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# Responsible innovation in CDR: designing sustainable national Greenhouse Gas Removal policies in a fragmented and polycentric governance system

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In the assessment of climate policies, the social sciences are sometimes assigned a restricted instrumental role, focused on understanding and mitigating social and political "constraints" seen to impede the fullest achievement of a particular technological imaginary. The work presented in this paper draws on an alternative intellectual tradition, in which the technical, social and political dimensions of the problem are seen as closely intertwined, shaped by values and interests specific to each jurisdiction. The Greenhouse Gas Removal Instruments and Policies Project (GRIP), applied this approach to the design of policies for carbon dioxide removal (CDR) in the United Kingdom. GRIP explored what policy incentives and pathways might improve the societal assessment of different CDR technologies for further development and potential deployment. Here we analyze the views of UK policy actors questioned on different CDR options, and outline policy pathways to incentivize the research and demonstration processes necessary to determine what role CDR techniques should play in climate policy. We conclude by discussing recent policy developments in the UK, and the contours of a research agenda capable of supporting a responsible evaluation of CDR options.

KEYWORDS

**responsible innovation, carbon dioxide removal (CDR), Greenhouse Gas Removal (GGR), bottom-up governance, policy pathways, United Kingdom (UK)**

## 1 Introduction

### 1.1 Framing: defining responsible innovation in the development of CDR

Tackling climate change poses different challenges in different political jurisdictions. The decentralized nature of the processes set in motion by the Paris Agreement is realistic in acknowledging these differences. That agreement signaled that the planetary problem of rising temperatures is best addressed through agendas of action that are formulated locally and respond to the political, socio-economic and environmental diversity of the world. One would expect that this approach to climate policy would result in a radical change in scientific agendas, with research focused on building nuanced portfolios of ecologically and socially balanced climate actions, driven by local capacities and concerns.

Yet current policy research on carbon dioxide removal (CDR) options remains universalistic in tone, focused on the generic potential of individual technologies, with matters of public or political acceptability being regarded as external constraints on those idealized technological trajectories. In this context, the social sciences often have a narrow instrumental role in characterizing and allaying public resistance or opposition to those expected technological developments (Victor, 2015; Carton et al., 2020; Markusson et al., 2020).[1] These universalistic models of research and policy design have become increasingly inadequate as the need for realistic scenarios for CDR deployment grows.

In contrast to what we might characterize as a *planetary* approach, the GRIP project was firmly grounded in a *world* perspective. It takes the view that the social sciences should be equal partners in the process of building interdisciplinary research agendas—agendas centered on issues of governance, and capable of balancing top-down planetary perspectives with bottom-up portfolios of climate action built one at a time, jurisdiction by jurisdiction. Table 1 summarizes the contrast between these two perspectives.

In the case of the UK, the centrality of governance to the public assessment of CDR options is well-established in policy discourse. The early and influential 2009 Royal Society report *Geoengineering the climate: science, governance, and uncertainty* concluded that "the greatest challenges to the successful deployment of geoengineering may be the social, ethical, legal and political issues associated with governance, rather than by scientific and technical issues" (Royal Society and the Royal Academy of Engineering, 2018, p. xi). It recommended that "the governance challenges posed by geoengineering should be explored in more detail, and policy processes established to resolve them" (Royal Society and the Royal Academy of Engineering, 2018, p. 60). A House of Commons Select Committee responded by establishing in 2010 an enquiry into geoengineering governance. The Oxford Principles (Rayner et al., 2013), developed in conjunction with this enquiry, were accepted by the Commons Committee, and became widely adopted after the 2010 Asilomar conference on Climate Intervention Technologies (Lezaun et al., 2021). A bottom-up, jurisdiction by jurisdiction approach to the assessment and development of CDR was further elaborated in the Hartwell Paper (Prins et al., 2010), which concluded that "decarbonization will only be achieved successfully as a benefit contingent upon other goals which are politically attractive and relentlessly pragmatic." Further UK work on climate geoengineering governance, bringing together social scientists, ethicists and lawyers (Climate Geoengineering Governance Project, 2015), developed the "principles and protocols" model of climate governance, it consisting of: (a) general governance principles (such as the Oxford Principles); (b) technology-specific protocols related to the opportunity and risk profiles of particular CDR approaches; and (c) geopolitical considerations related to the environmental, social and political characteristics of each country or jurisdiction where the deployment of a particular technology is being considered.[2] A further commitment, following on from the second Oxford Principle, is to deliberative engagement and multi-criteria mapping with publics and stakeholders. This has two purposes: first, to maintain a broad range of criteria and framings in the assessment of CDR options, avoiding premature closure around certain approaches, assumptions or interests (Bellamy et al., 2013); second, to ensure that the portfolios of potential CDR techniques developed in each jurisdiction fully respond to local resources and priorities. This approach establishes a cultural and social *realpolitik* of locally based research, experimentation, regulation and action; a model in which the local has the initiative in framing as well as in responding to international governance and law.[3]

A growing number of studies exemplify the injunction to "govern $CO_2$ removal from the ground up" (Bellamy and Geden, 2019). The State of CDR report (Smith et al., 2023) combines a global assessment of CDR development with studies of relevant policy-making in different national jurisdictions. Schenuit et al. (2021) offer a comparison of early-stage CDR policies across nine OECD countries, arguing for "niche" national CDR initiatives that respond to local environmental, governmental and industrial capacities. Boettcher et al. (2023) describe the emergence of CDR policy in Germany, mapping how actors and positions evolve as a new domain of policy takes shape. Other studies zero in on policies for specific forms of CDR in individual countries (e.g., Fridahl and Bellamy, 2018; Fridahl et al., 2020; Hansson et al., 2020; Fuss and Johnsson, 2021; Bullock et al., 2023), or compare stakeholder preferences across different jurisdictions. Bellamy et al. (2021), for example, compare the views of policy actors on bioenergy with carbon capture (BECCS) in Sweden and the UK. Samaniego et al. (2021) examine four CDR approaches in relation to their potential economic and environmental contribution across Latin America and the Caribbean. Some recent studies explore the fit of specific CDR techniques with the priorities and capabilities of sub-national levels of government, as in Wedding et al.'s (2021) analysis of the potential role of blue carbon in California's climate strategy. In some valuable cases, new or speculative forms of CDR are placed in the context of longer historical experiences of carbon sequestration and removal (Carton et al., 2020; Kreuter and Lederer, 2021).

