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Anticipatory Regulation: Lessons from fracking and insights for Greenhouse Gas Removal innovation and governance

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A B S T R A C T

The UK has incorporated a net-zero emissions target into national legislation. A range of Greenhouse Gas Removal (GGR) options will likely play a key role in the government's strategy toward meeting this goal. Governance frameworks will need to be developed to support GGR development and manage the potential impacts, particularly those on the diverse local communities where the various options will be deployed.

This research examines the UK's experience with development and regulation of shale gas - using the technologies of hydraulic fracturing combined with horizontal drilling - with a focus on governance and the implications for the development and widespread deployment of GGR. We evaluate the approach used against the principles of good governance, which emphasizes the critical role that local communities and publics play in deployment.

The UK's top-down governance of shale gas highlights the risk of regulation driven by assumptions about national and local need, value and a lack of transparency or meaningful stakeholder participation in decision-making. The use of existing legislative frameworks for conventional fossil fuel extraction proved inadequate to address unanticipated consequences such as induced seismicity. Moreover, the support for unconventional hydrocarbons in UK energy policy appeared inconsistent with the goal of meeting greenhouse gas targets and passing significant legislation in 2019 to bring carbon emissions to net-zero.

To gain social acceptance at the local level, deployment of new technologies needs to be evaluated from a variety of framings and viewpoints. Where new technologies or practices are deployed, such as fracking and GGR, the knowledge and understanding of the impacts - a fundamental principle of good governance - may be less certain or more contested. Early inclusion and participation of local communities would allow issues of concern to inform how trials are undertaken and regulation designed. This anticipatory and participatory approach fits with the principles of good governance and procedural justice, which can help build the trust needed to ensure social legitimacy leading to development and implementation of technological innovations.

1. Introduction

In June 2019, the UK became the first major economy to commit to bringing greenhouse gas emissions to net-zero [1]. Greenhouse Gas Removal (GGR) is increasingly recognised as crucial for the UK to meet these emissions goals [2,3]. GGR aims to remove previously emitted greenhouse gases from the atmosphere through biological or chemical methods, including afforestation, Bioenergy Carbon Capture and Storage (BECCS) as well as Direct Air Capture (DAC) and biochar [4]. Text Box 1 (below) provides a summary of GGR techniques.

The rate required of GGR development is unprecedented in the post-industrial era. New GGR innovations, often untested, are being developed [5]. In the UK, the chemical GGR sector is expected to grow from its current small - <ktCO$_2$ - scale to removing between 60 and 100 MtCO$_2$ per year in 2050 - equivalent to between 13% and 22% of 2019 emissions [6]. In October 2021, the UK government pledged that at least 5 MtCO$_2$ of chemical negative emissions will be deployed by 2030 [7]. Global estimates suggest that GGR operations could be similar in scale to the current oil and gas sector [8]. A substantial proportion of this capacity will need to be built and operational within the next 30 years and will likely continue to expand.

A sector at this scale will require multiple large industrial facilities and associated infrastructure, in addition to that required for abating emissions. Even familiar nature-based options such as tree planting will

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Text Box 1
Major GGR techniques.

A range of different techniques are being developed to deliver GGR. These vary from large industrial facilities to nature-based techniques, which will lead to modification or enhancement of existing land use. A mix of options is expected to be required as no option is likely to be capable of dominating [1].

Direct Air Capture - the design of which is emerging but is likely to require 10's of square kilometres of capture units and pipelines, along with pipeline and storage infrastructure.

Bioenergy with Carbon Capture and Storage (BECCS) - power station type facilities with CO_2 pipeline and storage facilities. Feedstock will be imported or require extensive land conversion to bioenergy crops.

Enhanced Weathering - operations similar to the UK's existing mineral mining, with the crushed rock spread on a regular basis across large areas of land.

Afforestation - a mix of commercial forestry and static mixed woodland. Tree cover across the UK is expected to increase by up to 50%. Land value and constraints on use mean planting will be spread unevenly. It could lead to some areas experiencing significant changes to their landscapes.

require substantial changes to land use and landscapes, and may lead to an increase in tree cover of up to 50% across the UK [1].

Many of the GGR methods long-established in the research literature have limited development with only a handful in the demonstration phase [9,10]. Much of the discussion about GGR has focused on the technical ability to scale-up processes to meet national need and the risk of displacing mitigation, rather than addressing where installations will be located and what they will look like. Little consideration has been given to understanding how the various proposals might affect and interact with the locations, cultures and communities of proposed deployment and the potential social impediments to deployment, including issues of 'social legitimacy' [11–13]. While attitudes to some aspects of GGR, and to the specific options that will be used, appear favourable, particularly nature-based solutions such as tree planting, it is unclear if attitudes to the chemical process, which require new industrial plants and supporting infrastructure, will be as accepted. Both nature-based and industrial schemes will change landscapes at a local and national scale.

The challenge is how to encourage the technologies that might solve a problem (carbon emissions and impacts) while also ensuring establishment of trust by communities in which they are deployed. For GGR, the governance and regulatory frameworks to support and manage these new and emerging techniques are fragmented or non-existent and likely inadequate. The temptation will be to retrofit existing frameworks without full awareness of the gaps in understanding of the potential impacts and the likely response of local communities.

1.1. Learning from experience

Experience with deploying other nationally important technologies highlights where failure to achieve balance between support and protection have led to disruption, delays, and unsatisfactory outcomes - including the suspension of implementation.

