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Perspective

Investing in Carbon Dioxide Removals: A new analytical and policy paradigm

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ABSTRACT

Carbon dioxide removals (CDR) have become central to climate policy. Current policy approaches, however, are insufficient to create the basis for CDR technologies to scale because they are not yet aligned with the complexity shaping the emerging sector. In this article, we provide an approach to understanding the characteristics of CDR which we argue is composed of both market-creation and market-led complexity. Our engagement with market actors since 2020 suggests that we have entered this new paradigm of complexity earlier than was the case for renewables and in a different way due to the nature of demand. We illustrate how these complexity characteristics are not well captured by existing tools that support policymaking. And we provide an alternative approach to the support of decision-making which is both exploratory and participatory in nature. We call for governments to embrace new tools to facilitate engagement between the public and private sector actors in ways that can more directly capture the sector's complexity. Public-private collaborations for the next phase of CDR investment will be needed to allow governments to both guide the sector whilst also providing a backstop to risk for private sector partners. Participatory and dialectic stakeholder deliberation processes should be integrated throughout analysis, policy design and cross-sector approaches rather than being thought of as separate in order to facilitate timely, targeted interventions that are robust to different possible futures.

1. Introduction

Over the past decade, the discourse on carbon dioxide removal (CDR) technologies has shifted. A decade ago, there were concerns that these technologies, also referred to as negative emissions, would distract policy attention and resources away from deep mitigation [1]. However, the lack of action on mitigation aligned with climate targets and limited remaining carbon budget has made it clear that there is a need for both [2]. Since then, the focus of discourse has turned towards identifying ways of integrating CDR into economies that are complementary to mitigation efforts on the path to net-zero [3]. To achieve this integration, four strands are required: (i) funding of research, development and demonstration; (ii) building bottom-up policy support for low-cost, early deployment opportunities; (iii) integrating technologies into emissions accounting; and (iv) laying the systemic groundwork to ensure future options remain viable, avoid lock out, and facilitate scaling [3,4].

Today, the US, EU and UK have shown progress in the first two strands, and the Intergovernmental Panel on Climate Change (IPCC) is laying the foundations for the third [5]. In this article, we argue that the fourth strand is underdeveloped and requires a new paradigm due to the complexity characteristics of CDR [6]. To build on strong initial foundations, a shift in focus in CDR policy is required to unlock private risk-adjusted capital as a means of scaling the sector. We argue that this represents a new paradigm for policymakers different to that of a decade ago, and different to the trajectory of policy support for renewables and conventional decarbonisation. This is due to the nature of complexity shaping the emergence of the CDR sector, which we suggest is composed of both market creation and market-led complexity [7].

We illustrate how these features of complexity are not well captured by existing tools that support policy decisions. To navigate a new policy

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paradigm, we suggest that tools are required that can capture the complexity of CDR integration into our economies. The underlying paradigm shift is based on approaching the future through a lens of the possible rather than the probable. Tools that involve participatory processes and two-way exchange allow for this focus on what might be possible and the development of policy approaches that are robust to multiple possible futures. Without acknowledging this complexity and adopting a more comprehensive decision-support toolkit, policymakers will be inadequately prepared to navigate the dynamic and multidimensional net-zero decision space. In particular, we make the case that without additional and novel policy interventions focused on attracting private risk-adjusted capital into the sector in the next 2–5 years, the ability to achieve net-zero targets will be severely delayed. This stands to jeopardise not only the 1.5 °C target but also the 2 °C. Furthermore, the cost of attaining net-zero targets in the long term will be increased if, in the short-term, private-sector confidence and willingness to invest is not fulfilled.

2. State of the sector - the role of investors in a complex market environment

The IPCC stipulates that achieving net zero emissions requires the establishment of a CDR sector larger than the oil and gas, and agricultural sectors combined by 2050 [8]. The US, EU, and the UK have introduced a raft of direct and indirect policies to stimulate the CDR sector in their respective jurisdictions [9]. Estimates of the economic opportunity for actors in the US and UK by 2050 stand at $100's and 10's of billions, respectively [8,10]. This has kickstarted a number of initiatives and ventures that have answered the call to meet the net-zero challenge. For example, the UK has 145 active CDR companies [11]. However, the pioneering CDR start-ups and pilot plants to date have been funded through attracting concessionary capital from investors with a high-risk appetite. This has been augmented by grant funding from philanthropic organisations and governments - effectively on the CDR start-up balance sheets. However, sources of private concessionary capital are limited - of the order of a few $billions - and governments face fiscal constraints which will make long-term commitments to CDR grant funding politically sensitive in an era of populist politics which does not prioritise climate [12,13].