1 The Markusson et al. (2018) paper is of particular interest in that it brought together social scientists that had been working individually to contribute to the assessment of different technologies within the UK's first dedicated CDR research programme, who set out a common position for a more critical, socially and politically sensitized approach, grounded in work in the social sciences and humanities.

2 One consequence of this geopolitical dimensions is the need to recognize that broad sets of principles, such as the Oxford Principles or key tenets of the Responsible Research and Innovation programme (Stilgoe et al., 2013; Stilgoe, 2015), embody liberal democratic assumptions that may not always apply (Wong, 2016).

3 Elsewhere, we have argued that such a narrative of responsible innovation should replace the overwhelming emphasis on control in research governance (Bellamy and Healey, 2018). Responsible innovation, from this perspective, requires not only an acknowledgment of the risks and uncertainties raised by particular techniques, the means of mitigating them, and clarity about remaining uncertainties, but also work to determine potential steps to implementation in particular environmental and social contexts.

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TABLE 1 A social-science led approach allowing world rather than planetary perspectives on CDRs/GGRs in climate action.

| Dimension | Planetary perspective | World perspective |
|---|---|---|
| Overall framing and approach | Climate physics and climate economics are the basis for universalistic climate scenario modeling. Local scenarios based on increasing model resolution. Either entirely apolitical and asocial, or assume that key social parameters are fixed spatially or temporally. | Rooted in belief that more ambitious climate actions are only likely to be adopted if they are congruent with local conditions and linked to local strategies for the remaining sustainable development goals (SDGs). |
| Geographical/epistemological focus | Focus on global potential. Particular CDR approaches considered individually. Assessment of global potentials leading to identification of local targets. Use of burden-sharing approaches based on top-down assessments of local potentials ('under-utilized land', etc) to allocate national targets. | Focus on local potential; culturally and politically sensitive to local environmental and human resources and their synergies and trade-offs. Assessment of local potentials leading to identification of global contributions. |
| View of social and political agency: role assigned to governments and stakeholders | As consultees in granting 'social license to operate', often in terms of consent for experimentation or deployment of a particular CDR technique (although sometimes inappropriately extended to other places and times). | As customers for scientific and governance capacities to set CDR portfolio strategies in line with other development requirements; co-working with interdisciplinary science/social science researchers. |
| Wider social engagement, outreach and dissemination | Primarily an 'end-of-pipe' add-on | An integrated function of the co-creation of locally appropriate CDR portfolios and their governance. |
| Broader legacy of research | Restricted application. Applicability to national portfolio building typically, beyond scope of approach. | Multidimensional mapping allows broad general conclusions and knowledge transfer, but always subject to local test. |

### 1.2 Aims of the GRIP study and the purpose of this paper

GRIP was the Greenhouse Gas Removal Incentives and Policies Project, carried out at the University of Oxford between 2016 and 2019, with the intention of providing an initial country case study of CDR potential within the Principles and Protocols approach. GRIP was funded by two US based philanthropic foundations, and its central objective was to explore what policy incentives and policy pathways might facilitate the responsible development and potential deployment of CDR in the UK.

In this study, the CDR techniques considered were improved agricultural practices for carbon sequestration and storage (including new approaches to soil management), afforestation, peat bog enhancement, biochar, enhanced weathering, ocean alkalinity enhancement, ocean fertilization, bioenergy and carbon capture and storage (BECCS), ocean afforestation (chiefly seen as marine BECCS but with some claimed co-benefit for fisheries), and direct air capture and storage of carbon dioxide (DACCS). This list survived the interviews intact, with the partial exception of peat bog enhancement.[4] We were not looking for definitive assessments of these technologies, but for an initial view on whether they might individually be candidates for inclusion of a UK CDR research, development and demonstration portfolio.

GRIP included two components: interviews with a set of informed stakeholders drawn from UK government, academia, industry, and non-governmental organizations, and a set of public engagement exercises designed to characterize perceptions on different CDR technologies and policies (Bellamy et al., 2017, 2019, 2021). In this paper we present and analyze the materials obtained in stakeholder interviews.

## 2 Materials and methods

Here we present results from 35 interviews: 11 government (public or civil servants), drawn from different government departments or agencies; four parliamentarians, drawn from the House of Commons, the House of Lords and officers of the Parliamentary Estate; five people drawn from NGOs/Civil Society; four from industry; and 11 academics (the majority, but not all, natural scientists). Interviewees from industry, academia and NGOs had all contributed to academic and public discourse on Greenhouse Gas Removals; government and parliamentary representatives had either similarly contributed, or held roles that were concerned with climate policy. The interviews were carried out jointly by Tim Kruger, a natural scientist, and Peter Healey, a social scientist, between Autumn 2016 and Spring 2017.[5] An initial list of individuals in each category was expanded through asking each interviewee for further suggestions.

The interviews covered the criteria that might be employed to assess the various techniques, and the regulatory, financial and communication strategies that might be used to develop or inhibit them as appropriate. Interviews lasted roughly 90 min each, and were conducted using a semi-structured schedule (see Annex 1). The interviewers alternated in leading on the different sections of the schedule. At predetermined points, show sheets (see Annex 2) were used to prompt interviewees on the full range of possible responses to a question. This approach might have

4 Several interviewees suggested that peat bog enhancement focuses on the restoration and maintenance of carbon stocks in peat bogs, and that the very slow pace of expansion of this stock puts it beyond consideration for policies concerned with expanding carbon drawdown.