Large-scale infrastructure projects have mainly followed a top-down model, with policy and regulation determined centrally, often using existing governance mechanisms and frameworks, which in turn have informed the technology design and innovation.

Our concern, and the reason for this paper, is that previous experience has demonstrated the failings of this approach, where inadequate consideration of aspects of local deployment has led to disruption and delays, which action on climate change cannot afford. In many cases, attempts by industry and national governance partners to gain acceptance of the technology, or social license to operate, at the local level, were inadequate with the result that proposed activities encountered growing community opposition [14]. There is a need to learn from these experiences and to develop best practices in governance frameworks to regulate novel technologies.

Solar arrays and wind energy installations have faced opposition due to concerns over land use, neighbourhood noise or other nuisance, lack of understanding of the technology, concern over use of natural resources or for other reasons [15].

In Germany, Japan, and the Netherlands, for example, Carbon Capture and Storage (CCS) projects have failed due to local opposition and lack of public acceptance [11,16,17]. A CCS project at In Salah in central Algeria was stopped when CO_2 leaked into the local water supply, despite assurances that that the project was safe. Inadequate scientific and technical analysis of the local geology, and failure to incorporate the vulnerability and importance of the water resource in the risk assessment, resulted in failure to prevent contamination [18].

The attempts to introduce hydraulic fracturing, or *fracking*, in the UK by means of a top-down approach, which assumed the relevance of existing legislation was adequate for this novel technology, illustrates problems with the current strategy. This research examines how the UK government's approach to developing fracking in the UK emphasized the positive impacts - economic and energy security - but failed to ensure adequate consultation and protection of communities.

We contend that regulatory challenges and social issues that led to community distrust and lack of support for fracking can inform thinking on how to develop a robust regulatory framework to encourage scale-up of GGR technologies, for the following reasons:

- GGR similarly constitutes the potential for an emerging risk as it introduces a range of new and as yet untested technologies;
- Rapid adoption of these technologies is needed to meet climate targets, leading to potential for side-stepping protracted community engagement due to the urgency of deployment;
- Numbers and scales of installations are growing, meaning that exposure to risk from these events is also growing and more communities in the future may be situated in proximity to GGR value chains.

GGR technologies represent a substantive and disparate suite of technologies (as identified in Text Box 1), each likely with its own unique specific governance and regulatory requirements. This contribution considers the technologies as a generic group. While this might result in generalisations with potential for misapplication, it sufficiently highlights the need for anticipatory regulation and bottom-up community engagement. It is acknowledged that deployment of specific GGR value chains will take place in specific contexts, with each context likely having unique characteristics.

We explore the principles of good governance and how the approach used for innovation and deployment of novel technologies can lead to

better regulation and help inform the design of the innovation, and wider energy policy, leading to more positive outcomes. Using an adaptation of the principles of good governance from Lockwood and the UNECE Aarhus Convention as a lens, we evaluate how the regulation of fracking in the UK was developed and implemented and then benchmark it against the approach proposed for Anticipatory Regulation [19–21]. We assess how an Anticipatory Regulation approach to developing a future-facing governance framework for GGR could lead to the effective development of the UK GGR sector and embed societal concerns and protection into regulation leading to effective and accepted outcomes.

2. Methodology

The research aimed to understand how policy outcomes - in this case through the example of fracking - are affected by adequacy and appropriateness of a governance framework. The aim was to identify *normative or ideal* mechanisms for decision-making leading to optimum outcomes, and to consider *actual* practices and policy results and their impacts on communities [22,23].

The UK's experience with regulation of fracking offers potential lessons in the regulation of other new and developing technologies such as GGR. The methodology employed for researching the relevant case of fracking focused on Lancashire in the north-west of England, where the government has hoped to develop shale deposits. The local community, on the other hand, has engaged in protest to prevent development in response to episodes of induced seismicity and fears over potential social, environmental and health impacts [24–26].

Central to the methodology was an exhaustive literature review with searches conducted on regulatory schemes for oil and gas in the UK, attitudes toward fracking and ethnographic research undertaken in proposed fracking sites, and assessments of potential risks and benefits of fracking. Included in the evaluation were peer-reviewed research; government reports; UK, UN and EU legislation and policy documents; publicly available quantitative data on attitudes toward fracking such as the UK's BEIS annual survey; and grey literature, including media accounts. Site visits and interviews were conducted at Preston New Road, Lancashire. Interviews focused on the perceived specific health and environmental impacts of fracking; attitudes toward implementation of the technology; perceived gaps in current regulation; and public perspectives on the technology and potential positive and negative impacts nationally and locally [27].

The lessons learned from proposals to develop shale gas in the Lancashire region are used to evaluate the governance and regulatory gaps applicable to GGR, that are then assessed against tenants of the Anticipatory Regulation construct [21]. Details of the implications of the deployment of GGR in a local context were based on unique research involving 70 interviews and two workshops in which a total of 28 local stakeholders participated. This bottom-up engagement sought to explore the opportunities and risks of deploying a number of GGR value chains in the Leeds Yorkshire Region [13].

This contribution explores the recent and emerging literature as to how new technologies can be governed against Lockwood's [19] principles of good governance in Section 3; it also includes an explanation of the Anticipatory Regulation construct. Section 4 highlights the inadequacies of existing mechanisms and substantive knowledge gaps around the multiplicity of GGR value chains that are being considered for large scale deployment to meet net-zero. Most salient are the societal, community, local and other bottom-up impacts, which this research considers fundamental to good governance to realise the scale of GGR development needed in the UK. The impact of inadequate consideration of societal, community and local issues in UK shale gas development is then analysed in Section 5. This is followed by an analysis of the lessons that might be learned in the deployment of GGR in the UK from the shale gas discourse framed around the six tenants of Anticipatory Regulation in Section 6. Section 7 concludes the analysis.

3. Governing new technologies

Emergent and fast-moving sectors present complex regulatory challenges for governments, promoting incentives for innovation to capture the potentially significant benefits that these innovations can bring, while at the same time protecting environmental and public health.

Technological innovation tends to outpace governmental policy and regulatory frameworks as well as public understanding of risks and benefits of novel developments [11,13]. This may lead to technologies advancing faster than society's ability to adapt to and regulate them, with potential negative consequences if they are misapplied.

The emergence of novel technologies, such as fracking and GGR, often brings increased complexity and uncertainty. The issues this raises, as this analysis highlights, may go beyond the bounds of existing regulatory frameworks. This argues for thinking beyond existing approaches for developing regulation to include more novel and flexible strategies.

An effective approach for new technologies should seek to deliver social acceptance, which is based on building and retaining public trust. This should engage a wide group of stakeholders in a meaningful and inclusive way, and where publics and local communities are not 'framed out' of decision-making. As this research seeks to illustrate, when the principles are not present in decision-making processes, the result may be potential rejection of development or deployment of a technology by a community.

Stakeholders can be defined as individuals or groups with an interest in, or concern with, the proposed or on-going operations of the technology, following a *fairness-based* approach under which stakeholders have shared responsibilities and benefits [28]. Stakeholders may include - but are not limited to - local communities, other communities with concerns or opinions about operations, industry actors, other commercial or business entities, NGOs, governance and decision-making entities at all levels, compliance enforcers, and those who support and oppose development and deployment of these technologies.

A governance framework can include national regulation and policy, such as amendments to Acts and procedural requirements, and extend to national and local planning processes, which include mechanisms at national and local scale to collect and incorporate public response.

3.1. Principles of good governance

Various principles have been set out as to how to achieve effective governance systems.

In June 1998, the Aarhus Convention (UNECE Convention on Access to Information, Public Participation in Decision Making, and Access to Justice in Environmental Matters) was signed by 35 states and the EU [29]. It is anchored around three foundational 'pillars':

- access to information
- public participation in decision-making
- access to justice in environmental matters.

These pillars seek to ensure that members of the public and their representative organizations can and do play a full and active role in bringing about the changes in consumption and production that we urgently need to build a sustainable society [30]. Entered into force in 2001, this legally binding Convention seeks to ensure the right to access environmental information and public participation in decision-making is applied consistently within all signatory countries [29,31–34].

Lockwood [19,20] reframed these principles of *good governance* of natural resources to include legitimacy, transparency, accountability, inclusiveness, fairness, connectivity, and resilience. The framework emphasizes the ethics that underpin a system of governance, including 'anthropocentric values, human rights [and] duties, [and] ecocentric values' [19]. The framework draws on international documents including the United Nations 1948 Declaration on Human Rights, the UN's 1966 International Covenant on Civil and Political Rights, and the

Table 1
Summary of good governance principles and expected outcomes. Expected outcomes are the measures used to determine the extent to which these principles are observed to be present in governance.

Governance principle	Expected outcome
1. Justice, Equity, Social Legitimacy, Fair Balance of Power	■ Rights of stakeholders are respected; stakeholders participate fairly in decision-making ■ Governance considers needs and values of local communities ■ Partnerships among diverse local and national stakeholders ■ Well-defined and -functioning mechanisms to address potential power imbalances
2. Legitimacy or Acceptance of Authority by Stakeholders	■ Community demonstrates consent for activity proposed for local implementation (local social license to operate) ■ Communities accept decision-making authority of governing body ■ Decisions are made within local, national or international legal and policy frameworks and with respect for culture and social constructs of communities ■ Decision-making by governing body can be contested in fair, open and clear processes ■ Consensus achieved among the communities consulted
3. Transparency/access to Information	■ Information leading to decisions is accessible to all stakeholders in appropriate, clear, understandable and inclusive language and form ■ Rationale behind decisions and decision-making process is communicated clearly and comprehensively ■ Governance structures/hierarchies are clear and understood by stakeholders
4. Accountability	■ Decision-makers are accountable to stakeholders at all levels for decision-making processes and outcomes ■ Processes ensure policy is enacted with meaningful consideration of community's interests ■ Mechanisms for dispute resolution are well-understood
5. Inclusiveness	■ Stakeholders are defined inclusively ■ Vulnerable, less advantaged or marginalized stakeholders have access to information and ability to engage in decision-making ■ NGOs, groups and local stakeholders have access to information about decision-making processes and access to justice or mediation ■ The public is engaged in decision-making and public opinion meaningfully considered for incorporation in decisions
6. Integration, Coordination and Cooperation	■ Demonstrable communication and coordination between governance levels—community, region, national, international ■ Needs and intentions are communicated horizontally and vertically
7. Capability and Competence	■ Decision-makers have access to adequate information, including knowledge of local culture, social context, economy, decision-making frameworks and needs ■ Scientific or other 'experts' or stakeholders with specific (or traditional) knowledge are included in decision-making ■ Local decision-makers have adequate devolved authority to make meaningful decisions
8. Adaptability and Innovation	■ Robust mechanisms analyse/identify resources and skills needed for decision-making ■ Decision-makers assess new information and adapt approaches ■ Opportunities and risks are assessed; policy is amended or adapted ■ Changing needs and attitudes of stakeholders are anticipated and incorporated in frameworks
9. Respect for Human Rights	■ Environment and resources are protected for current and future generations ■ Human rights, including health, are protected ■ Right to access to energy is acknowledge and respected

UN's 2007 Declaration on the Rights of Indigenous Peoples [19].

Table 1 summarises the good governance principles, incorporating the Aarhus Convention into Lockwood's framework, and explicitly including human rights as well as power relationships and potential for power imbalances. Section 5 applies this framework to the UK government's management of fracking and provides insights into the regulatory challenges and gaps.

The ethical underpinnings of Lockwood and the Aarhus Convention acknowledge the importance of developing mechanisms to ensure environmental justice, applied to operations such as those of extractive industries or others posing potential risk. The key principles are:

- fair *distribution* of benefits and risks in activities
- fair and equal opportunities for all stakeholders in activities to *participate* in decision-making
- *legitimacy* or acceptance by all stakeholders of both decision-making processes and outcomes from those processes.

These are important determinants of the effectiveness of a governance system and the legitimacy or acceptance by all stakeholders of both decision-making processes and outcomes from those processes. The cornerstone or first principle of social organizations is *justice as fairness*, and thus is required for good governance, as proposed by Rawls [35].

3.2. Anticipatory Regulation

The Anticipatory Regulation approach proposed by Nesta (formerly NESTA, National Endowment for Science, Technology and the Arts) takes the elements of good governance and procedural justice further and embeds them in the governance of innovation [21].

The uncertainty associated with the emergence and deployment of new technologies and innovation requires a more inclusive approach based on the idea of gaining early insight into the factors that will affect deployment so they can be incorporated into the design stages with the intention of minimising delays, improving the governance mechanisms and, importantly, identifying opportunities to enhance the product and its supply chains.

Fig. 1 identifies three different roles for the regulator, based on the appropriateness of existing regulation for the management of new technologies [21]. These include an advisory role, where new products are introduced and need testing against existing regulations. While the product may be new, its impacts are expected to be short-term with fewer uncertainties. Adaptive approaches are appropriate when the regulatory bodies hope to encourage development of new products, but existing regulatory frameworks need adaptation. For technologies that are still in development or emergent, and their potential longer-term impacts more substantive, an anticipatory role is proposed. Here existing regulatory frameworks become harder to apply as the impacts are

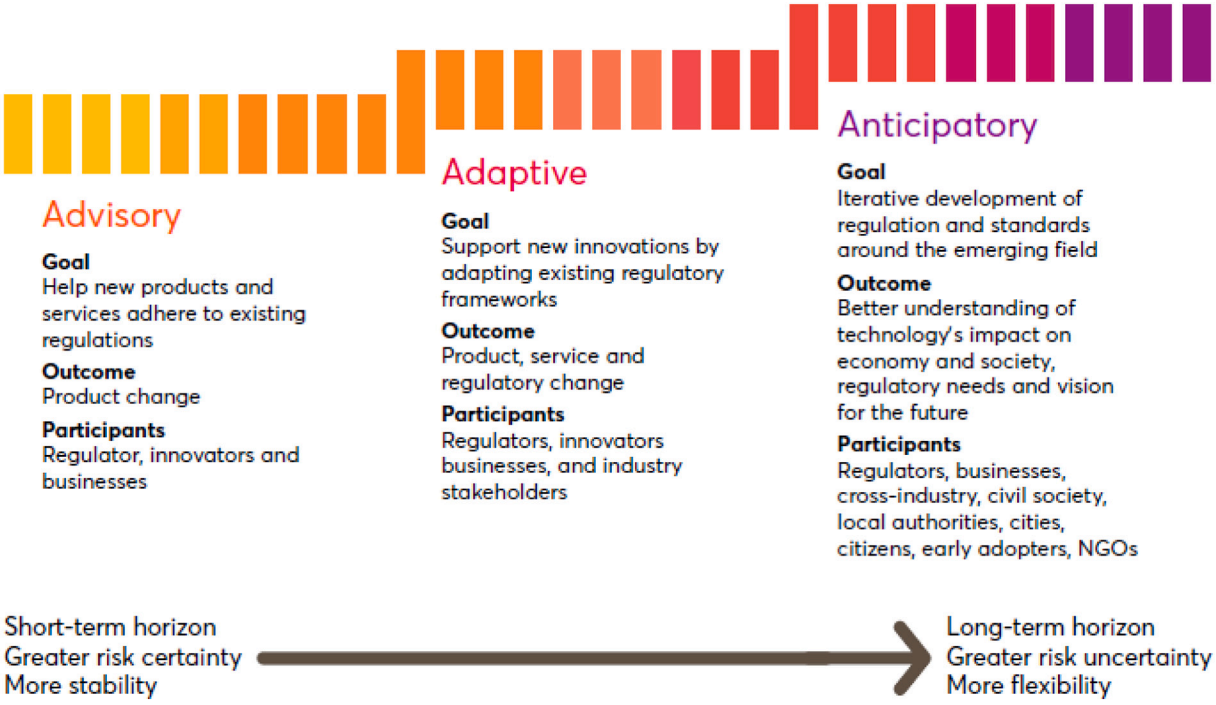

Fig. 1. The Advisory, Adaptive and Anticipatory Model of Anticipatory Regulation [21].

either unknown, or there is incomplete evidence.

Rather than the regulator acting as a gatekeeper to innovation by ensuring adherence to regulatory requirements, with supply and demand characteristics,[1] the anticipatory approach to regulation is based on flexible and iterative co-development and partnership between regulators, policymakers and innovators.

This evolution in regulation and policy making allows for better management of risk and uncertainty in innovation. Importantly, it requires a shift in the role of the State in the development of innovation policy, as summarised by Bakhski et al. [36] who advocate '*a learning-focused, network-brokering and information-discovery role for innovation policy, focused on the opportunities for, and constraints to, entrepreneurial action…It would seek to achieve the goals of innovation policy by, whenever possible, reducing uncertainty for entrepreneurs…[there will need to be] a more experimental conception of the role of the state…*'.

The importance of the 'State' in innovation, even in the most liberalised and unregulated sectors of the economy has been empirically validated by Mazzucato [37] and the co-generation with stakeholders of possible energy regulatory constructs is explored in Sandys et al. [38].

Anticipatory Regulation captures this in its six principles:

- Inclusive and collaborative - involve a wide range of stakeholders and provide platforms and information to enable deliberation. Platforms are physical and/or digital fora whereby communities and stakeholders can meet to discuss issues in a dialectic fashion. Information is data that can be transmitted through a variety of means including platforms.
- Future-facing - identify what factors will be important, how they might affect the outcomes, and how the factors interact.
- Proactive - provide open and accessible information and data and promote innovative ideas and space to test them.
- Iterative - enable a flexible approach to test and review proposals, rather than working toward a single solution.
- Outcomes-based - determine desired outcomes and measures of success and identify how to achieve them rather than focussing on rules that can constrain outcomes.
- Experimental - allow a diversity of solutions to be developed that can be adapted to the specific situation rather than determining generic rules.

These elements echo those set out by the Engineering and Physical Sciences Research Council (EPSRC) for Responsible Innovation, which are proposed as a means for researchers and innovators to evaluate the societal relevance of their activities and anticipate societal perspectives and values that might affect how the research or outputs are implemented [39,40]. The two approaches contend with similar issues, and Responsible Innovation can inform Anticipatory Regulation. While the participation and gathering of perspectives is important, building trust and social legitimacy is a key aspect of Anticipatory Regulation that requires demonstrating the impact of the concerns raised.

Responsible Innovation makes explicit mention of reflexivity and the importance of framing. This is picked up in other studies that note that the framing of a discussion affects the perceptions of the issues and in turn influences public acceptance of the technology [41–44].

A key part of achieving this is the early engagement with interested parties, including potentially impacted communities. Transparent information sharing and collaborative solution development provides the basis of procedural justice.

The anticipatory approach creates a platform where any issues or uncertainties - either at a national or local scale - can be identified early and integrated into the innovation and regulatory processes. To enable this requires a fundamental restructuring of existing engagement processes that aligns them more closely with the goal of seeking opportunities and developing solutions rather than creating potential barriers or constraints.

This shift embeds the participation of a wider group of stakeholders in the governance process. Early engagement aligns closely with the elements of procedural justice that underlie social legitimacy.

[1] I.e., where market service *need gaps* in existing regulatory constructs - the **demand** - are identified by innovators who then **supply** the value proposition which is vetted by the regulator.

4. The future of Greenhouse Gas Removal in the UK

In response to the Paris climate ambitions of remaining below a temperature rise of 1.5 °C, the UK enshrined a net-zero emissions target into law in 2019. GGR will likely be part of the government's strategy to address climate change.

Analysis by the Committee on Climate Change [1] suggests that even with aggressive mitigation efforts to achieve this target the UK will need a portfolio of engineered and land based GGR techniques to draw down about 100 million tonnes of CO_2 per year by 2050 to compensate for emissions from hard to abate sectors such as industry, freight transport and aviation.

Globally GGR is expected to reach the scale of some of the world's largest activities, such as the oil and gas sector and agriculture. At present, the combined CO_2 removals using chemical GGR amounts to less than a few tens of thousands of tonnes per year. It will need to expand rapidly to multiple $GtCO_2$ in the next 30 years. Any delay risks constraining the role of GGR in tackling climate change, putting greater onus on the effort to deliver emissions abatement.

Most analyses of the amount of GGR that could be delivered in the UK have taken a top-down technical and least-cost perspective. However, a unique study in Yorkshire highlights that a wide variety of framings and perspectives are needed to provide insights into the likely scale of deployment [13].

At the scale indicated by the UK Climate Change Committee (CCC), GGR technologies will need to be deployed extensively across the UK landscape. This will raise social, cultural and environmental issues in the local communities and regions, as well as questions about their social legitimacy. Yet, little is known about how the communities will respond as a function of this being an under researched area [45]. The limited deployment or intended development of large scale chemical plants have tended to be in remote, low populated areas, as for example the Climeworks plant in Iceland [46] and Carbon Engineering's plant in Texas [47].

What is known is that the technologies will interact with other key policy areas that are important to society, such as biodiversity, flood management and soil protection. The scale and breadth of each GGR technology means there will be a wide range of parties with varied interests and concerns. Any process will need to balance national and local interests. Afforestation, for example, will lead to wholesale changes to landscapes affecting land use, agriculture, and local communities. This drive for rapid land use change to tackle climate change will require a balance to be struck between priorities such as managing the biodiversity crisis, regional flood risks and local economic and cultural interests.

Social attitudes and perspectives may be altered by proximity to a GGR development. For example, while tree planting may be widely regarded as positive by the general public, imposing extensive tree planting and large monoculture plantations on local landscapes will lead to changes in farming practices and the utility of the land, which may affect the value of the landscapes and the cultural identity of the local community. Conversely, large industrial clusters forming around Carbon Capture Utilisation and Storage (CCUS) infrastructure may provide local employment but be resisted by national interests based on concerns about their feedstock, trust in the operators, or in the science behind geological storage.

The UK government's Ten Point Plan, published in 2020, promotes industrial clusters around a CO_2 pipeline infrastructure that services large emitters and GGR technologies, such as BECCS and DAC [48]. These are expected to grow around existing industrial areas. These will provide local employment and early engagement with local businesses can identify commercial opportunities and innovative solutions. While this may strengthen local support and social license to operate, it does not negate concerns over the safety of the CO_2 pipeline infrastructure, ongoing concerns about air quality, the potential for activity within the cluster to intensify and expand, and impacts of transportation for feedstocks and products. Such proposals also risk overlooking the indirect effects on energy demand and land use.

The rate and scale of deployment of GGR will be strongly determined by the social legitimacy of each option. If public concerns are not identified and addressed early, then each of the options - including large-scale tree planting - risks delay as aspects of their deployment are contested.

The complexity of the GGR supply chains, spanning several economic sectors, means it will affect a large number of different communities and interested parties. While there may be local issues that need to be considered for specific projects, there are common issues that will be contested for all developments, such as land use, where there is a pressing need to develop strategic guidance. Common concerns are also likely to arise for GGR options such as Direct Air Capture (DAC), where there will be aspects affecting infrastructure design and deployment and resource use.

The lack of awareness and understanding of GGR, and the various techniques, among the publics - and even those professionally engaged with climate change - is a substantive risk to deployment. As many of the GGR options are yet to be demonstrated, much of the knowledge is held by the developers, and may lack outlets trusted by stakeholders.

Uncertainty about new technologies undermines social acceptance and questions the motives of the developers. Provision of open and honest information, combined with a participatory approach, will allow a more informed debate of the issues. Developers along with national and local governments need to raise awareness and build capacity to allow engagement on carbon removal as a matter of priority. This suggests that the current requirement of a simple consultation will be inadequate, instead requiring a wider public approach that allows deliberation and builds a social understanding of the issues.

5. Framing fracking: the UK's regulatory framework for shale gas

Section 4 highlighted the extent to which the UK will seek to depend on a novel suite of GGR technologies - likely equivalent in scale to the UK water sector - to meet its net-zero targets. This will have to be undertaken in the absence of experience in establishing and scaling these technologies elsewhere. A $MtCO_2$ UK GGR sector will therefore have to be established and scaled in an untried governance and regulatory regime. The UK's experience with the regulation of hydraulic fracturing or *fracking* provides insight as to how the UK had introduced and intended to scale-up novel technologies in the past. The example highlights the potential inadequacy of *adapting* existing regulatory frameworks when impacts of the new technology are not fully understood, as well as the importance of a local community's role in the implementation of a new technology.

5.1. Fracking in the UK

Following the US's argued economic 'success' with extraction of shale gas, the UK government announced plans to develop its own resources, after assessment of likely viable deposits [49,50]. The UK government determines policy on fracking in England, with permitting and regulation devolved to the parliaments of Scotland, Wales and Northern Ireland. Wales' government is pursuing a precautionary approach, while Northern Ireland has devolved the issue to a future government, with a current *presumption* against the technology [50]. Scotland's government instituted a moratorium in 2015, followed by a Strategic Environmental Assessment and Business Regulatory Impact Assessment that included evaluation of statutes and consultation responses. Based on results, Parliament concluded: '… an unconventional oil and gas industry would not be of sufficient positive benefit to Scotland to outweigh its negative impacts' with the government confirming in 2019 that fracking would not be supported 'based on the evidence on impacts and the clear lack of social acceptability' [51].

Petroleum Exploration and Development Licences (PEDLs) for shale

gas exploration in England were first granted in 2008 [52]. Cuadrilla Resources began exploratory drilling in Lancashire in 2011. Unexpected earth tremors near Blackpool, however, halted operations to allow for study, with researchers concluding that fracking had induced seismicity [52]. The moratorium was lifted in 2012, as the government continued to be optimistic about shale gas. Seismic risk was addressed through a traffic light system (TLS) that required operators to exercise 'caution' in the event of *any* seismicity and suspend drilling with tremors above 0.5 on the Richter scale [53].

Cuadrilla began high-volume exploratory drilling again in 2018 but stopped after further tremors. In 2019 UK's government took a presumption against issuing further consents in England, which remains in effect.

In February 2022 Cuadrilla announced it would abandon fracking plans and permanently plug its wells in Lancashire, per government decommissioning requirements [54]. The UK regulator has since agreed to delay decommissioning: environmental groups have expressed concern that this might leave the door open to future drilling while according to Cuadrilla executive Francis Egan '…the regulator has taken the sensible decision not to abandon the UK's only two viable gas wells' [55].

The UK government had supported shale gas development as an 'urgent national priority' for energy security and economic growth, and as a bridge fuel with arguably lower carbon emissions until renewable sources can be produced at scale [56]. Fracking has been advanced as creating local jobs, accessing previously unavailable energy supplies, offering potential export income, and reducing dependence on coal [57]. The UK government's approach to regulation arguably grew from the position that fracking would indeed take place and that policy initiatives should support the technology; and that the *currently unknown* but *knowable* risks could only be understood by pursuing development [58]. Guidance was published on navigating the local planning process and financial help was offered to local planning authorities for processing applications [58].

Local communities where exploration has been proposed have argued that the decision was made because of national energy and economic interests without meaningful assessment of the environmental, social, political and economic contexts specific to targeted regions. This included potential damage to water sources in largely rural and agricultural regions, danger of increased traffic and risk of seismic activity [25,59,60].

A perceived lack of transparency in how fracking policy was enacted and an absence of meaningful and inclusive engagement of local communities in decision-making, resulted in collective action and organized protest by what Gullion [61] termed 'reluctant activists' [25,26,62–64]. Community opposition to what was initially the specific risk of impacts expanded to broader concerns over unfair decision-making processes [11,25].

The UK's experience with shale gas illustrates that a complex system of policies and procedures, argued inadequate exchange of information among stakeholders, along with unequal balance of power between local and national governments, can impede citizens from meaningful participation in decision-making. This is significant with respect to technologies with potential impact on communities and may lead to distrust in a government's ability to protect communities, which in turn can result in rejection of the technology [26,65]. There was also the perception that a required government report on shale gas and climate change had been withheld to '…help the oil industry' [66]. The public's distrust in management of risk in one sector, such as fracking, can lead to lack of trust in other technologies such as GGR [67].

While UK law and policy on land use planning (revised under the Localism Act 2011), requires public engagement, it has been argued that this process is not adequate to build community trust, social legitimacy and support for a social license to operate [13]. Moreover, access to information may not be fair and well-balanced. For example, local communities where fracking has been proposed may not be able to afford the cost of commissioning their own independent impact assessments, meaning they rely on evaluations commissioned by the government or industry partners, which may not identify potential risks to the community, including impacts on health and human rights and social and cultural values, or may not be trusted by the community [60]. This can be particularly significant when the government is strongly in favour of a project, as with fracking.

Permission to frack for shale gas involves complex requirements and processes under four separate national regulatory authorities[2] [26] - see footnote for a link to a fuller explanation of the planning and permitting process.[3] The process (updated 2019) begins with application for a license (PEDL) through the Oil and Gas Authority, and includes landowner consent, evaluation of environmental risk by the national Environmental Agency, and technical examination of well design but also local planning permission, which *may* require an environmental permit and consultation with the community [68].

While an analysis of the permitting process is beyond the scope of this paper, there is a substantial body of literature that describes the Lancashire community's perceptions of power imbalances between national and local levels, lack of accountability on the part of industry and the UK government, lack of access to justice, and unfair processes - all of which contributed to growing opposition to proposed operations [62]. In interviews conducted in Lancashire by Short and Szolucha [62], subjects described central government interference in local affairs and 'riding roughshod over local opposition' with changes to planning rules, perceived bias by planning officers in favour of the industry applicant, lack of procedural fairness, such as negative treatment of expert testimony when in opposition to an application, and a perception that the company was 'always given the last word' in hearings.

As part of the evidence collected in Cuadrilla Resource's appeal of Lancashire Country Council's denial of exploratory drilling permits, and included in a report of the government-appointed Inspector, testimony was provided about the potential climate impact of shale gas - a fossil fuel - in light of the UK's carbon goals [69]. This issue, however, was dismissed as a matter of national energy policy beyond the scope of the local planning board, and not relevant to the decision.

5.2. Regulation

Regulation of unconventional hydrocarbons in the UK falls mostly under the body of law designed for conventional resource extraction [27,31,59,70,71]. However, fracking poses unique risks - including seismicity and potential chemical contamination - with greater potential for health and environmental impacts, even during exploratory drilling [57,72,73].

This need to modify existing regulation is explicitly acknowledged as the UK government commissioned a Royal Society and Royal Academy of Engineering study [3] in response to earth tremors. The report recommended steps to mitigate a range of fracking-specific impacts, including groundwater contamination; well integrity; induced seismicity; gas leaks; management of water use; management of potential environmental risks; and recommendations on general oversight [3]. The report concluded that risks could be managed assuming that 'best practices are implemented and enforced' [3].

5.3. Government steps

Stokes [58] posits that the UK government adopted two distinct regulatory schemes in response to planned development of fracking: (1)

[2] Oil and Gas Authority (OGA), Environmental Agency (EA), Health and Safety Executive (HSE) and Mineral Planning Authorities.

[3] Process for hydraulic fracturing consent: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/591631/Hydraulic_Fracturing_Consent_Guidance.pdf.

'Regulatory domain' where current regulation is adequate and will not be modified significantly, under the assumption that fracking is analogous to conventional extraction; and (2) 'regulatory dexterity' where reform is needed to make fracking implementation easier through actions such as improved tax incentives, streamlined planning processes and easier access to land.

As public opposition increased, the government implemented strategies to engender public confidence in shale gas exploration [11,74–77]. A Shale Wealth Fund was proposed to persuade communities to accept shale gas by offering economic benefits through tax revenues from fracking. Also, the Shale Community Engagement Charter was established with the goal of promoting transparent communication between industry, stakeholders and local communities [78–80]. But while the Charter 'uses the language of engagement', Cotton [65] argues that the Charter is in fact more focused on information provision with limited feedback rather than meaningful participation.

Other proposed regulatory responses strengthened the pro-fracking position. The UK government in 2018 conducted a public consultation on whether 'major' shale applications should be included in the Nationally Significant Infrastructure Project (NSIP) regime, and criteria for determining which projects should be brought under the scheme [78,81,82]. If enacted, the change would mean that shale projects meeting the threshold would be solely approved through NSIP rather than by local Mineral Planning Authorities, thus reducing local control over potential operations.

The Infrastructure Act 2015 (modifying the 1998 Petroleum Act) was proposed to reform law relevant to shale gas [83]. Debate in Parliament was contentious between those arguing the need to make shale exploration easier and those advocating for strengthened environmental protections [84]. The final Act that passed Parliament inserted 13 new provisions (new clause 19), including mandatory EIAs for fracking; a ban on fracking in groundwater sources and protected areas; and required individual notification of local residents. However, the Act was weakened as the Secretary of State was given authority to define 'protected areas' and the requirements for individual notification and mandatory Environmental Impact Assessments (EIAs) were deleted [84]. The process included public consultations, in which 99% of respondents opposed a change to UK trespass law included in the Act that allowed access to hydrocarbons or geothermal sources without *consent* from or notification of landowners before drilling *underneath* their land at a defined depth [65,84]. The consultation was disregarded, however, with the government throwing out most of the public comments as an 'organized campaign' or not addressed to the specific question.

The UK government's policy on fracking has arguably incorporated industry self-regulation that may be inadequate, as evidenced by transgression of procedures and regulations [85]. Concerns identified in Lancashire included breaches of environmental permits and planning conditions, inadequate information provided by the operator, inadequate emergency procedures, and potential weakening of the traffic light system [85]. Moreover, according to Hawkins [86] the UK environmental permitting system was 'target based' meaning that industry could develop strategies and an oversight system, leading to public perception that there were no clear rules and enforcement mechanisms. This can lead to loss of trust in 'experts', a necessary condition for legitimacy [86]. The problem may become more acute with scale-up. The experience of the US highlights that overseeing many thousands of wells is not feasible, leading to reliance on self-regulation [71].

The example of fracking highlights how introduction of the new technology contravened the principles of good governance. We content that this illustrates what happens when a regulatory framework and top-down assumptions are imposed that do not account for the needs, values, and concerns of local populations [24,25,42,59,60].

This is especially important in the early stages of development of a new technology where the risks are unclear. While the government may hope to instigate research and development for important reasons, including meeting climate aims and generating economic benefits, if the local community is not part of the process to develop regulatory frameworks there is a risk that the technology will not be accepted [26].

Table 2
Summary of outcomes observed by the UK fracking governance process against principles of good governance.

Governance principle	Observed outcome
Justice	Community perception that decisions are top-down without consideration for local priorities and needs. Lack of demonstrable social license to operate by corporate entities
Legitimacy	National government ignored local governance authority by overturning Planning Committee decision
Transparency	Communities lacked adequate information on planned activities and potential risks/impacts
Accountability	Lack of accountability of regulators, complex regulatory process challenging to know who has responsibility, Infrastructure Act 2015 (changes to trespass laws)
Inclusiveness	Lack of meaningful local stakeholder participation in decision-making
Integration	Local governance is not well-integrated with national governance, as evidenced by hierarchical decision-making
Capacity	National governance lacks understanding of local context for decision-making. Local level lacks decision-making authority; lack of seismic/geological data, for example, led to inadequate information for decision-making/regulation
Adaptability	Demonstrable lack of consistent policy with fracking implementation. Lack of consistency with environmental targets. Unclear plans for shale gas regulatory transition post-Brexit
Human rights	Arguable lack of specific attention to human rights protections: risk to physical health and safety and mental health, access to clean water, environmental wellbeing, potential loss of safe shelter, and more. Regulatory adaptations arguably biased toward pro-fracking.

5.4. Analysis of regulatory outcomes in the case of UK fracking

This section and Table 2 summarise observed outcomes of the mechanisms used to deploy fracking in the UK within the framework of principles of good governance.

5.4.1. Justice

Justice refers to the real or perceived fair sharing of benefits and risks among actors, including local communities, and access to meaningful redress in the case of harm. Research has found that Lancashire communities: feared unfair police and industry surveillance of those opposed to fracking; felt powerless due to perceived 'collusion' between industry and the UK government; and believed that what happened locally would be meaningless as decisions would be made nationally [62]. The government's perceived intervention in overturning a local planning decision added to the community's perception of an unjust process [25,65]. Moreover, high legal costs, including costs of expert witnesses, impeded the right to appeal government decisions [62].

5.4.2. Legitimacy

According to Hawkins [86] how '…a decision is made, and its perceived legitimacy, is fundamental in determining whether a decision will be respected.' Lancashire residents reported 'little faith in the regulatory system' [25]. It was perceived that decisions rendered at the national level - such as overturning the local planning board decision - were not legitimate as they ignored local concerns. Moreover, studies of Lancashire found a perception of bias in the planning process, with the extractive industry viewed as favoured in the processes [62]. Residents also described a power imbalance due to corporate lobbying and a national government able to intervene to approve fracking permits regardless of local processes [62].

5.4.3. Transparency

Transparency in assessment of risks and benefits is necessary for a decision to be accepted [86]. