavioural transformations occur over the next 30 years that curtail global primary energy demand to well below 300 exajoules (EJ) in 2050 – or about 43% below 2018 levels. Such outcomes are equally uncertain and risky. Other (less radical) scenarios generated by integrated assessment models have been unable to achieve atmospheric GHG concentrations of 450 ppm CO_2-equivalent or lower by 2100 if limitations exist on key technologies such as CCS (IPCC, 2014).

On this latter basis, we consider the Paris Agreement to offer a timely opportunity to rethink the potential of stock-based, supply-side, climate policy to establish a multilaterally agreed approach to stimulating deployment of CCS and NETs. Our proposal is based on linking rates of carbon extraction and deposition from and to the geosphere, drawing upon the work of Allen et al. (2009b), Allen et al. (2015) and Haszeldine (2016) among others, and evolving the proposal set out in Zakkour and Heidug (2019). We consider the option to be 'progressive' insomuch as it differs from previous supply-side climate policy proposals in seeking to mobilise fossil fuel resource holders in ambitious and meaningful climate action.

Our focus is on large-scale, permanent, geological sequestration of CO_2 as a stable non-atmospheric repository for carbon. The enhancement of terrestrial sinks, such as afforestation and reforestation, are addressed elsewhere in the literature. In some respects, geological sequestration may provide advantages over terrestrial sinks as the latter are inherently vulnerable to disturbance and risk of storage reversal (Raupach & Canadell, 2008).

We start by setting out the basic principles of our proposal, before describing a potential policy mechanism and phased approach for implementation under the Paris Agreement's Article 6. We then discuss whether and how the approach might enhance deployment of CCS and NETs relative to experiences of the past, and finish with some summary observations, potential constraints, and areas for further investigation.

2. A progressive option for supply-side climate policy

Shortly after establishing the 'trillionth tonne' concept (Allen et al., 2009a), two of the paper's co-authors proposed that increasing geological carbon stock at rates commensurate with those at which it is being extracted and released into the atmosphere offers another way to solve the looming planetary carbon stock imbalance (Allen et al., 2009b). Their 'sequestered adequate fraction of extracted' carbon ('SAFE-carbon') concept involves the placement of a global mandate on all fossil fuel producers to geologically sequester an amount of carbon corresponding to the amount of carbon they extract from the geosphere. Interim 'adequate fractions' would be recalculated and adjusted over time until a sustained balance is reached between carbon extraction and carbon sequestration. All the while, global emissions will also need to decline towards atmospheric equilibrium (Fuss et al., 2016; Zakkour et al., 2014).

Thus, net-zero CO_2 emissions can equally be framed as a geological carbon stock management challenge as much as an emissions control and removals – or a carbon flow management – problem (Allen et al., 2009b). Therein, SAFE-carbon offers a pathway by which to implement stock-based targets for carbon storage on the supply-side of fossil fuel markets that can – to a large extent – be separated from, and therefore complementary to, flow-based emissions goals on the demand-side. The SAFE-carbon approach also shows that sequestration activities can be phased in over time, smoothing financial and economic impacts within an orderly transition to net-zero emissions.

A further corollary of SAFE-carbon is the opportunity presented to establish *virtual* 'low carbon' and 'fully decarbonised' fossil fuels, which holds potential for encouraging the engagement of fossil fuel producers. Such products could potentially be generated by respectively balancing, through geosequestration, either a portion or all of the life cycle CO_2 emissions embodied in supplied fuels (scope 1, 2 and 3 emissions),[3] or only the embodied carbon that is emitted upon its use (i.e. defined as scope 3 emissions from the perspective of fuel suppliers). This could be achieved using a range of approaches, including CCS and direct air capture (DAC).

A decarbonised fossil fuel as described would not be an entirely new idea for climate policy but would somewhat mirror measurement and reporting rules presently applied to bioenergy resources. Under these approaches (e.g. IPCC, 2006), managed biological carbon stock accounts are recorded and converted to annualised flows (net emissions or removals) depending on the relative balance of harvesting (emissions) and biomass growth (removals). Since the approach assumes that the carbon contained in the wood is instantaneously oxidised to CO_2 upon harvesting (i.e. an emission in the *Land Use* sector accounts) – harvested wood products aside

– emissions arising from the subsequent combustion of biogenic fuel are zero-rated to avoid double counting the emission in the *Energy* sector accounts. Biomass combustion does produce CO_2, but accounting requires those emissions to be zero-rated to avoid double counting in the *Land Use* and *Energy* sector accounts.

The same accounting principle would apply to fossil fuels decarbonised via SAFE-carbon. Rates of extraction and sequestration from, and to, the geosphere would determine the level of net emissions or removals, and downstream emissions from product use would be zero-rated to avoid double counting of the emissions.

A reframing of the climate mitigation problem as a geological stock challenge presents a significant predicament for fossil fuel resource holders. On the one hand, comprehensive and sustained climate action poses a threat to their fossil carbon resource endowments, as highlighted by much of the supply-side activity to date. Simply referring to the principle of polluter or emitter pays and the use of demand-side climate policies may not be enough to preserve their current business models. On the other hand, stock-based accounting presents them with opportunities to develop proactive and progressive policies based on an extended producer responsibility principle and a change in perspective towards stewardship of carbon stocks. Such a shift in emphasis could help fossil fuel producers align their business models to a carbon constrained world, place the incentive to develop geosequestration activities in their hands as the entities with the best know-how to develop them, and, ultimately, mobilise their technical and financial resources to deliver ambitious and meaningful climate action.

Some oil and gas producing companies have made pledges to address most or all of the full life cycle GHG emissions associated with their products. These include Occidental Petroleum's 'carbon neutral aspiration' (Occidental Petroleum, 2019) and various 'net-zero pledges' by Repsol, BP, Shell and Total (BP, 2020; Repsol, 2019; Shell, 2020; Total, 2020). Policies that can foster effective and meaningful progress against these ambitions would therefore seem like a timely addition to the toolbox of measures available to enhance climate ambition.

3. Storage crediting as an enabler for progressive supply-side action

Policy approaches built around carbon stock management by supply-side actors point to a practical need for a type of transferable unit or credit that provides a trusted measure and record of tonnes of stored carbon or CO_2. This could be a 'carbon sequestration or storage unit' (CSU), for example, that represents a verified tonne of CO_2 securely sequestered in a geological reservoir, and which could either be held or surrendered by fossil fuel extractors to demonstrate a balance – or offset – against produced carbon. A CSU would therefore differ from units used in conventional climate policy mechanisms and accounting, which typically measure either *allowable emissions* (i.e. allocated emission allowances) or *emission reductions* (e.g. emission reductions credited against an emissions baseline for an activity), both of which avail the holder with a right to emit.