5 Before each interview, Kruger declared his interest in Origen Power, a company developing a technology that aims to combine carbon capture and power generation, and which could in principle benefit from some of the policy proposals set out in this paper.

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led to a certain convergence of interviewee responses. However, although we worked from a predetermined set of questions, we often followed up on particular responses that reflected individual interests or expertise. Together with respondents' own choices as to what to give emphasis to, this meant that not all questions were answered by all respondents, and similarly not all CDR techniques were assessed by each interviewee.

Toward the beginning of the interview, we asked each interlocutor whether they agreed with the working assumption of the project—namely, that appropriate and permanent CDR technologies would need to be deployed, along with mitigation and adaptation strategies, to stabilize our climate—and, if so, whether they would say that CDR techniques and policies were being developed at an appropriate pace. Given that we had framed our research in this way we thought it appropriate to find out if our informants agreed with us. Toward the end of the interview, we asked them whether they thought that CDR was becoming more or less salient over time.

For the more detailed analysis of CDR techniques reported below, NVivo was used to help identify 422 evaluative comments associated with particular techniques, ranging from 19 comments on ocean afforestation to 73 comments on agriculture and forestry. Each of these was coded by one author on a five-point scale, ranging from −2 to +2, based on whether the comment was positive or negative about the technique being addressed, and the strength of the comment. Additionally, a score of two (positive or negative) was given to multiple comments lying in the same direction; a score of one to a single comment. A comment would receive a zero score either for a neutral opinion, or for a comment which raised a negative issue about a technique, but then pointed to its solution. Repetitions of the same point by the same respondent were scored only once; if the same positive or negative point was made by different respondents, it would be scored in each case. A total score for the acceptability of the technique was defined as the total of all positive scores minus the total of all negative scores. The method is analogous to that by which approval ratings of politicians have long been assessed. In parallel with the scoring, the first two authors working together noted recurring positives and negatives about each technique, together with suggested steps to progress the technique/reduce uncertainties. Results are reported in Sections 3.1–2.

In addition, we analyzed the interview responses with the aim of determining which potential policy pathways might fruitfully be applied to the development and assessment of different CDR approaches, although here the interviews provided less guidance. We used this analysis as the basis for our views on potential UK strategies to develop and deliver responsible CDR, which we report in Section 4.1.

# 3 Results

## 3.1 General conclusion: growing salience and uncertainty, in a context of slow research, development, and demonstration

Greenhouse Gas Removal presents particular challenges in that policy-makers need to make decisions about technologies which mostly do not yet exist as full socio-technical propositions (or even, in many cases, as full technical propositions), and which in consequence cannot yet be fully assessed for their potential role in climate policy. Reflecting this challenge, most of our interviewees agreed with two statements: that CDR techniques were not developing at an appropriate pace; and that, at the same time, CDR was growing in policy salience as emissions reductions were not keeping pace with the targets set in the Paris Agreement. Some interviewees sharpened the paradox by combining these judgments with a third one: that, in the minds of policymakers, the uncertainties surrounding CDR techniques were increasing.

## 3.2 Views of the individual potential of CDR techniques in detail

### 3.2.1 Results of the scoring of comments

The overall analysis of interviewees' comments showed a strong tendency toward negative comments: 118 were scored positive, against 156 negative. Further, the use of comments that were scored "very negative" (−2 score) exceeded the "very positives" (+2 score) by more than 2 to 1 (28 to 11). Possibly even more significantly, the number of comments reflecting neutrality or uncertainty about techniques, 148, nearly matched the negative total. Overall, only 28% of the comments made by interviewees were positive, and although we are reluctant to give too much significance to relative technique scores given current gaps in our knowledge, only three techniques by this assessment—DACCS, peat bog restoration, and agriculture and forestry—attracted net positive scores. Despite these qualifications, we see it as significant that none of our interviewees was willing to rule out *any* technique as a possible candidate for deployment in some possible scenario, subsequent to further research, development and demonstration.

### 3.2.2 Results of the qualitative analysis of comments focused on possible ways forward for each technique

Interviewees offered diverse views as to the main requirements for each technique to progress, pointing to a possible future agenda for further research and more appropriate governance. The results of the detailed analysis of respondents' views on each technique are set out below. For each technique a characteristic positive and negative comment are given, together with a summary assessment of the main requirements identified by interviewees for that technique to progress to a point when it could be fully assessed for deployment. Actual quotes from the interviews were considered too long to be included here in full, but all the comments on one technique—enhanced terrestrial weathering—is available as Annex 3 to conveys something of the richness of views offered by interviewees. The full set of views are available on request as a source for independent secondary analysis, and has already been used by Boettcher (2020).

Abbreviations used in the text are CCS, Carbon Capture and Sequestration; MRV, monitoring, reporting and validation;

ETS, emissions trading scheme(s); IMO, International Maritime Organization.

#### 3.2.2.1 Ocean fertilization

**Main positives for this technique**

- A framework for regulation of ocean fertilization is already in place through the International Maritime Organization (specifically, through the London Convention/London Protocol);
- Possible co-benefits to fish stocks;
- Micro experiments may be possible, but these would be very difficult to assess.

**Main negatives for this technique**

- There are questions about our present capacity to measure the effectiveness of the technique;
- This is further hindered by the lack of a marine MRV framework;
- It would be even more difficult to assess complex ecological impacts.

**Requirements for this technique to progress**

- R&D focused on the science of nutrient distribution and impacts;
- Local experiments emphasizing impacts and costs may be useful in places where the oceanic flux is geographically contained;
- Further IMO work to establish a framework for the assessment of impacts.