The ability for CDR start-ups to raise private risk-adjusted capital off their balance sheets going forward will be essential in scaling the sector. It will allow a broader range of sources of capital to be attracted including from the investment banking sector, private equity and pension funds which have $trillions to invest. It will also maintain the financial health of the CDR start-ups by keeping debt to equity ratios low allowing them to borrow in the short run at cheaper rates whilst they establish a pipeline of CDR projects. But today the ability for CDR start-ups to attract private risk-adjusted capital off their balance sheets is problematic due to the extent of uncertainty facing financial organisations seeking to invest in the CDR sector.

3. The new paradigm of complexity - an inclusive approach working with CDR sector characteristics

Over the last 5 years, through interviews and workshops, we have engaged with 100's of market actors and investors to understand the key challenges to investing in CDR. These challenges are related to two key complexity characteristics of the sector. First, there are several characteristics that are related *to* ***market creation complexity:*** (1) the CDR sector is technologically highly heterogeneous, fragmented and fraught with information asymmetries [14] and uncertainty [15] as to how the CDR technology portfolio will develop; (2) though the CDR market is a new one, start-ups will unlikely be able to rapidly establish the sector on their own. The CDR sector is dependent on incumbents for its realisation in the short term. This results in a complex political economy due to the intersection between CDR value chains and the fabric of capital-intensive economies whereby incumbents will need to trade-off the stranding of highly profitable existing assets by investing in a new high risk untested asset class that will in turn further accelerate the stranding of their existing assets [16,17]; (3) they will intersect with culturally sensitive and historic landscapes for which public acceptance and understanding is largely untested [18]; and (4) there is a need to understand the impact of high capital-intensity and other barriers to entry on firm level strategic investment decisions of first movers and incumbents as they invest in CDR [19].

Second there are several characteristics that we refer to as **market-led complexity**: (5) the uncertainty about who pays for CDR and how markets will shape demand is chief among these [20]; (6) yet the market is running ahead of regulation and policy in shaping best practice which creates challenges in terms of integrating negative emissions with land and infrastructure systems [7]; and (7) much of the data given the market-led nature of the sector is privately held limiting systemic visibility to different actors including policymakers, academia, funders and participants [21]. At present, the Voluntary Carbon Market (VCM) is the sole source of direct revenues for CDR credits generated. The VCM, however, has structural flaws as a market-based instrument to allow the CDR sector to scale as a discrete stand-alone asset class and an oligopolistic buyer side whereby a handful of purchases set defacto standards on price, deal structure, standards etc. [22,23]. Stipulations establishing guidance on demand for CDR, specifically the role of carbon credits for corporate net-zero strategies are in flux, as evidenced by the SBTi scandal that unfolded over the course of late 2023 to mid-2024 [24]. This raises questions about the role of CDR credits, which as it stands currently constitute <10% of VCM volume - with the majority of removals being sold on a future delivery basis in anticipation of CDR plants attaining investment funding - many of which have not - and generating credits in the future [25].[1] These offsets, driven by corporates, are in danger of seeing a race to the bottom where standards become weakened over time as corporates attempt to reach their climate goals as cheaply as possible [26]. Overcoming uncertainty for investors will require clear differentiation of credits for CDR in both the existing voluntary and emerging compliance markets [10,25]. To February 2025, only 620,000 technical credits have been delivered which pales relative to the 5 $MtCO_2$ that the UK aspires to achieve by 2030 annually - let alone other national jurisdictions interim CDR targets.

For investors this means that although many recognise the importance of the CDR sector in addressing climate risk, the extent of market-creation and market-led complexity and the capital-intensive nature of some of the technologies makes it a less attractive asset class as investment uncertainty is considered too high. The absence of reliable precedent, and the lack of long run past data needed for future financial risk projections inhibit the quantification of uncertainty to risk [15].[2]

These complexities require governments to go beyond establishing the `*rules of the game'* for CDR in their role of addressing economic market failures in the long-term interests of society. This role for government is important, as has been the case for the renewables sector, in establishing clear standards and regulations. But for investors to allocate

[1] See CDR.fyi - https://alliedoffsets.com/cdr-data/ [Accessed 5th February 2025] CDR including nature-based removals off registry purchases = 30.6 Mt. credits and on registry retirements = 75.2 Mt. credits. | Total tonnes permanent CDR sold = 14 Mt. credits with 0.62 Mt. credits or 4.4% delivered.

[2] Indeed the CDR sector is considered to be steeped in the characteristics of Deep Uncertainty. This is a situation where analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes. In particular, the long-term future may be dominated by factors that are very different from the current drivers and hard to imagine based on today's experiences – see reference [15]

financial resources to the sector, there needs to be additional signals and strong long-term guidance [9]. Governments are currently introducing policies to support CDR such as the development of carbon Contracts for Difference - effectively a floor price for CDR credits sold [27,28] - and integration into Emissions Trading Schemes [29] as well as purchasing credits directly [30]. These will establish market-wide CDR credit standards but the policy roll-out dates remain vague, volumes of off-take remain small as a proportion of that needed to stimulate the market to realise investor confidence and therefore uncertainty remains. As a result corporate credit purchases on the VCM have fallen from a $2.3B peak to $0.75B in 2021–2023, respectively [31]; and OnePointFive, which issues the highest quality CDR credits, are presently finding it difficult to get their third Direct Air Capture plant past Final Investment Decision due to a lack of long term locked in offtake for CDR credits [32,33].

The financial markets are unable to accommodate the extent of complexity associated with CDR projects. The absence of reliable precedent to calibrate uncertainty and price risk, the lack of market standards, frameworks and policy certainty are resulting in an under-allocation of private risk-adjusted capital to develop CDR technologies at scale. Though the governments pioneering the sector have committed billions, this support has been supply-side dominant i.e., pump priming CDR projects. There is a need for concurrent long run demand-pull measures to be established i.e., that will encourage long-term offtake market signal, for example, an obligation on aviation fuels to have a Well to Wheel life cycle below a specific CO_2 threshold that requires substantial volumes of CDR to be realised in the long term [34]. Only then will off-take certainty of sufficient volume be created to allow the pricing of capital for supply-side projects to facilitate project finance and concomitant learning to be undertaken to reduce costs [35]. However, unlike past transitions at such an early state of establishment, such as for example support for renewable energy technologies where there was an existing electricity infrastructure and market, there is foundational work to do on the demand-side for CDR. This involves clarifying who is going to pay and how - is it fossil producers through a takeback obligation, consumers through a levy, society through general taxation etc.? Without a clear understanding of these core questions, the sector will struggle to advance further along a scaling pathway. There is a clear need for a new set of policy and governance requirements for the CDR sector in the period 2026–35 responsive to the new circumstances that the sector faces at its present stage of establishment. This will be essential to allow CDR policy to co-evolve on a pathway commensurate with the realisation of a $GtCO_2$ scale sector to achieve net zero by 2050. Policy design, prioritisation and implementation, however, require a new approach to work within this new paradigm; one that is very different to that of 10 years ago.

To adequately account for these complexities, decision makers need a new decision support paradigm. Traditional whole systems approaches, built on cost-optimization models, dominate the orthodox policy toolkit based on their important role in renewables and decarbonisation policy design. These are excellent tools for exploring aspirational pathways that meet energy and climate targets and are effective at providing insight into the provision of infrastructure and public goods at least cost from a whole system policymaker's perspective. On their own, however, they are unable to manage the extent of complexity inherent to the nascent CDR sector [36]. This inadequacy stems from the neoclassical economic assumptions that underpin these approaches i.e., that the resources of firms are mobile, that their foresight is perfect and that they maximise utility and profits. These assumptions are far removed from the complexity required to navigate the deeply uncertain possible futures that policymakers are designing CDR policies and strategies for - as has been evidenced in recent policy failures in analogous contexts across security [37], macro-economic inflation forecasting [38] and pandemic response [39]. This is also relevant in the case of the CDR sector's characteristics, where a range of factors are still unknown to decision-makers, there is a lack of reliable historical data, and as a result it is not possible to reliably quantify risks [40]. Consequently, decision-makers are incapable of effectively assessing the impact of policy interventions on firm's strategic investment decisions. This makes it particularly challenging to design policies that stimulate the allocation of resources by firms into an economically functioning and self-realising CDR sector [41]. The problem is further exacerbated in liberalised markets such as the US, UK and EU, which are leading nations in pioneering CDR sector development. In such economies, there is a need for decision support to generate nuanced and granular insights that are relevant to firm-level decision making by incorporating insights on skills requirements, spatially explicit economic mapping, land use planning, the behaviour of other firms/actors, and integration into existing and planned infrastructure systems. Indeed, any analysis which solely adheres to neoclassical techno-economic assumptions will result in policymakers being blind to actor and sector needs - potentially unintentionally distorting decision-making. This is evidenced in a review of decision support tools undertaken by the authors.[3] These include:

- Orthodox econometric optimisation tools, as described above, which serve as the reference for comparison as policy decision support tools which include UKTIMES [42] and MONET [43];
- Industrial metabolism which is an assessment of the whole integrated flow of materials and energy through industrial processes, transforming raw materials into their end products and generating waste and emissions in each step [44];
- Skills assessment for new sector development which can be based on a variety of tools. The three reviewed include Econometric Models: Input-Output Analysis Employment Factor Computable General Equilibrium Modelling; Data Models – Indicators; and Qualitative Methods [45];
- Land-use decision support tools including Geographical Information Systems (GIS), several approaches used in land use impact assessments, namely, Material Flow Analysis (MFA)/Input-Output Analysis (IOA), Environmental Impact Assessment (EIA)/Strategic Environmental Assessment (SEA) and Ecological Footprint Analysis (EFA), agent-based models (ABM), and Multi-Criteria decision making (MCDM) [46]; and
- Approaches for infrastructure co-ordination and planning - for which the National Infrastructure Systems Model (NISMOD) was reviewed [47].

Fig. 1 maps the capability gap between current decision support tools and the two categories of complexity shaping the CDR sector and the six additional requirements of policymakers seeking to establish a new sector across national economies. The gap between present approaches and the complexity characteristics of the CDR sector is substantive - especially for whole system optimisation tools. Furthermore, no single tool can address all features of complexity implying the need for a diverse suite of tools. For instance, skills requirement analysis across economic modelling, data indicators and qualitative participatory approaches provide significant insight at an aggregated level but lack granularity in terms of geography and application to specific skills or

[3] The ability for different tools to accommodate both the characteristics of the sector as defined by market-creation and market led complexity, to facilitate highly targeted interventions to stimulate `*firm*' level allocation of resources and realise economically functioning CDR value chains as prioritised by market actors from interviews were mapped by the authors to generate Fig. 1. This involved using reference optimisation tools: In this case, UKTIMES and the Modelling and Optimisation of Negative Emissions Technologies (MONET) models were chosen, due to their role in UK CDR policy design. These models were reviewed to see how they function, to identify what they omit in their analysis relative to CDR sector characteristics and policy design needs. Then tools and approaches to fill the insight gaps MONET and UKTIMES are unable to generate were then also mapped and surveyed based on a systematic search of available tools in the literature.

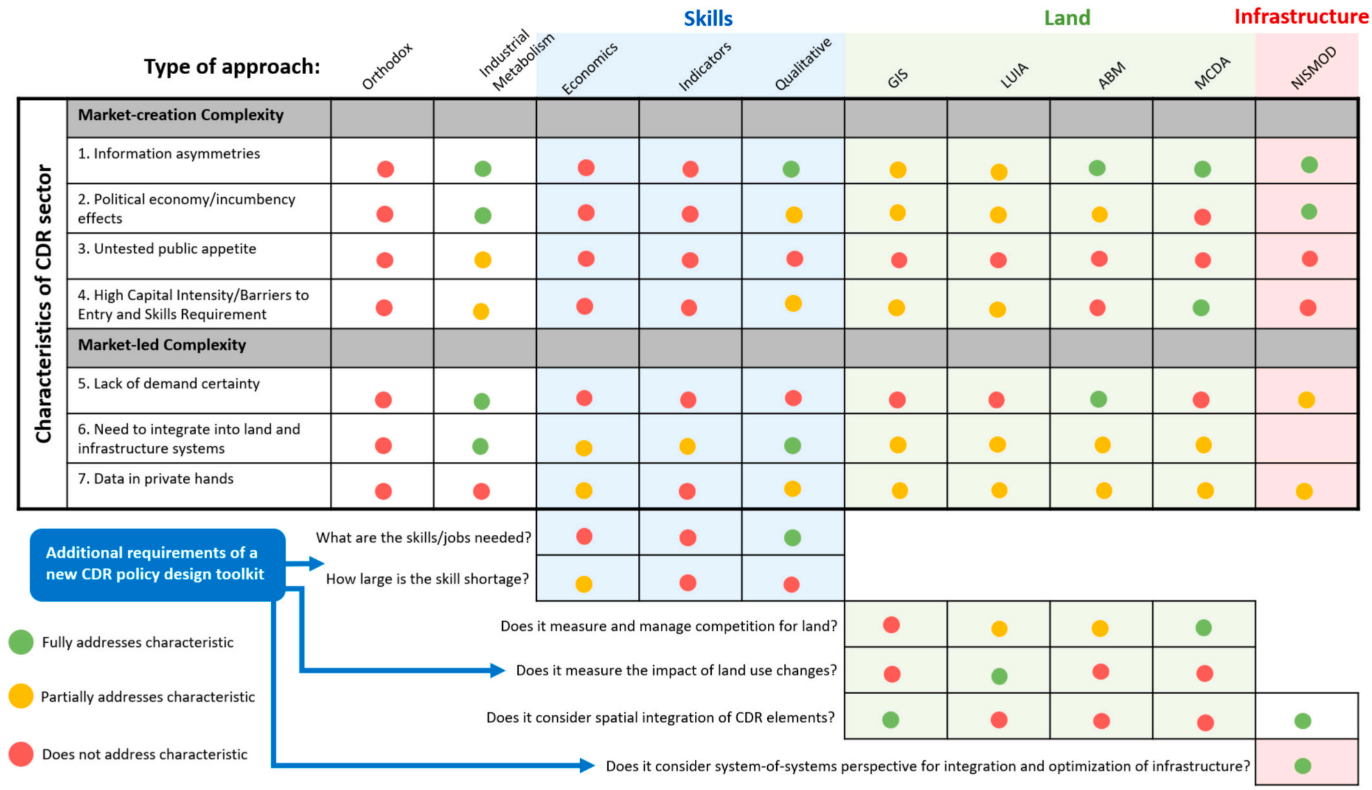

Fig. 1. Evaluation of approaches for their suitability for CDR sector policy analysis and design.
Key: Orthodox – whole system optimization and econometric simulation **IM** – Industrial Metabolism | **GIS** – Geographic Information System | **LUIA** – Land Use Impact Assessment | **ABM** – Agent-Based Models | **MCDA** – Multi-Criteria Decision Analysis | **NISMOD** – National Infrastructure Systems Model.

trades. Spatially explicit approaches partially address a range of characteristics, including untested public appetite and political economy issues. Approaches such as Agent Based Modelling (ABM) and Multi-Criteria Decision Analysis (MCDA) are particularly well suited to understanding the behaviour of other firms/actors in CDR value chains and the integration of negative emissions into existing and planned infrastructure systems e.g., NISMOD.

Developing a new paradigm will require decision-support tools that can accommodate ***both*** market-creation and market-led complexities.

4. New ways of working with *market creation* and *market led* complexity across sectors

Regardless of the specific policy analysis approaches adopted [48], the nature of complexity in the CDR sector requires participatory processes [49].[4] Approaches will need to facilitate participatory bottom-up definition of goals, values, potential policy options and uncertainties; modelling strategies; transparent identification of vulnerabilities; analysis of trade-offs; and co-development of strategies through opportunities for engagement across a diverse range of actors [18,50–52]. Novel approaches that can facilitate this dialectic two-way exchange process will allow CDR frontier actor needs to operate in lockstep with policy generation. This will allow policy to be designed to directly address specific actor needs, thus facilitating an approach to learning that captures multiple dimensions of technology instead of single factor learning assumptions [53,54].

Furthermore, the present CDR sector paradigm requires sufficient humility to recognise that the future is both unknown and unknowable. This case is also being made for renewables [55] and other sectors [56]. It recognises the need to move to beyond techno-economic centric analysis [50,52] - in that once a technology has reached a critical mass as to the volumes that are being added to the grid network - the systemic implications of the integration of those novel technologies then outweigh individual technology cost reduction in determining diffusion rates. For example, managing 1% of electricity grid generation which is intermittent solar and wind has negligible `system operating costs' whereas 30% is geometrically more burdensome on system operation and will have direct and indirect cost implications for system operators and market participants. We argue that this level of complexity has been realised much earlier in the CDR sector than decarbonisation in other sectors such as the integration of renewables into electricity systems. This, therefore, requires analysis for the CDR sector to ask a different set of questions now in order to replicate the trajectories of these previous transitions. Rather than using models to `predict' the future – analysts need to flip the traditional paradigm on its head and - use them to explore the decision that has to be made [15]. There is also the need to realise that generating probabilistic outputs when the decision space is steeped in such complexity is delusional. Instead possibilistic constructs need to be embraced by asking the following types of questions: *(1) What are the conditions that would affect how our current or leading strategies perform? (2) Under what conditions does our strategy fail to meet different stakeholders' goals? And (3) Are those conditions sufficiently*

[4] Pye et al., 2021 - identify three components of integrating decision support modelling from real-world sector insights to informing policy: (1) Scope Definition is the identification of modelling gaps in existing sector process, potential problems/concerns and uncertainties; (2) Function which evaluates whether the current models provide sufficient and relevant insights into system interactions, actor behaviour and policy implications; and Practice/Actor Interaction which examines how decision support tools, processes and approaches are applied in decision analyses. Identify key actions and special considerations regarding the implementation of the decision process. We argue that the present orthodoxy for CDR decision analysis tend to just focus on scope and often sidestep function and ignores the practice components and that there is a need for the new paradigm to integrate scope, function and practice requirements into a single organizing framework of analysis.

plausible that we should improve our strategy?

Recent approaches indicate that this is best undertaken by:

- Designing decision/policy portfolios and considering how ***feasible*** they are across multiple possible futures: The collection of future scenarios – comprising different combinations of uncertainties external to investment decision making - which should be as diverse as possible to facilitate the stress-testing of proposed policy packages and their impact on the CDR sector;
- Seeking strategies that are ***robust*** rather than \`optimal': Robust strategies perform well and are able to survive across a wide range of possible futures [56]; and
- Using novel computer visualization to ***engage*** stakeholders: This facilitates deliberation of systemic components integral to the establishment of the CDR sector from multiple parameters and allows consideration as to the implications of their trade-offs across stakeholder groups by emphasising uncertainties and capturing systemic issues regarding CDR deployment - see Fig. 2 (LHS), below for an example in contrast to Fig. 3 (RHS).

The visualization in Fig. 2 displays the outcome of an uncertainty analysis within a Robust Decision-Making (RDM) approach. It involves 144 scenarios with variations in CDR technology parameters based on the UK's Climate Change Committee's Balanced Pathway strategy for CDR in the 6th Carbon Budget (2032–2037) - which consists of 55 $MtCO_2$ of BECCS, 4.5 $MtCO_2$ of Direct Air Capture and the balance being made up of wood in construction. This approach brings stakeholders into the decision space where uncertainty is quantified across a range of metrics – in this case: water use; land-use; Technology Readiness Level (TRL); impact on UK electricity generation surplus margin indexed as a percentage - whereby a minus index means that the CDR demand for electricity will not be met – hence the greyed out lines as those scenarios are not feasible; emissions indexed to net zero – as in minus is surpassing net zero; and total cost of the CDR portfolio per year. The analysis highlights a number of systemic issues relevant to UK CDR policy, for example: the UK's technical CDR portfolio will require almost three times as much water as the UK residential sector consumes in a year – water sector capacity therefore needs augmenting to operationalize the portfolio; it will require a land footprint, including that to generate the feedstock of anywhere between 25% to 75% of UK landmass i.e., 6 to 18 MHa - which is likely impossible to source domestically and requires non-trivial logistics infrastructure to be developed for imports; the TRL of the UK CDR portfolio is ~6 which means that to get to commercial viability will also require substantial investment and policy support as TRL 6 to 9 is the most investment hungry phase of technology development and commercialization i.e., multiple billions rather than 10's of millions [58]; and most importantly, cost projections are subject to substantive vulnerability - ranging from £26 to 38 Bn/year.

This contrasts with the orthodox approaches as shown in Fig. 3 which obfuscate the extent of uncertainty that proliferates the establishment, development and scaling of a new CDR sector. Such orthodox analysis distorts decision and policy making by being insufficiently transparent as to the pervasive extent of systemic and exogenous uncertainties for CDR establishment and deployment. The different geographical focus of the data for Fig. 2 (UK) and Fig. 3 (global) do not change the implications. The key point is that the novel analysis we are suggesting in this article as exemplified by the RDM approach in Fig. 2 allows uncertainty to be more directly addressed than orthodox approaches as undertaken by Nemet et al. [57] - which tend to hide different sources of uncertainty. The novel analysis in Fig. 2 (LHS) by presenting the data in parallel axis plots helps stakeholders and decision-makers visualise and unpack how exogenous and systemic uncertainties might manifest for a CDR portfolio in an integrated framework. This allows stakeholders and decision-makers assess the vulnerabilities inherent in CDR portfolios and visualise the impact of the CDR portfolio across a range of metrics. These metrics emphasise and capture systemic issues regarding CDR deployment - additional metrics could be used to assess vulnerability for CDR portfolios relevant to different jurisdictions.

New approaches such as RDM and their associated visualisations rely on new types of engagement between the public and private sectors. This is particularly important given the market-led nature of the sector and the continued dependency of the CDR on policy interventions. As a result, public-private collaborations will be required for the next phase of CDR investment [59]. These types of collaborations will allow governments to guide the sector and provide backstop risk and uncertainty for private actors - thereby building on the grant-based, supply-side initiatives of the last 5 years - as was the case with Offshore Wind scale up with the Offshore Wind Accelerator. Furthermore, these types of collaboration allow a CDR technology-specific approach addressing the diversity of the CDR value chains and therefore the broad range of policy interventions required to backstop investor risk [60].

In combination, the application of a more participatory and dialectic

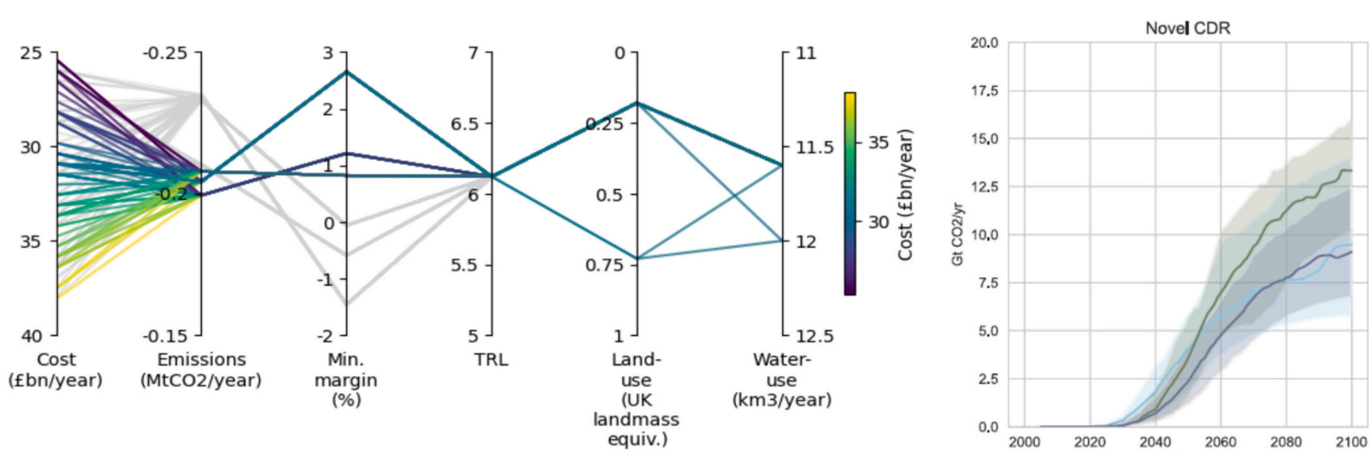

Fig. 2. ***(LHS):*** Parallel axis plot showing the outcome of the uncertainty analysis involving 144 scenarios with variations in CDR technology portfolio performance. Displayed are parameters for cost, emissions, ability for the electricity sector to meet the sector requirements, Technology readiness level (TRL), Land use footprint and water consumption per year for the CCC's Balanced Pathway strategy for CDR in 2050 associated with the realisation of the 6th Carbon Budget - for details see main text. Metrics are annotated with more positive at the top and east beneficial at the bottom. Costs are in £^{2020}. These plots, contrast with orthodox approaches which hide uncertainties - see Fig. 3 ***(RHS)*** which is extracted from [57] and shows global annual removal capacity for all Novel CDR Median plus p5–p95 range for <2 °C scenarios. Novel CDR includes DACCS, BECCS, and EW (only three scenarios with EW) for novel CDR deployment globally. Data are curated only for deployments after 2020 - see main text for further explanation.

set of processes for policy design and cross-sector approaches would address the main categories of complexity [61,62]. Firstly, the application of novel approaches would accommodate knowledge co-generation from market actors and reduce the potential for misaligned recommendations for policy design. For example, until an established demand curve is set for the CDR sector market-led complexity will remain. Therefore, any top-down extrapolation of learning curves based on other technologies which have an established market will be meaningless [57]. Indeed, multi-factor learning curves (MFLC) or bottom-up cost model (BUCM) development will be fundamental to the establishment of CDR technologies in the face of such complexity [35]. In such circumstances, context-specific drivers of learning will likely dominate, and this will remain the case for CDR and their associated technologies until there is a clear long-run demand curve for CDR. Until such time, context-specific factors would likely be useful to inform policy and will need to be harvested by government via such participatory and dialectic two-way processes with market actors. Otherwise, inappropriate lessons and insights will be developed.

Secondly, the need to integrate CDR value chains throughout the fabric of modern economies and the need for a social dialogue around their acceptability requires a systemic, cross-sector perspective including dialogue with stakeholders and audiences who are not usually engaged in net-zero. Novel dialectic approaches therefore offer a systemic perspective and a process for engaging in the co-production of challenges and opportunities across CDR sector actors. These in turn can be used to understand and identify the appropriate targeted innovation policy instruments required to incentivise actors along the value chain and their sequencing to ensure market confidence [63]. Targeting first movers and incumbents is particularly important, as their resources – financial, physical, human, organisational, informational, and relational – can be a barrier to systems change [64]. This is essential for a sector which seeks to retrofit value chains within existing economic sectors. Public-private collaborations would then share risk between sectors thereby establishing market confidence, experience in financing, conducting project legal due diligence and a pipeline of projects. This in turn would facilitate forward guidance as to how the sector is being shaped creating a trajectory for anticipatory investment whilst ensuring value for money for taxpayers. This need for anticipatory investment is not unique to the UK CDR sector [65] and likely requires new institutional and governance frameworks [66].

5. Conclusion

As articulated 10 years ago, the challenge of meeting climate targets is huge and the remaining carbon budget is now even more meagre, making it imperative to leverage all available technologies at our disposal to realise net zero. The societal cost of not doing so is too substantial and will be greater than if we act now [2]. Governments have brought CDR methods into mainstream climate policy opening up the landscape for market-led innovation and development by private sector actors. These essential initial steps have effectively started to integrate diverse technological approaches into the net zero socio-technical transition. There is now a need for governments to adopt a more diverse toolkit earlier than applied for renewables roll-out, one that can handle the features of complexity, ***and*** the associated process that can support engagement within and collaborations between sectors to work with deep uncertainty. This kind of approach will harness innovation across the public and private sectors, guiding and shaping the market and developing policy interventions that are tailored and timely to the imminent risks that CDR actors face. Rather than slowing down roll-out this approach would support CDR sector development ensuring that it can be robust across a range of possible futures. Applying exploratory approaches will also bring more clarity to critical questions concerning CO_2 off-take certainty. This clarity is integral to the policy design process and requires ongoing, co-creative stakeholder engagement rather than consulting stakeholders at the end of processes a is often the case at present. It will also foster much-needed business model innovation to shape the CDR sector and translate uncertainty into risk - through public-private collaborations. Only then will private investors be in a position to better price capital risk and therefore be more willing to invest in CDR commensurate with the needs and scale required to address net zero.

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CRediT authorship contribution statement

Mark Workman: Writing – review & editing, Writing – original draft, Visualization. **Aoife Brophy:** Writing – review & editing, Data curation. **Astha Wagle:** Investigation, Data curation. **Madison Cuthbertson:** Investigation, Data curation. **Lauren McCormack:** Investigation, Data curation. **Edoardo Taricco:** Investigation, Data curation. **Quillan Shaw:** Investigation, Data curation. **Jordan Calverley:** Investigation, Data curation.

Declaration of competing interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Data availability

No data was used for the research described in the article.

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