Several proposals have been made to operationalise policies built around storage crediting and CSUs, although none have yet been implemented (Allen et al., 2015; European Commission, 2013; Haszeldine, 2016; UK Parliamentary Advisory Group on CCS, 2016; World Business Council for Sustainable Development, 2015). In reviewing these proposals, Zakkour and Heidug (2019) noted several hindering factors and possible modifications to support implementation.

Firstly, proponents have tended to assume that a storage crediting mechanism involving CSUs would directly replace carbon pricing as a means to support CCS deployment, whereas it may be beneficial to enable storage crediting and carbon pricing to work in parallel to increase financial flows. Separation of emission reduction and storage targets would support such an approach.

Second, there has been a tendency to assume a need for direct accounting linkages between flow and stock measures, meaning adjustments must be made in carbon pricing schemes to allow for the introduction of a storage crediting instrument. This adds complexity to the approach, not least because of the variable disconnect between tonnes of CO_2 *stored* and tonnes of CO_2 *avoided* that arises from the energy penalty effects of capturing, transporting and sequestering CO_2 and in situations where CO_2 is stored as part of enhanced oil recovery operations (EOR; see International Energy Agency (2015) and Núñez-López and Moskal (2019) for analysis of emission reductions and CO_2-EOR). Limiting the credits only to the extraction and deposition of carbon on the supply-side of fossil fuel value chains can allow the accounting issues posed by downstream conversions and transformations to be by-passed, so long as double counting of the climate mitigation benefit is avoided. Thus, although there are implicit linkages between the storage of CO_2 and the avoidance of CO_2 emissions at source in the case of CCS, separation of targets can address this concern (see below).

Third, previous proposals also tended to presuppose, largely as a consequence of the first assumption, that no transitional situation can exist between carbon pricing and carbon storage crediting. The tendency has been to focus on the possible systematic policy mechanisms that could be used for implementation (e.g. the placement of a supplier (or emitter) obligation to acquire CSUs). However, an evolutionary approach may offer benefits for combining both storage crediting and carbon pricing in order to kick-start and support ongoing deployment through increased financial flows.

4. Establishing a storage mechanism under the Paris Agreement

The Paris Agreement offers a number of routes for countries to cooperate and support each other in their mitigation actions. While the current pledges for climate action set out in countries' nationally determined contributions (NDCs) remain insufficient to achieve longer-term warming limitation goals (United Nations Environment Programme, 2019), the Paris Agreement calls for significantly increased mitigation ambition beyond countries' current pledges. This includes encouragement to make progressively ambitious pledges in future NDCs, and the voluntary use of cooperation mechanisms under Article 6 to accelerate emissions reduction and removal activities.

Thus, there is scope within the broad ambit of international finance and cooperation to establish innovative approaches aligned around common interests, perhaps involving a 'club' of countries that expands in reach over time (e.g. Nordhaus, 2020). This could include the establishment of a CCS technology 'club' that adopts a storage crediting mechanism as a means to increase geological carbon stocks, and which could be used as an offset against fossil fuel supply. Although a variety of CCS 'clubs' already exist outside of the United Nations Framework Convention on Climate Change (UNFCCC; e.g. the Clean Energy Ministerial; the Carbon Sequestration Leadership Forum), they have so far lacked a unifying and catalysing mechanism through which to combine and channel finance for deployment (Hovi et al., 2016; Zakkour & Heidug, 2019). Establishment of CSUs under the auspices of Article 6 could therefore provide such programmes with firm foundations in measuring, reporting and verifying increases in geological carbon stock in a manner that fits within the context of the Paris Agreement, carries international credibility and legitimacy, and complements actions to link carbon markets on the demand-side. Rules governing CSU origination – including controls on leakage risk (e.g. site selection and monitoring), environmental impacts, health and safety impacts, and long-term liability for carbon reversal risk – could readily be drawn from existing standards for CCS, for example, as previously agreed under the Kyoto Protocol (UNFCCC, 2011).

While several core approaches for cooperation on a storage crediting mechanism can be envisaged in the context of the Paris Agreement, there is also a need to balance the urgency to accelerate CCS deployment with a pace that allows thinking to mature around longer-term approaches and possible transitioning to supply-side climate action. This suggests a need for a phased approach to policy development and cooperation.

Herein we propose a phasing that firstly uses results-based climate finance (RBCF) backed by CSUs, before moving to forms of international cooperation under Article 6 of the Paris Agreement that count international transfers of CSUs towards investing countries' NDCs and company-level storage commitments. Over time, a further shift in the approach could be possible through fuel suppliers or importers seeking to decarbonise fossil fuel supplies or imports. This progression of approaches is set out graphically below (Figure 1) and described in more detail in the next sections.

4.1. Phase 1: results-based climate finance 'club'

In early stages of implementation, storage crediting could be piloted as a technology-support mechanism by a group of like-minded Parties to the Paris Agreement with interests in fossil fuel use and CCS (Zakkour & Heidug, 2019). Around 40 countries make mention of CCS in their first NDCs (Potsdam Institute for Climate Impact Research, 2017), and a further 12 or so countries may also have interest (Zakkour & Heidug, 2019). These

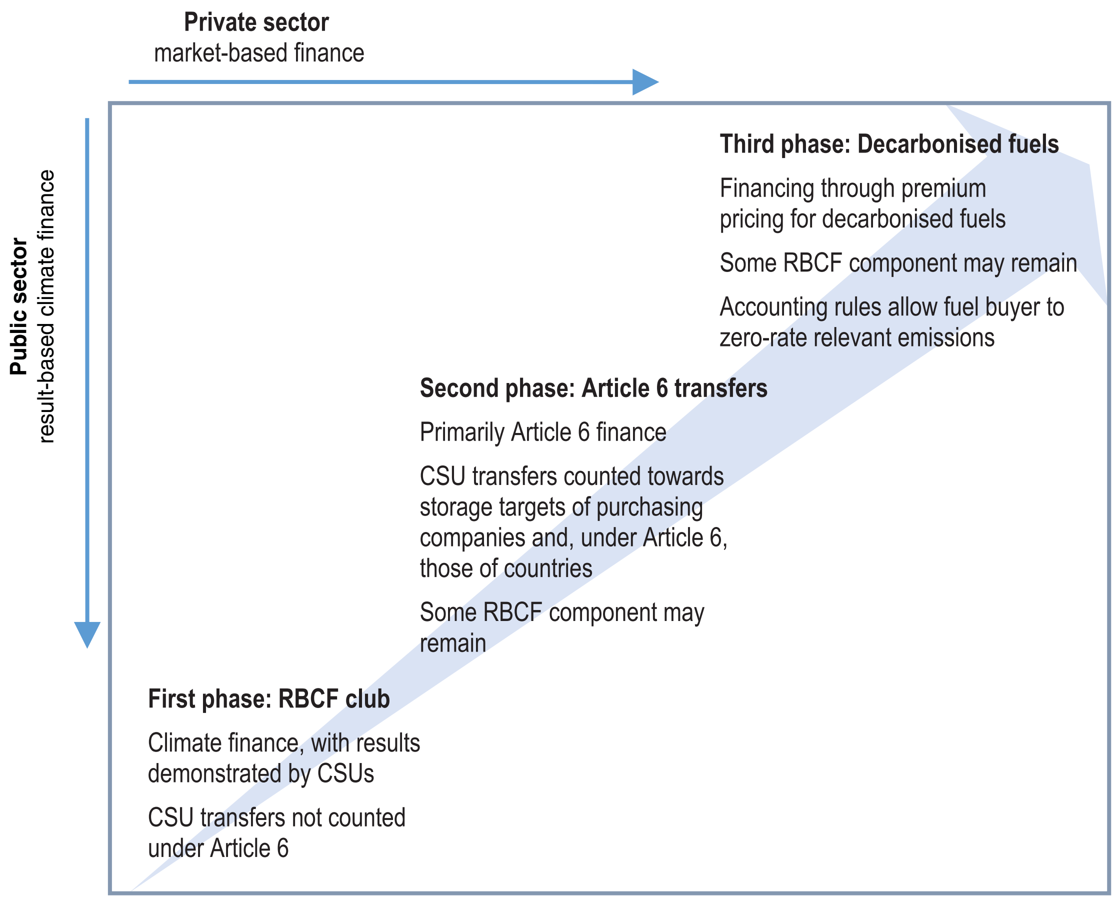


Figure 1. Phased approach to supply-side policies for CCS.

countries – and potentially also companies with aligned interests – could form a RBCF 'club' and establish the CSU as a means to unify cooperation. Rather than using transaction based cooperation and/or the use of developed to developing country climate finance flows under Article 6.4 to support NETs (Honegger & Reiner, 2017), the RBCF 'club' approach in Phase 1 would seek a broader effort to aggregate and augment existing finance for CCS and NET from across many countries.

Club members could make pledges to support carbon sequestration – for example, in the NDCs that many countries are expected to revise in 2020 – pool financial resources into a common RBCF fund and enter into forward contracts to procure CSUs from geological storage developers through an open tendering process. The prices, volumes and timeframes for contracted CSUs would be determined through the procurement process, driven by the size of the fund, technical details and costs of particular projects, availability of additional layers of revenue or incentives (including carbon pricing), provision of other sources of finance, financial metrics (e.g. agreed project internal rate of return), and any other priorities that the club deems appropriate (Zakkour & Heidug, 2019). Establishing the precise CSU procurement rules would be one of the first tasks for the 'club'. Monies would be disbursed to storage site operators in return for the surrendered CSUs.

Piloting the mechanism through RBCF would help increase climate ambition in several ways. First, it would augment flows of climate finance to large-scale geosequestration technologies relative to levels achievable by carbon pricing alone. Since the CSUs could not be directly used for any emissions compliance purposes, facilities – and ultimately countries – capturing and supplying the CO_2 could still record the emissions reduction achieved in their national GHG emissions inventory. These reductions could be retained and counted towards domestic

NDC targets or transferred as mitigation outcomes to other countries. This would provide a double incentive to supported CCS activities, but not double counting; the CSUs would not avail any explicit emissions rights to club members. Second, by directly targeting CO_2 storage the mechanism would help mobilize CO_2 storers to seek development opportunities independent of CO_2 capture, which could drive new business models and commercial transactions of physical CO_2 between parties. The absence of a price signal for CO_2 storage has been a major impediment to establishing a commercial market within which CCS could flourish (Zakkour & Heidug, 2019). A global mechanism to incentivise DAC with geological CO_2 storage (DACCS) would also be established.

While the surrendered CSUs could be disbursed among purchasing club members as a demonstration of geological carbon stock additions, under a RBCF arrangement this would not involve transfers of mitigation outcomes linked to Article 6. Thus, the incentive to participate would be limited to a shared interest in kick-starting CCS and DACCS deployment.

4.2. Phase 2: Article 6 transfers

This phase would involve switching from results-based finance as a means to drive demand for CSUs to using transfer-based finance under Article 6 of the Paris Agreement. Implementation could continue using the 'club' arrangements established under phase 1, but with the acquisition and transfer of CSUs contributing as mitigation outcomes towards acquiring countries' NDCs. As such, club members would need to establish specific geological storage targets in their NDCs against which the CSUs could be counted. For companies participating in a club, CSUs could potentially be counted against internal net-zero targets and could have value for financial disclosure purposes. The exact nature and ambition of the geological storage targets could be informed by experiences gained in phase 1, but could, for example, be bound to national forecasts of fossil fuel usage and the desired rate of offsetting – or the SAFE-carbon – of the carbon embodied therein.

Establishing CSUs as a currency of Article 6 transfers against NDC storage targets would deliver a number of benefits beyond the RBCF approach in phase 1. First, it would act to enhance mitigation ambition by establishing explicit geological storage pledges that would be additional to that of emission reduction pledges in NDCs. Second, the co-existence of the geological sequestration target and emission reduction targets in NDCs would give a basis for maintaining the amplified and parallel incentives for the capture and geological storage of CO_2 without double counting risking environmental integrity. Third, governments could seek to devolve responsibility for acquiring CSUs to the private sector using domestic policies such as low carbon fuel standards or other measures to oblige fuel suppliers to bundle CSUs with products (see below).

Direct linkages between national storage targets and emission targets will exist, however, because generating CSUs by storing CO_2 captured from point sources will implicitly drive a reduction in CO_2 emissions in national accounts. The parallel targets would provide a degree of transparency on the level of CCS and NETs embedded in national emissions reduction targets, while flexibility mechanisms would allow either or both emissions and CSUs to be transferred between third countries to enhance efficiency in implementation. Target separation would mean that CSUs would not be surrendered against emissions targets, or vice versa.

The conditions described notwithstanding, further work is needed to enhance clarity around the interaction between multiple targets within NDCs, the avoidance of double counting and impacts on the veracity of claimed mitigation. Resolving any concerns will be important for such Article 6 transfers to be implemented with confidence (Schneider et al., 2019).

4.3. Phase 3. Decarbonised fuels

This phase has the potential to preserve the parallel, and hence heightened, incentives seen in the earlier phases while offering a more coherent and joined-up view of demand- and supply-side policy approaches and stock- and flow-based accounts. It would involve an evolution from devolved obligation schemes established under phase 2, to a situation where fossil fuel producers could bundle CSUs together with fossil fuel supplies and thereby take direct responsibility for scope 3 emissions from their products. Bundling could be implemented voluntarily, based on fuel suppliers' own perceptions of the potential price premium available for low-carbon or decarbonised fossil fuels, or mandated by fossil exporters and/or importers (see below).

The supply of virtual decarbonized fossil fuels as described creates a potential pathway to an integrated, fully-fledged, supply-side approach that would allow end-use emissions from fossil fuels to be zero-rated in importing countries. In doing so, it could drive ambitious climate action by fossil fuel producers, spurred on by the need to maintain market access in a carbon constrained world. The approach could give rise to a long-term, enduring mechanism that supports the ongoing capture and geological storage of CO_2 from both point sources and direct from the atmosphere, paid for by the private sector.

Effective implementation of this goal is, however, reliant on the establishment of workable accounting approaches that avoid double counting of the emissions reduction effect. Double counting will occur where both the stored CO_2 is credited with CSUs that are used to certify fossil fuels as decarbonized, and the emission reduction effect of capturing and storing the very same CO_2 is counted by the facility or country where the CCS activity occurs. Only one or other effect can be claimed and credited towards emissions targets; counting the effect twice compromises the environmental integrity of either or both supply- and demand-side policy instruments. Longer-term viability of the phase 3 approach is therefore predicated on a move towards the use of stock-based accounts for the management of carbon in the geosphere that would replicate, for fossil fuels, methods currently applied to land use carbon stock accounts and the treatment of bioenergy resources.

The prevalence of territorial, flow-based, emissions accounting under the UNFCCC using IPCC methodologies (i.e. national GHG inventory reporting following, e.g. IPCC, 2006), is a recognised constraint on the wholesale implementation of supply-side climate policy. These methods are not able to readily recognise and reward mitigation actions that take place upstream of the point of use in fossil fuel supply chains. In considering how countries could be rewarded for action to curtail fossil fuel production, Piggot et al. (2018) proposed that parallel – or 'shadow' – extraction-based carbon accounts could be created alongside emissions-based accounts as a means of supporting early adoption of supply-side policies. Such an evolution may go some way to at least recognising supply-side actions, although further work will be required to consider practical implementation steps that could help integrate supply-side climate policy – and decarbonized fuels – within the global climate policy regime in a way that addresses important concerns around double counting.

5. Outlook for supply-side climate policy and CCS

Lazarus and van Asselt (2018) suggest that supply-side climate policies offer the potential to 'widen the mitigation cost curve' by broadening the portfolio of emission reducing measures available to policy makers. We take the view that a 'progressive' approach to supply-side climate policy as described would indeed increase the number of actors contributing to climate action and also leverage complementary and supplementary flows of climate finance to enhance climate ambition.

Supply-side technology mechanisms in electricity markets, for example, have proven to be an effective way of driving low carbon transformation in a supplementary way to carbon pricing policies. In jurisdictions such as the European Union (EU) – where carbon is already priced at several points in the economy – renewable portfolio standards have worked in tandem with the implicit price support provided by the EU ETS to augment the supply of renewable electricity across many member states. Similar supply-side approaches within global fossil energy markets could be used to provide much-needed targeted support for geosequestration technologies.

The IEA observed four years ago that without some form of targeted support it is unlikely that the momentum in CCS project deployment will be maintained, with progress likely to stall by 2020 (International Energy Agency, 2016). It also noted that this would substantially inhibit the availability of CCS to contribute to medium and long-term climate targets (International Energy Agency, *ibid*.). These sentiments remain valid today.

Efforts over the past decade or so to deploy CCS through carbon pricing alone suggest that a linear business model that passes an emission reduction value down the chain from capture to transport and storage do not work effectively outside of niche and captive situations (e.g. Sleipner, Snøhvit (Norway), Quest (Canada), Decatur (USA), Santos Basin (Brazil) and Gorgon CCS (Australia) projects – all captive, single-entity projects). So far, only the Norwegian CO_2 Tax – a highly focused sectoral carbon pricing scheme applied to Norway's offshore oil and gas industry – has offered a sufficiently high and stable carbon price signal to promote deployment of two captive CCS projects by Equinor, namely: Sleipner and Snøhvit. The scheme's narrow upstream scope means that, in essence, it functions as a supply-side climate policy. Similarly, carbon pricing employed in Alberta, Canada, was modified to offer a double credit alongside government grants to incentivise the construction of Shell's captive Quest project. The EU ETS, which imposes costs only on CO_2 emitters, has so far been unable to deliver any CCS projects in its 15 years of operation. Experience suggests that fully private multi-party CCS projects seem to work best where commercial markets allow prices for physical CO_2 to form between capturers, shippers and storers, as is the case with CO_2-EOR operations (e.g. Petro-Nova (USA), Boundary Dam (Canada), and Jilin CCS (China) projects).

Similarly, the model of large government grant funding for CCS projects has largely stalled (Lipponen et al., 2017), with funds either failing (e.g. EU's NER300), being withdrawn (e.g. UK CCS Competition), or imposing a sense of buyer remorse upon those that spent the money (e.g. as noted by the late Jim Prentice, former Premier of Alberta; see Morgan, 2014). Although various intergovernmental 'clubs' such as the Clean Energy Ministerial are considering ways to unlock finance for CCS, the underlying need for a genuine value proposition for developers must still be addressed.

Piloting a supply-side approach using RBCF under the Paris Agreement – as embodied in phase 1 – offers a possible fast-start option for a supply-side storage crediting mechanism that holds potential to enhance ambition and unlock the problems seen in the CCS business models of the past. While it still relies heavily on public sector funding, the approach applies additional political weight by establishing explicit support for geosequestration in NDCs, aggregates and pools finance to reduce the exposure of any single government or company to the full costs of deployment, and provides building blocks for commercial CCS deployment in future phases. By independently pricing the two main activities at either end of the chain – namely capture at the one end (where carbon pricing could apply) and sequestration at the other (i.e. through CSU generation) – commercial transactions of physical CO_2 between parties can also be established, creating a more viable business model for geological carbon storage. This, in turn, would increase the flow of finance to such activities as a supplement to carbon price signals.

Moves being made by G20 governments and the Oil and Gas Climate Initiative (OGCI) suggest that interest exists in forming a club or coalition between public and private entities to fast-track CCS (Clean Energy Ministerial, 2019). The creation of transferable CSUs linked to a technology mechanism within an RBCF framework could be a way to unify and catalyse these actions, sharpening their effectiveness in reducing emissions relative to similar CCS 'club' activities of the past (Hovi et al., 2016; Zakkour & Heidug, 2019). It remains an open question as to whether countries would be willing to enter into enhanced modes of operation of existing CCS and NETs dialogue 'clubs' (Hovi et al., 2016), however, and the potential barriers remain unexplored and untested.

The Paris Agreement's mechanisms under Article 6 can provide a more unified, mutually-agreed, platform upon which to base more systematic models for implementation over the medium-term (phase 2). At time of writing, the Agreement's Article 6 rules remain under negotiation, and draft rules have so far offered latitude by which to include *storage* units like the CSUs described herein. Moving to Article 6 based transfers of CSUs could, among others, establish pathways to address 'moral hazard' concerns posed by CCS and NETs development. Firstly, separating mitigation targets between fossil fuel use (emissions targets on the demand-side) and supply (storage targets on the supply-side) offers a potentially coherent basis upon which to ring-fence targets for NETs, a necessity noted by McLaren et al. (2019) to reduce mitigation deterrence. While the approach may not entirely address all the issues noted for mitigation deterrence, the separate targets would at least give an indication of the anticipated level of emission reductions to be achieved through CCS and NETs. Second, by devolving the storage target to fossil fuel producers through obligations to acquire and surrender CSUs with fuel supplies, an exit strategy from the moral hazard presented by continued dependence on government subsidy (as in phase 1) can be established. Such an evolution could help storage sites built under phase 1 become functioning operations within a thriving commercial geosequestration industry, rather than stranded assets paid for with taxpayers' money – a genuine risk if there is insufficient incentives to ensure storage sites get used.

To illustrate by way of example: the 'Northern Lights' consortium – a group developing a CO_2 storage site in the North Sea – has indicated that it will allow, from 2030, third parties outside of the demonstration programme to access the site upon payment of a storage fee (Aasen & Sandberg, 2020). The tariff will need to be paid by capture plant operators wishing to dispose of their CO_2 at the site on top of their cost of CO_2 capture, all of which would need to be covered by the single incentive of the allowance price in the EU ETS. Analysis has indicated that the EU allowance price would need to be 10 times higher than 2020 levels for the project to be ordinarily viable (Oslo Economics and Atkins Norge, 2020). Since about 80% of the site development and operating costs will be subsidized by the Norwegian Government (with possibly more funding coming from the European Commission under its Innovation Fund), the consortium presently faces limited exposure to investment risk, no direct incentive to ensure long-term site usage while also apparently maintaining control over fee-setting for storage services. If fossil fuel producers were instead mandated to originate (or otherwise acquire) and surrender CSUs as part of market access requirements for fuel supply – as foreseen in phase 2 – the site operators would be incentivised to seek CO_2 for storage. In turn, commercial transactions and prices for physical CO_2 could start to form between capturers and storers, according to the point of custody transfer, respective capture, transport and storage costs, EU allowance prices and the value of CSUs to the storage site operator.

Longer-term prospects for decarbonising fossil fuels through supply-side climate policy offer a possible pathway to systematically unlock previous deployment problems. It could allow a move away from the historical reliance on government grants and the linear business model for CCS driven solely by carbon pricing to more enduring forms of price support for geological storage of CO_2. Allowing continued use of an essential portion of 'decarbonised' fossil fuels in a carbon constrained world is also a useful corollary of a carbon stock-based policy approach, providing a powerful incentive to mobilise fossil fuel resource holders in ambitious climate action.

Roots of the concepts described are already beginning to emerge in some regional policies. Since 2018, California's Low Carbon Fuel Standard – a supply-side climate policy designed to reduce the full lifecycle emissions of liquid fuels used in the state – has allowed projects undertaken anywhere in the world using DACCS to generate credits for each tonne of CO_2 captured and stored. These can be used by regulated fuel suppliers as credits against the carbon embodied in the fossil fuels they supply in order to meet obligations under the scheme. The approach adopted by Californian policymakers offers a useful analogue for the supply-side decarbonised fuel concepts outlined herein.

Extending the analogue described presents a plethora of possible mechanisms that could be used to generate demand for CSUs across various phases and jurisdictions, including (see also, Zakkour & Heidug, 2020):

- Phase 1: technology mechanism using RBCF and club (Zakkour & Heidug, 2019); sectoral approaches (e.g. voluntary pledges such as oil company net-zero and 'carbon neutral aspiration' pledges and/or the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) 'Low carbon fuels' initiative); bilateral approaches (e.g. as assurances for geological CO_2 storage in the supply of 'blue' hydrogen under, for example, Japan's Hydrogen strategy).
- Phases 2 and/or 3: low carbon fuel portfolio standards (e.g. EU Renewable Energy Directive II; various Low Carbon Fuel Standards in US States and Canadian Provinces); mandatory offsetting of embodied carbon in fuels (e.g. Swiss CO_2 Law); 'carbon take back obligation' schemes (Jenkins et al., 2020; Kuijper, 2019).

Thus, a bottom-up patchwork of regional policies and mechanisms could operate alongside the club approach under phase 1 while supporting the transition toward systematic incentives for supply-side actions under phases 2 and 3. Collectively, therefore, the common currency of CSUs offers possibilities to establish both global and regional policies and mechanisms that could enhance deployment of CCS and DACCS.

6. Conclusion

We observe that the driver of anthropogenic climate change is not the rate at which fossil CO_2 is emitted, but the total stock of such fossil CO_2 accumulating in the atmosphere and active climate system. Efforts to mitigate climate change must therefore seek to limit, and reduce, that stock. Policies and measures focussed on regulating emissions and emitters have yet to find ways – or reach levels of effectiveness – by which to promote widespread sink enhancements and permanent storage of CO_2 that limits and ultimately entirely prevents ongoing carbon stock accumulation in the atmosphere. Present-day storage of CO_2 is largely tied to isolated projects, which are subsidised by government actions, or have found local markets for the CO_2 produced such as with CO_2-EOR. Consequently, projections for CCS rollout as a climate change mitigation technology are currently 1,000 times below the levels of capacity that will likely be needed to limit global warming to within 1.5°C or 2°C (Haszeldine et al., 2018). A new framing is therefore required.

The bottom-up architecture of the Paris Agreement offers opportunities to reframe the mitigation challenge as being as much about stock as it is about flows, and therein move at least part of the approach upstream into the supply-side of fossil fuels. We anticipate that this can provide the pace, tonnage, and pricing of CO_2 sequestration needed to enhance climate action. The approach can build on mechanisms of cooperation among like-minded countries beginning with a CO_2 storage club that pilots the approach through a framework of results-based climate finance. Later, the lessons learned can be used to move to financing arrangements and transfers of mitigation outcomes under Article 6 of the Paris Agreement.

These types of supply-side actions can be unified around a CSU (carbon storage unit) as a certificate representing a monitored and verified tonne of CO_2 sequestered. Such units can underpin the credibility of results-based climate finance (phase 1) and, under Article 6 arrangements, potentially evolve into a transferable measure of progress towards meeting national storage targets set down by countries in their NDCs (phase 2). The CSU could evolve further still, alongside developments in stock-based accounts for carbon in the geosphere, as a basis for producers and suppliers of fossil fuels to offset carbon embodied in their products (phase 3).

National governments, individually or in a 'club' with others, can mandate increasing percentages of CO_2 storage according to national fossil carbon supply or use to be achieved in each year, which can create a reliable and stable forward market for CSUs and, thus, carbon sequestration. The initial stages of establishing a market could mandate storage of small percentages of the fossil carbon delivered in fuel supplies, building reliability and creating confidence in the market. Increases in this mandated storage percentage can be scheduled to match growing mitigation ambition and increasing market liquidity as the tonnage of disposal and numbers of actors rise. This would foster a framework for establishing low-carbon or fully decarbonised fossil fuel products for applications that are particularly difficult or costly to eliminate, while still remaining consistent with the shift to a world of net-zero emissions. The approach also optimises the value of sink enhancements by counting such actions against a portfolio of fuel products rather than the traditional linear focus that counts emission reductions against only a single CO_2 source facility.

Progressive supply-side climate policy action as outlined can therefore offer ways for large fossil fuel producing countries and companies to use technologies they are familiar with to increase their contribution to the ultimate goal of the Paris Agreement. Implementing CO_2 storage can immediately offset the build-up of fossil CO_2 dumped in the atmosphere and, in the medium-term, can recover already emitted carbon (via bioenergy and DACCS) and store it in secure underground reservoirs.

Taking policy steps in this direction will raise a number of legitimate questions around, among others, political economy, accounting and measurement, interactions with demand-side policies and double counting. The approach outlined considers some of these factors, although further efforts will likely be needed to enhance clarity and understanding. In particular, as noted by Lazarus and van Asselt (2018) among others, the political and economic interests tied to fossil fuels can pose a formidable obstacle to climate action. Tentative signs suggest outlooks may be changing, as evidenced in recent net-zero pledges of several oil firms and the placing of climate change at the core of Saudi Arabia's 2020 G20 Presidency Agenda. Whether these ambitions stand up to the test of time remains an open question, however, suggesting policies that can facilitate movement in this direction would be a timely intervention. Further, there is an emerging policy debate on the use of parallel and complementary targets for NETs (Geden & Schenuit, 2020; McLaren et al., 2019), indicating that further evaluation of the governance of these technologies is necessary.

Given the backdrop described, an evolutionary and adaptive approach to supply-side policymaking on geological carbon storage that allows for learning-by-doing seems essential, starting first with a pilot phase that can accelerate climate ambition whilst also buying time for enhanced implementation concepts to further mature.

Notes

1. Cement making also involves the extraction of fossil carbon in the form of limestone, and its subsequent emission to atmosphere as CO_2 from cement kilns.
2. Currently estimated to exceed 9 gigatonnes (Gt) or 27% of global annual CO_2 emissions and growing, covering emissions from load-following electricity generation, aviation, shipping, long-distance road transport, iron and steel and cement making (Davis et al., 2018).
3. Scope 1 emissions are those produced by activities directly undertaken by a reporting entity (e.g., fuel extraction or refining). Scope 2 emissions are indirect emissions associated with bought-in goods or services used by the reporting entity (e.g., electricity and heat). Scope 3 emissions are those generated by a customer using a product supplied by the reporting entity.
4. Workshop report available at: https://www.kapsarc.org/research/publications/paris-agreement-ccs-policy-and-mechanisms/

Acknowledgment

This paper expands on research set out in Zakkour and Heidug (2019). That research was discussed at a 2-day expert workshop ('Post-Paris Agreement CCS Policy and Mechanisms') in which all of the authors participated along with representatives from government, industry, intergovernmental organisations, multilateral lending institutions and academia.[4] The workshop was sponsored by and held at the King Abdullah Petroleum Studies and Research Center (KAPSARC) in Riyadh on 9–10 April 2019. KAPSARC is a non-profit institution for independent research into global energy economics, funded in perpetuity by an endowment provided by the Government of Saudi Arabia. We also extend warm thanks to the Climate Policy team, and Joanna Depledge in particular, for providing tireless editorial support to improve and sharpen the paper.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

PZ was part-funded through a 1-year part-time Visiting Researcher position at KAPSARC. SH is funded by EPSRC EP/P026214/1. MA is funded by NERC NE/P019900/1; Engineering and Physical Sciences Research Council; Natural Environment Research Council.

ORCID

Paul D. Zakkour http://orcid.org/0000-0001-7720-2629
Andrew Howard http://orcid.org/0000-0001-5108-6834
R. Stuart Haszeldine http://orcid.org/0000-0002-7015-8394
Myles R. Allen http://orcid.org/0000-0002-1721-7172

References

Aasen, E. I., & Sandberg, P. (2020). *Northern lights. A European CO2 transport and storage network* [Presentation] Equinor to the Zero Emissions Platform (ZEP) Conference, European Parliament. 28 January 2020; Brussels.

Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., & Meinshausen, N. (2009a). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, *458*(7242), 1163–1166. https://doi.org/10.1038/nature08019

Allen, M. R., Frame, D. J., & Mason, C. F. (2009b). The case for mandatory sequestration *Nature Geoscience*, *2*(12), 813–814. https://doi.org/10.1038/ngeo709

Allen, M. R., Haszeldine, R. S., Hepburn, C., Le Quére, C., & Millar, R. (2015, September 9). *Certificates for CCS at reduced public cost: securing the UK's energy and climate future, Energy Bill 2015*. SCCS Working Paper 2015–04.

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science*, *354*(6309), 182–183. https://doi.org/10.1126/science.aah4567

Ayling, J., & Gunnigham, N. (2015). Non-state governance and climate policy: The fossil fuel divestment movement. *Climate Policy*, *17*(2), 131–149. https://doi.org/10.1080/14693062.2015.1094729

Baumol, W. J., & Oates, W. E. (1971). The use of standards and prices for protection of the environment. *The Swedish Journal of Economics*, *73*(1), 42–54. https://doi.org/10.2307/3439132

Bellamy, R. (2018). Incentivize negative emissions responsibly. *Nature Energy*, *3*(7), 532–534. https://doi.org/10.1038/s41560-018-0156-6

BP. (2020). *BP sets ambition for net zero by 2050, fundamentally changing organisation to deliver*. Press Release, February 12, 2020. https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bernard-looney-announces-new-ambition-for-bp.html

Carbon Pricing Leadership Coalition. (2017, May). *Report of the high-level commission on carbon prices*. Supported by the World Bank, ADEME and the Ministry of Environment, France.

Carbon Tracker Initiative. (2011). Unburnable carbon: Are the world's financial markets carrying a carbon bubble?

Clean Energy Ministerial. (2019). *Clean energy ministerial CCUS initiative and the oil & gas climate initiative agree to collaborate on speeding up CCUS*. Press Release, May 30, 2019. Retrieved September, 2019, from https://www.cleanenergyministerial.org/news-clean-energy-ministerial/clean-energy-ministerial-ccus-initiative-and-oil-gas-climate

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., Benson, S. M., Bradley, T., Brouwer, J., Chiang, Y.-M., Clack, C. T. M., Cohen, A., Doig, S., Edmonds, J., Fennell, P., Field, C. B., Hannegan, B., Hodge, B.-M., Hoffert, M. I., … Caldeira, K. (2018). Net-zero emissions energy systems. *Science*, *360*(6396), 6396. https://doi.org/10.1126/science.aas9793

European Commission. (2013). *Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions on the future of carbon capture and storage in Europe*. COM(2013)180 Final. 27.3.2013, Brussels.

Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., Jackson, R. B., Jones, C. D., Kraxner, F., Nakicenovic, N., Le Quéré, C., Raupach, M. R., Sharifi, A., Smith, P., & Yamagata, Y. (2014). Betting on negative emissions. *Nature Climate Change*, *4*(10), 850–853. https://doi.org/10.1038/nclimate2392

Fuss, S., Jones, C. D., Kraxner, F., Peters, G. P., Smith, P., Tavoni, M., van Vuuren, D. P., Canadell, J. G., Jackson, R. B., Milne, J., Moreira, J. R., Nakicenovic, N., Sharifi, A., & Yamagata, Y. (2016). "Research priorities for negative emissions. *Environmental Research Letters*, *11*(11), Article 115007. https://doi.org/10.1088/1748-9326/11/11/115007

Gaulin, N., & Le Billon, P. (2020). Climate change and fossil fuel production cuts: Assessing global supply-side constraints and policy implications. *Climate Policy*. https://doi.org/10.1080/14693062.2020.1725409

Geden, O. (2018). Politically informed advice for climate action. *Nature Geoscience*, *11*(6), 380–383. https://doi.org/10.1038/s41561-018-0143-3

Geden, O., & Schenuit, F. (2020). *Unconventional mitigation: Carbon Dioxide removal as a new approach in EU climate policy*. SWP Research Paper 8. SWP, Berlin.

Goulder, L. H., & Parry, I. W. H. (2008). *Instrument choice in environmental policy*. RFF Discussion Paper No. 08-07. https://doi.org/10.2139/ssrn.1117566

Green, F., & Denniss, R. (2018). Cutting with both arms of the scissors: The economic and political case for restrictive supply-side climate policies. *Climatic Change*, *150*(1-2), 73–87. https://doi.org/10.1007/s10584-018-2162-x

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., Rao, N. D., Riahi, K., Rogelj, J., De Stercke, S., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., … Valin, H. (2018). A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. *Nature Energy*, *3*(6), 515–527. https://doi.org/10.1038/s41560-018-0172-6

Haszeldine, R. S. (2016). Can CCS and NET enable the continued use of fossil carbon fuels after CoP21? *Oxford Review of Economic Policy*, *32*(2), 304–322. https://doi.org/10.1093/oxrep/grw013

Haszeldine, R. S., Flude, S., Johnson, G., & Scott, V. (2018). Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *376*(2119), Article 20160447. https://doi.org/10.1098/rsta.2016.0447

Hawkins, S. (2016). *Carbon market clubs under the Paris climate regime: Climate and trade policy considerations*. International Centre for Trade and Sustainable Development (ICTSD).

Honegger, M., & Reiner, D. (2017). The political economy of negative emissions technologies: Consequences for international policy design. *Climate Policy*, *18*(3), 306–321. https://doi.org/10.1080/14693062.2017.1413322

Hovi, J., Sprinz, D. F., Sælen, H., & Underdal, A. (2016). Climate change mitigation: A role for climate clubs? *Palgrave Communications*, *2*(1), 16020. https://doi.org/10.1057/palcomms.2016.20

International Energy Agency. (2015, November). *Storing CO_2 through enhanced oil recovery*. IEA Insight Series.

International Energy Agency. (2016, November). *20 Years of carbon capture and storage: Accelerating future deployment*. IEA.

IPCC. (2006). 2006 *IPCC guidelines for national greenhouse gas inventories*. Prepared by the National Greenhouse Gas Inventories Programme [Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds).] Published: IGES, Japan.

IPCC. (2014). *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change* (O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, & J. C. Minx, Eds.). Cambridge University Press.

IPCC. (2018). *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield, Eds.). Cambridge University Press.

Jakob, M., & Hilaire, J. (2015). Unburnable fossil-fuel reserves. *Nature*, *517*(7533), 150–151. https://doi.org/10.1038/517150a

Jenkins, S., Mitchell-Larson, E., Haszeldine, S., & Allen, M. (2020). Sustainable financing of permanent CO_2 disposal through a Carbon Takeback Obligation. Under review.

Keohane, N., Petsonk, A., & Hanafi, A. (2017). Toward a club of carbon markets. *Climatic Change*, *144*(1), 81–95. https://doi.org/10.1007/s10584-015-1506-z

Kuijper, M. (2019). *Carbon take back obligation*. Presentation to CCUS developments in the North Sea region workshop, 26 June 2019, CO_2 Capture Transport and Storage in The Netherlands (CATO).

Lazarus, M., & van Asselt, H. (2018). Fossil fuel supply and climate policy: Exploring the road less taken. *Climatic Change*, *150*(1-2), 1–13. https://doi.org/10.1007/s10584-018-2266-3

Lipponen, J., McCulloch, S., Keeling, S., Stanley, T., Berghout, N., & Berly, T. (2017). The politics of large-scale CCS deployment. *Energy Procedia*, *114*, 7581–7595. https://doi.org/10.1016/j.egypro.2017.03.1890

Marcu, A. (2016, October). *Governance of carbon markets under Article 6 of the Paris Agreement*. In R. N. Stavins & R. C. Stowe (Eds.), *The Paris Agreement and beyond: International climate change policy post-2020* (pp. 47–51). Harvard Project on Climate Agreements.

Markusson, N. (2012). Born again: The debate on lock-in and CCS. *Energy and Environment*, *23*(2-3), 389–394. https://doi.org/10.1260/0958-305X.23.2-3.389

Markusson, N., McLaren, D., & Tyfield, D. (2018). *Towards a cultural political economy of mitigation deterrence by greenhouse gas removal (GGR) techniques. Assessing the mitigation deterrence effects of GGRs*. Lancaster Environment Centre. http://wp.lancs.ac.uk/amdeg/files/2018/03/AMDEG-Working-Paper-1.pdf

Matthews, H. D., Gillett, N. P., Stott, P. A., & Zickfeld, K. (2009). The proportionality of global warming to cumulative carbon emissions. *Nature*, *459*(7248), 829–832. https://doi.org/10.1038/nature08047

McKibben, B. (2012). Global warming's terrifying new math. *Rolling Stone*, July 19. http://www.rollingstone.com/politics/news/global-warmings-terrifying-new-math-20120719

McLaren, D. P., Tyfield, D. P., Willis, R., Szerszynski, B., & Markusson, N. O. (2019). Beyond "net-zero": A case for separate targets for emissions reduction and negative emissions. *Frontiers in Climate*, *1*(4). https://doi.org/10.3389/fclim.2019.00004

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., Frame, D. J., & Allen, M. R. (2009). Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, *458*(7242), 1158–1162. https://doi.org/10.1038/nature08017

Millar, R. J., Fuglestvedt, J. S., Friedlingstein, P., Rogelj, J., Grub, M. J., Mathews, H. D., Skeie, R. B., Forster, P. M., Frame, D. J., & Allen, M. R. (2017). Emissions budgets and pathways consistent with limiting warming to 1.5°C. *Nature Geoscience*, *10*(10), 741–747. https://doi.org/10.1038/ngeo3031

Morgan, G. (2014). Jim Prentice says to wind down carbon capture fund in Alberta, new projects 'on hold'. *Financial Post*, October 6, 2014. Retrieved September, 2019, from https://business.financialpost.com/commodities/energy/jim-prentice-to-wind-down-carbon-capture-fund-in-alberta-new-projects-on-hold

Nordhaus, W. (2020). The climate club - How to fix a failing global effort. *Foreign Affairs*, May/June, 2020.

Núñez-López, V., & Moskal, E. (2019). Potential of CO_2-EOR for near-term decarbonization. *Frontiers in Climate*, *1*(5). https://doi.org/10.3389/fclim.2019.00005

Occidental Petroleum. (2019). *Climate-related risks and opportunities: Positioning for a low-carbon economy*. Retrieved September, 2019, from https://www.oxy.com/SocialResponsibility/overview/SiteAssets/Pages/Social-Responsibility-at-Oxy/Assets/Occidental-Climate-Report-2019.pdf

OECD. (2001, March 20). *Extended producer responsibility: A guidance manual for governments*. https://doi.org/10.1787/9789264189867-en

Oslo Economics and Atkins Norge. (2020). *Kvalitetssikring (KS2) av tiltak for demonstrasjon av fullskala CO_2-håndtering (Quality assurance of a demonstration of full-scale capture and storage (CCS))*. Report for the Norwegian Ministry of Petroleum and Energy. 29 June 2020, Oslo.

Peters, G. P. (2018). Beyond carbon budgets. *Nature Geoscience*, *11*(6), 378–380. https://doi.org/10.1038/s41561-018-0142-4

Peters, G. P., & Sognnæs, I. (2019). *The role of carbon capture and storage in the mitigation of climate change*. CICERO Report 2019:21.

Piggot, G., Erickson, P., van Asselt, H., & Lazarus, M. (2018). Swimming upstream: Addressing fossil fuel supply under the UNFCCC. *Climate Policy*, *18*(9), 1189–1202. https://doi.org/10.1080/14693062.2018.1494535

Potsdam Institute for Climate Impact Research. (2017). Intended Nationally Determined Contributions (INDCs) & Carbon Capture and Storage. webpage dated 15th August 2017. November, 2019.

Raupach, M. R., & Canadell, J. G. (2008). *Observing a vulnerbale carbon cycle in the continental-scale greenhouse gas balance of Europe* (A. J. Dolman, R. Valentini, & A. Freibauer, Eds.) (pp. 5–32). Springer.

Repsol. (2019). *Repsol will be a net zero emissions company by* 2050. Press Release, December 2, 2019. https://www.repsol.com/en/press-room/press-releases/2019/repsol-will-be-a-net-zero-emissions-company-by-2050.cshtml

Schneider, L., Duan, M., Stavins, R., Kizzier, K., Broekhoff, D., Jotzo, F., Winkler, H., Lazarus, M., Howard, A., & Hood, C. (2019). Double counting and the Paris Agreement rulebook. *Science*, *366*(6462), 180–183. https://doi.org/10.1126/science.aay8750

Shell. (2020). *Responsible investment annual briefing updates*. Media Release and Investor Presentation, April 16, 2020.

Sinn, H.-W. (2012). *The green paradox: A supply-side approach to global warming*. Massachusetts Institute of Technology.

Somanathan, E., Sterner, T., Sugiyama, T., Chimanikire, D., Dubash, N. K., Essandoh-Yeddu, J, Fifita, S, Goulder, L, Jaffe, A, Labandeira, X, Managi, S, Mitchell, C, Montero, J. P., Teng, F, & Zylicz, T. (2014). *National and sub-national policies and institutions*. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, . .., & J.C. Minx (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.https://www.ipcc.ch/report/ar5/wg3/

Stephens, J. C. (2014). Time to stop investing in carbon capture and storage and reduce government subsidies of fossil-fuels. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(5), 169–173. https://doi.org/10.1002/wcc.266

Total. (2020, May 5). *Total adopts a new climate ambition to get to net zero by 2050*. Press Release.

UK Parliamentary Advisory Group on CCS (PAG). (2016, September). *Lowest cost decarbonisation for the UK: The critical role of CCS*. Report to the Secretary of State for Business, Energy and Industrial Strategy from the Parliamentary Advisory Group on Carbon Capture and Storage (CCS).

UNFCCC. (2011). *Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities*. Decision 10/CMP.7.

United Nations Environment Programme. (2019). *Emissions Gap Report 2019*. UNEP.

World Bank. (2016). *Carbon Market Clubs and the New Paris Regime*. Paper for the World Bank Group's Networked Carbon Markets Initiative by Climate Strategies [Brewer, T., Derwent, H. and Błachowicz, A.].

World Business Council for Sustainable Development (WBCSD). (2015). *Carbon capture and storage*. Paper from the WBCSD under the Low Carbon Technology Partnerships initiative. WBCSD: Geneva.

Zakkour, P. D., Cook, G., & French-Brooks, J. (2014). *Biomass and CCS - Guidance for accounting for negative emissions*. IEA Greenhouse Gas R&D Programme, Report 2014/05. Cheltenham.

Zakkour, P. D., & Heidug, W. (2019). *A Mechanism for CCS in the Post-Paris Era: Piloting results-based finance and Supply side policy under Article 6*. King Abdullah Petroleum Studies and Research Center discussion paper. April 2019. https://doi.org/10.30573/KS–2019-DP52

Zakkour, P. D., & Heidug, W. (2020). *Supply-side climate policy for crude oil producers: Exploring policy pathways for decarbonizing fossil fuels*. King Abdullah Petroleum Studies and Research Center discussion paper. (Forthcoming).

Zickfeld, K., Eby, M., Matthews, H. D., & Weaver, A. J. (2009). Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proceedings of the National Academy of Sciences*, *106*(38), 16129–16134. https://doi.org/10.1073/pnas.0805800106