#### 3.2.2.2 Ocean alkalinity enhancement

The positives and negatives for ocean alkalinity enhancement closely followed those for ocean fertilization: on the possible extension of the IMO London Convention/London Protocol case-by-case approach to the governance and assessment of ocean fertilization to this technique; on the difficulties of assessment, especially of second and third order impacts on complex oceanic ecology; and on the need for work on alkaline distribution. As a potential positive, increasing alkalinity would counter ocean acidification and this might benefit some species.

#### 3.2.2.3 (Terrestrial) enhanced weathering

**Main positives for this technique**

- The chemistry and scalability are broadly known;
- Use of industry waste (e.g., mine tailings) could reduce costs and improve acceptability;
- Claimed co-benefits in crop yields.

**Main negatives for this technique**

- Potential energy costs involved in milling, transportation and distribution;
- The challenges and costs of identifying and removing contaminants;
- The efficiency/safety trade-off in particle size;
- Other environmental impacts of marine or land distribution.

**Requirements for this technique to progress**

- Progress with MRV and adoption of acceptable proxies for effectiveness;
- Life-cycle assessment to establish costs and benefits under different assumptions of mining industry inputs and scales;
- Regulation on contaminants and particulates;
- R&D on possible co-benefits and co-costs;
- Public engagement to test acceptability, especially in areas of environmental sensitivity.

#### 3.2.2.4 Bioenergy with carbon capture and storage (BECCS)

**Main positives for this technique**

- Potential use of waste feedstocks, especially from pulp and paper;
- Industry interest suggests routes to scale-up;
- Also suggests local, integrated applications.

**Main negatives for this technique**

- Life cycle assessment critical;
- Potential land use competition with food and biodiversity;
- Might be limited application in the UK on local feedstocks;
- Challenges of longevity, safety and acceptability of $CO_2$ storage.

**Requirements for this technique to progress**

- R&D on different feedstocks and their different potential uses in energy/heat production;
- An adequate and stable $CO_2$ price;
- Carbon transport and storage infrastructure—state provision of these could subsidize costs.

#### 3.2.2.5 Biochar

**Main positives for this technique**

- Provides long-term capture;
- Claimed co-benefits to soil quality;
- Potential local integrated use;
- Commercial models of use are available.

**Main negatives for this technique**

- Difficult to assess benefits;
- Risks of soil contamination or air-borne particulates;
- Irreversibility of soil additives;
- Application at high rates (the Royal Society/RAE report 2018 cites 50 tons per hectare) over very large land areas would be required to yield a significant contribution to CDR.

**Requirements for this technique to progress**

- R&D to establish efficacy, claimed co-benefits and scalability;

- Standards and regulation to protect soil safety, especially where crops are grown, and to protect the public against particulates;
- Carefully assessed local demonstrators might be useful in assessing impact and reversibility.

#### 3.2.2.6 Ocean afforestation

**Main positives for this technique**

- IMO regulatory framework in principle in place;
- Claimed co-benefits to fish stocks;
- Micro experiments would be possible in contained environments.

**Main negatives for this technique**

- Nutrient loss resulting from growing macro-algae will be amongst wider ecological impacts which will be hard to assess;
- These assessment challenges are compounded by the lack of a marine MRV framework;
- Possible energy costs of drying macro-algae;
- Challenges of longevity, safety and acceptability of $CO_2$ storage.

**Requirements for this technique to progress**

- Importance of life cycle assessment;
- Further IMO work on regulation;
- Local experimentation emphasizing impacts and costs.

#### 3.2.2.7 Direct air capture and storage (DACCS)

**Main positives for this technique**

- No point sources of $CO_2$ needed.
- Can be located over storage facility.
- Least environmental/social impact.

**Main negatives for this technique**

- No co-benefits.
- May involve high energy and water resources.
- Process chemicals may raise issues of supply and disposal.
- Needs large/heroic cost/ton reductions.

**Requirements for this technique to progress**

- Innovation incentives driving R, D, and D.
- Probably big industrial involvement to drive down costs in scale-up.
- CCS infrastructure.

#### 3.2.2.8 Peat bogs

**Main positives for this technique**

- Peat bogs are well-represented in the UK;
- They enjoy a culturally/socially positive status;
- They have strong environmental co-benefits;
- They represent a possible step to paludiculture—wet agriculture—which may be more environmentally sustainable.

**Main negatives for this technique cited**

- They are more about greenhouse gas retention—about maximizing and maintaining existing sinks—rather than new capture.
- Peat bogs are vulnerable to climate change (e.g., if they dry out they release methane).

**Requirements for this technique to progress**

- Specially protected status, ideally international;
- Work to calculate net carbon benefit and the impacts of exposure to climate change in the longer term;
- Targeted R&D on paludiculture.

#### 3.2.2.9 Agriculture and forestry

**Main positives for this technique**

- "Natural" technique;
- High on social acceptability;
- Many potential co-benefits, including agro-forestry.

**Main negatives for this technique**

- Benefits and co-benefits depend on forest design: species selection, harvesting schedule and use of timber/harvested crop, etc.;
- Potential land-use competition between forests, food, and fuel;
- MRV issues—history of local and state cheating;
- Limited UK scope;
- Developing and applying UK policy is complicated by diversity of UK soils.

**Requirements for this technique to progress**

- R&D on MRV and proofing of benefits against the impacts of future climate change;
- Work on financial and informational incentives and regulation.

# 4 Discussion

## 4.1 A potential UK strategy for assessing and developing carbon dioxide removal

One of our research aims was to develop, and to feedback to our respondents, a potential UK strategy for developing CDR broadly consistent with the views expressed in the interviews and our own assessment of the UK's innovation environment and policy pathways.[6] The proposed strategies set below, along with other

6 Of course, treating the UK as unified entity is itself a simplification, since environmental capacities vary and policies affecting some CDRs (notably

project findings, were fed back to interviewees in the last quarter of 2019. Subsequent significant developments since then are covered in Section 4.4.2.

#### 4.1.1 A national adaptive learning strategy for CDRs

Before decisions on CDR deployment are made, research, development, and demonstration projects need to be more fully employed to reduce uncertainties (and acknowledge which uncertainties are irreducible). We do not see the function of the state as picking winners among CDR technologies, but as the source of a legal and policy framework that will allow a national adaptive learning strategy on the possible utilities, co-benefits and co-costs of a diverse set of CDR options. Such a framework should comprise an overall consistent national narrative for CDR in the context of climate policy, mechanisms for public deliberation, incentives for the emergence of "winners," and the formulation of any necessary regulatory constraints. This should create opportunities to progressively strengthen collaboration and mutually shared expectations among all the parties involved: government, industry, academia, civil society organizations and wider publics. We accept the message a number of interviewees put to us that industry in particular needs both a clear direction of travel and predictable incentives to lower the risks of innovation with these technologies. Whilst policy needs to be neutral as to technologies and minimize lock-in and path dependency for those eventually selected for deployment, a degree predictability is necessary to facilitate the necessary investments.

#### 4.1.2 A key reference point for policy—the carbon price

One of the radical policy initiatives that has been proposed and which received a broad level of assent from interviewees was a carbon price set at a relatively high level (at the time we were thinking of something of the order of $50/ton). This price would operate as a tax on emissions, would be zero-rated for net zero emission technologies, and act as a rebate/positive payment for net negative CDR systems. This could be revenue neutral as far as the UK Treasury is concerned, and indeed could be organized to avoid payments passing through the government accounts at all, as is the case with some payments under waste disposal policies (see policy pathway 2 below). It would be designed to ensure that the carbon polluter pays, but also that those capturing carbon were rewarded at a level that would prompt innovation and thus hopefully draw down the cost of capturing and storing greenhouse gases over time (and thus the scheme's floor price).

Interviewees were generally supportive of such a scheme *in principle*, but were conscious of some of the possible implementation problems. Notably, that it would make sectors of British industry and transport uncompetitive (this risk might be partially mitigated by basing it on carbon budgets allocated to individual consumers, but this would introduce additional complications). Brexit played both ways on this and indeed on most possible policy interventions on CDRs: it allows the UK more policy freedom but also exposes it to more risks if policies were not applied simultaneously across major economic competitors. Further, as the Royal Society/Royal Academy of Engineering pointed out in its comprehensive report on Greenhouse Gas Removal, "as carbon emissions are reduced (in consequence of the scheme's success) the income from an emissions tax could fall, while GGR [CDR]levels would need to be maintained, or even increased" (Royal Society and the Royal Academy of Engineering, 2018, p. 81). Although such a scheme is not immune to such perverse incentives and unintended outcomes, the steps we set out below are referenced to this aspirational policy.

grounded in land use changes), are the responsibilities of the devolved administrations in Wales, Scotland, and Northern Ireland.

#### 4.1.3 An innovation environment that will enable the responsible development of CDRs

The key task remains: to develop what are, by and large, immature technologies along the research development and demonstration chain, until they can be assessed as fully specified sociotechnical options. The initial stages of the strategy we advocate calls for the development of an innovation environment, because a primary purpose is to ensure that a wide range of competing potential technical options emerge. Over time, this approach will evolve capacities for demonstration, scale up and potential deployment, involving the skills and capacities of larger-scale industry, encouraging a process of consortia-building and the development of an active market in relevant intellectual property. Crucially, the state will also be responsible for setting standards for measuring, reporting and verification (MRV) and other regulatory requirements as each technique evolves. It would also of course have a responsibility in addressing market failures, or limits to the market's willingness to bear costs and risks. One such issue that will need to be tackled at an early stage is the public provision of relevant infrastructure, in the form of pipelines and storage facilities, for example (Oxburgh et al., 2016).

### 4.2 Potential policy pathways: contracts for difference and producer responsibility obligations

Here we discuss two potential general policy pathways to advance this agenda, drawing on our interviews and recent policy proposals to incentivise CDR development (Cox and Edwards, 2019; Jenkins et al., 2021, 2023; Burke and Gambhir, 2022).

#### 4.2.1 Contracts for difference

The central financial mechanism to advance this agenda is analogous to the *contracts for difference* (CFD) successfully employed to incentivise the development of low carbon electricity generation within the UK. As described by the UK Department for Business, Energy and Industrial Strategy et al. (2022; BEIS—currently the Department for Business and Trade), a generator party to a CFD is paid the difference between the "strike price"—a price for electricity reflecting the cost of investing in a particular low carbon technology—and the "reference price"—a measure of the average market price for electricity in the UK market. In the case of electricity generation, the stated aim is "to give greater certainty and stability of revenues to innovator electricity generators by reducing their exposure to volatile wholesale prices, whilst protecting consumers from paying for higher support costs when electricity prices are high."

In the case of CDRs, the strike price would be the cost of carbon capture and long-term storage and the reference price would be the carbon price operating in the EU Emissions Trading Scheme (or a UK national alternative). We propose that the strike price should be set initially at a price high enough to incentivize innovation—for illustrative purposes $50/ton, but limited at around this figure in order to weed out some of the more high cost propositions. Contracts for difference would commit actors to deliver stored carbon at a stated date at the contracted price.

As innovation and competition intensified, one might expect the strike price to be driven lower. There would be a clear advantage, however, in not letting the market concentrate around a single winner too early. For a range of reasons: the emergence of unanticipated problems or externalities with that particular technological configuration; the fact that the mix of technologies advanced under the Paris Agreement targets is likely to be different in countries with different geographies, geologies and priorities; and the possibility that slower to develop technologies might ultimately prove more cost-effective and/or publicly acceptable.

In many cases CFD contracts would themselves cover the costs of R&D&D leading to a capacity to capture and store carbon; but in some cases, where there are no offers to do so for an otherwise promising technique, it may be appropriate for further R&D efforts to be carried on the public purse by direct government expenditure. It will also be necessary to maintain R&D capacity on the public purse to ensure that the development of standards for measuring, reporting and verification (MRV) keep pace with technological development.

A second phase of the CFD policy pathway will allow the gains of the innovation stage to be utilized in the wider economy. It is at this second stage, that we would propose the introduction of a significant tax on emissions, relating this to the then CDR strike price. This change will have been clearly signaled at the same time that phase one on innovation was launched, together with as much detail as possible about its terms of operation. The knowledge that this was coming will itself have incentivized industrial investment in phase one. We suggest that the tax should be introduced in phases through the use of a "emissions tax escalator," starting at a low level but converging with the strike price after a further 5 years.

Industries that face special challenges in reducing emissions might be offered concessions in the form of a less steep convergence slope over a longer period, plus the possibility of emissions trading for that period (trading that would include CDRs). Other than these exceptional cases, we believe that including CDRs in emissions trading is problematic. On the one hand, an emissions trading scheme that allows CDR may increase demand for some techniques and speed up their introduction at the right price; on the other hand, such a market may lower the incentive for industries to decarbonize and thus postpone, potentially indefinitely, the successful decarbonization of the economy.

### 4.2.2 Producer responsibility obligations

The GRIP project also explored whether regulations designed to manage waste could be adapted to address excess greenhouse gases in the atmosphere. One example is the adoption of Producer Responsibility Obligations (PROs) similar to those used for the management of packaging waste. Packaging is one of several areas which are governed by such regulations, which were developed by the UK Government in response to the obligation, under the EU's Waste Framework Directive, to meet targets for the recovery and recycling of waste.

The key elements of the Packaging PROs are a registry of packaging producers, material-based recycling targets, and an obligation on packaging producers to demonstrate that they have achieved the relevant recycling target. This recycling can be achieved by a third party. Under a PRO scheme, the principle of "the polluter pays" is applied. The regulations provide an incentive to producers of waste to reduce the amount of waste that they produce, and an incentive to recyclers of waste to innovate. The specific material-based recycling targets can be tightened as the capacity of the recycling industry increases. Furthermore, the regulator does not directly dictate the price—the system creates a market-clearing mechanism whereby there is a transfer of resources from the producer of waste to the recycler of the waste. The regulator can indirectly influence the price, however, by setting the tightness (or looseness) of the material-based recycling targets.

Under the provisions of UK and EU law, all companies that handle packaging above a *de minimis* threshold are required to register. A producer of waste must demonstrate that a certified recycler has recycled the required proportion of produced waste. The price of the certificates that demonstrate recycling are set through a market mechanism where demand for the certificates is determined by the amount of waste produced multiplied by the material-based recycling target, and supply of the certificates is determined by the capability of the recycling companies. Money thus flows from the producer of waste to the recycler of waste, with the government's role limited to the formulation and enforcement of regulations, the setting of materials-based recycling targets, and the collection of registration fees.

How could such a scheme be used to incentivize CDR? The first step would be to establish a register of emitters of greenhouse gases (Companies are already required, above a *de minimis* threshold, to report emissions of greenhouse gases as part of The Companies Act 2006). The government would then need to set a Removal Fraction (the proportion of emissions that is required to be stored) for each greenhouse gas. These fractions would be analogous to the material-based recycling targets for packaging waste. Initially the Removal Fraction would be set at a low level and would increase as the capability to store greenhouse gases develops.

Obviously, the removal and storage of greenhouse gases raises a number of specific issues. Not all greenhouse gases can be treated in the same way, and it may be necessary to start the system with carbon dioxide and develop separate regulatory structures for other greenhouse gases at a later date. The requirement for a significant investment in infrastructure (namely pipelines to transport carbon dioxide to suitable storage sites offshore) is likely to be a significant barrier to achieving storage. The Oxburgh

Report of 2016 recommended the creation of a government-backed company tasked with delivering transport and storage infrastructures. This is in recognition of both the large amount of investment required (especially in the context of an absence of commercial incentive), and of the fact that pipelines are often natural monopolies that require regulation.

Those companies that would receive payment from emitters for storing carbon dioxide may seek to obtain high-purity carbon dioxide from sources such as ammonia production facilities and bioethanol plants, as these sources would be cheaper to treat and store than more dilute sources (such as the flue gases from a natural gas fired power plant). As the Removal Fraction increases, those companies that store carbon dioxide would use increasingly dilute sources of carbon dioxide. This approach would work with both "conventional" CCS from concentrated sources of emissions, such as the flue gases of fossil power generation plants and industrial processes, and also CDR techniques that remove carbon dioxide from the atmosphere. Indeed, proposed CDR techniques could hypothetically enable the Removal Fraction to increase to beyond 100% at some future point.

## 4.3 Comparative geopolitical perspectives on CDR policy

To explore how early-stage CDR policy in the UK compared to developments elsewhere in the world, we commissioned reports from experts in India, Sweden, Germany and the EU as a whole. Several key themes emerged from this work. First, that there was no one-size-fits-all model—each jurisdiction has its own unique issues and approach, and policy development is of necessity country-specific.

At the same time, there was a significant gap between policy objectives and actions required to achieve those objectives in all jurisdictions. Many countries want to see themselves as climate policy leaders, but they are unwilling to actually lead on CDR, despite evidence that CDR will be needed to meet climate targets.

There is a bias toward approaches that have "perceived naturalness"—despite concerns about effectiveness, scalability, and potential side-effects on food supply, biodiversity and land tenure. There were also concerns about the potential for LULUCF accounting criteria to be gamed and be used as a way to offset emissions from other sectors. There was, moreover, an emphasis on techniques that create co-benefits. This can be seen through both economic and political lenses—if they entrench, for example, pre-existing vested interests with strong lobbying capacity such as farmers and land owners.

CCS confronted significant political challenges in all jurisdictions, which undercuts many CDR techniques. If CCS is not an option politically, many CDR techniques are off the table, including BECCS, which underpins many of the integrated assessment models (IAMs) that inform policy. There is furthermore widespread concern about emphasis of CDR undermining efforts on emission reduction.

There is a willingness in many jurisdictions to see CDR undertaken in geographies other than their own—a sort of national NIMBYism—such as the UK importing biomass from North America for BECCS; Sweden looking to purchase certified carbon reductions from other countries; Germany being unwilling to countenance CCS in its own country while leading the development of integrated assessment models that imply vast quantities of BECCS; or India seeing the obligation of CDR as chiefly residing with countries which have greater historic emission responsibilities. It seems that countries wish to garner the benefits of CDR whilst ensuring that the detriments are borne by others.

Overall, there seemed to be few incentive structures in place to motivate development of CDR, and the creation of such structures was not anticipated in the short term. This gap has remained despite the proliferation of commitments to achieve net zero emissions in the second half of the century.

## 4.4 Recent developments in UK CDR policy

Schenuit et al. (2021) see the UK as a typical case for their ideal type of *proactive policy entrepreneurship*, and note that "none of the [eight] other countries studied have such explicit policy support for the development and deployment of CDR methods." Is their positive assessment justified?

In the period since the start of the GRIP project several factors have changed the external environment of climate policy: a rapid growth in global average temperatures and increased incidence of extreme weather events; increasing awareness of climate change as a problem and increasing salience of public mobilization (School Strikes for Climate, Extinction Rebellion, Just Stop Oil, legal challenges to country and corporate climate policies); the publication of the IPCC's Special Report on One Point Five Degrees, which highlighted the damage resulting from a 1.5C rise and the need to achieve net zero emissions in the near future; a ratcheting up of climate ambition in terms of the adoption of Net Zero targets, first in Sweden (2017), followed by the UK (2019) and the G7 (2021).

In the UK, policy action on climate change in general, and CDR in particular, has been impacted by the socio-economic shocks of the past few years: the implementation of Brexit has increased the burden on policymakers, diverting attention from other priorities; the severe consequences of the COVID-19 pandemic have constrained economic resources and the bandwidth for policy development; and the "cost of living crisis" threatens to fracture the broad political consensus about the Net Zero goal. Opinion surveys, however, give little indication that popular support for climate action has diminished (European Investment Bank, 2023).

The UK Government started to seriously consider removals in the Clean Growth Strategy (published in 2017 and amended in 2018; UK Department for Energy Security and Net Zero, 2017). It made two recommendations: (i) "A Government programme of research and development," and (ii) "The Government will consider the scope for removing barriers and strengthening incentives to support the deployment of CDR."

The GRIP project played a role in the development of the first of these recommendations. An engagement exercise convened by one of the authors and interviewers (Tim Kruger) and one of the interviewees (Richard Templer) involved a series of meetings with senior representatives of government departments and research councils (many of whom were themselves people we had interviewed as part of this study). These meetings highlighted the lack of resources for research, development and demonstration in the UK, and led to the proposal of a programme of work through the UK's Strategic Priorities Fund. In due course, £31.5 m of funding was secured for a range of CDR Demonstrator projects and a coordination hub to research the development of policy to responsibly incentivize the deployment of CDR techniques. Subsequently, the amount of resources dedicated to CDR research and development was boosted to £100 m, with resources being used to support a wider range of early-stage CDR techniques.

The second recommendation is in the process of being fulfilled, albeit slowly. A consultancy report commissioned by the government from Vivid Economics (Vivid Economics, 2019) laid out a broad array of potential policy mechanisms and the Government recently published the results of two consultations, one on business models to support Power BECCS and the other on business models to support other engineered CDR techniques. The UK Government is minded to support the development of CDR techniques by providing a mechanism similar to the Contracts-for-Difference approach. However, further development continues to be hampered by a number of factors, including a lack of clarity as to what actually constitutes a qualifying removal, and slow progress on $CO_2$ pipeline development (both the physical infrastructure itself and the supporting regulations.

The *Biomass Strategy* (UK Department for Energy Security and Net Zero, 2023), which is intended to determine the appropriate uses to which the supply of biomass in the UK should be allocated, was belatedly released in August 2023. While the strategy continues to affirm that BECCS will have a role in the UK's approach to achieving Net Zero, it highlights the wide range of unresolved issues rather than resolving them—or indeed detailing the process or timeline for such resolution. Finally, there have been repeated delays in announcing the details of a business model that would allow businesses to determine whether to invest in deployment.

In addition, while there is a stated ambition to take a "technique-agnostic approach," the indications in the consultation briefings suggest different levels of support for different techniques. This approach would inevitably lead to technology developers gaming the system to fit themselves into the most generously supported "technology bucket," rather than focusing on delivering the lowest-cost system.

The approach the UK Government is taking draws inspiration from the processes that were used to support the diverse range of approaches to producing renewable electricity. However, renewable electricity and CDR are sufficiently different in character for this extrapolation of policy approach to present serious challenges. Electricity generation is constrained in both space and time—to be efficient it needs to be generated close to where it is to be consumed, and supplied in a manner that balances supply and demand on a second-by-second basis. Neither of these constraints is pertinent for CDR. From a climate perspective it does not matter where in the world $CO_2$ is removed from the atmosphere—the atmosphere is well-mixed and a ton of $CO_2$ removed from the air above the UK is fungible with a ton of $CO_2$ removed from the air above, say, Australia. With regards to the time considerations, unlike electricity generation CDR does not need to be balanced on a second-by-second basis.

The UK Government is proposing that individual CDR projects will negotiate bilateral cost-plus contracts, as a way of stimulating a wide range of proposed techniques. This will inevitably lead to cost padding; complication, uncertainty and delays resulting from the negotiation process; and will result in gaming of the system, if not outright corruption. Cost-plus contracts will constrain price-discovery and foster subsidy-dependence rather than promoting innovation which could drive down costs.

It is important to consider the UK's lack of progress on policy in the context of policy developments elsewhere. In particular, the Inflation Reduction Act (IRA) passed in 2022 in the United States provides an incentive of $180 per ton of $CO_2$ removed from the air (Global CCS Institute, 2022). This stimulated the EU to develop the Net Zero Industry Act (NZIA), an initiative to provide support for technologies essential to achieve net-zero emissions. At this point in time, the NZIA is in the process of development and it is still unclear whether or not there will be policies specifically focused on accelerating the development and deployment of CDR techniques. In addition, the US Department of Energy has allocated funding of up to $1.2 billion for two direct air capture demonstrators or "hubs," each of which is expected to remove more than 1 million tons of $CO_2$ from the atmosphere and permanently store it (US Department of Energy, 2023).

The cost-plus approach favored by the UK Government contrasts unfavorably with the fixed price approach of the US Government. This contrast means that lower-cost approaches would prefer to operate in the US, while higher cost approaches would prefer to operate in the UK. For example, if the UK were to apply a cost-plus-20% approach while the US applies a flat-rate $180 per ton approach, this would mean that a technique that costs $100 per ton of $CO_2$ removed from the air would locate in the US (they can make a profit of $80 per ton, while profits would be limited to $20 per ton in the UK), whereas a technique that costs $300 per ton would locate in the UK (they would make a profit of $60 per ton in the UK and a loss of $120 per ton in the US). At vast expense, the UK would subsidize costly processes and incentivize cheaper processes to relocate abroad. This can be described as a process that separates the wheat from the chaff—by throwing away the wheat while keeping the chaff.

The UK established an early lead in this space—it was the first major economy to commit to Net Zero and established a strong start in CDR research and development. Yet it has been leapfrogged by other jurisdictions that provide the required policy clarity. In the absence of a rapid acceleration in policy action in the UK, it can be expected that CDR will become yet another industry sector pioneered in the UK but commercialized elsewhere.

## 5 Conclusion: what we have learned, and what remains to be studied

The GRIP project is far from being a complete example of a bottom-up country study. The missing elements include a full exploration of how competition between interests and for limited resources might be resolved in a national portfolio of candidate CDRs and a road map for their development toward possible deployment. Nevertheless, the project provided a first detailed empirical case study of possible CDR policy instruments and pathways in one jurisdiction.

A notable finding from the interviews was the degree of discrimination our respondents showed in assessing different CDR techniques. The interviews were also striking for the unanimity with which a range of stakeholders supported further research, development and demonstration (even on the least favorably assessed approach) to test the scope of their possible contribution to climate action. This needs to be taken together with the significant finding from the public engagement work that an initially favorably assessed CDR technique could be rejected if coupled with a financial incentive structure that was not favored (Bellamy et al., 2019). This emphasizes the importance of assessing each possible deployment of CDR as unique and complete sociotechnical proposition, inseparable from its environmental and political context.

Stilgoe (2015), invites us to think of geoengineering as a "verb" rather than a "noun," as a process "inviting new discussions of responsibility, ethics and experimentation," involving "care rather than control" and applying the four key principles of responsible innovation: anticipation, inclusivity, reflexivity and responsiveness (2015, p. 205–6; see also Stirling, 2014). Our study suggests that central sites for such activity are the national or sub-national contexts where CDR may be developed or applied. The fullest application of responsible innovation to CDR faces significant challenges, however. At a general level, the commitment of financial and technoscientific resources requires large scale, multi-year mobilizations, involving "imaginaries" or "grand challenges" in which the results are pre-sold politically in advance, and applicants for funds are encouraged to minimize the risks of failure to achieve them (which quite often involves tightly controlling the range of actors allowed to influence the outcome). A second complication applies specifically to CDR. Here, particularly at the "nature-based solution" end of the spectrum, powerful "nouns" already exist, in the shape of highly socially embedded technologies, such as forestry and agriculture, whose purposes are not primarily CDR, but which could contribute to it. In these cases, the process of developing portfolios of candidate CDRs—reconciling different resource and stakeholder demands—becomes extremely complex.

Can a different model of research and research funding be devised to allows a more tentative process of socio-technical learning? Will central governments, or for that matter international policy and funding bodies, be willing to accept the degree of humility needed for more open, inclusive and contingent processes of policy formulation? Will all such refinements be swept aside by renewed framings of extreme policy urgency, driven by evidence of rapidly shrinking carbon budgets as the world stubbornly refuses to reduce emissions?

The development and application of CDR techniques will be essentially an issue of polycentric governance, and studies of individual jurisdictions are critical in finding a way forward. We believe such studies should ground their work in the policy constraints and development priorities of individual countries. They should include for analysis a core group of CDR approaches, sufficiently diverse as to their environmental demands and interactions and stages of technological readiness to respond to these varying contexts, and ensure that social acceptability and environmental sustainability factors are central in the assessment process. The governance issues involved in each stage of CDR development must be fully explored, from the design and conduct of experiments through to the standards, regulations and reporting and verification procedures. We need to make special efforts to develop our understanding of the processes of bargaining around the composition of national portfolios of CDRs, and the distribution of those portfolios' effects. Finally, it is important to make sure that the local focus still allows for interaction with international political and industrial capacities that will need to be mobilized if early-stage CDRs are to be scaled up to the point where they can make a useful and safe contributions to climate action at a global level.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by Central University Research Ethics Committee, University of Oxford. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

PH: Formal analysis, Investigation, Writing – original draft. TK: Investigation, Writing – original draft. JL: Conceptualization, Writing – review & editing.

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## Conflict of interest

TK declares his interest in Origen Power, a company developing a technology that aims to combine power generation with carbon capture, and which in principle could benefit from some of the policy proposals set out in this paper.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2023.1293650/full#supplementary-material

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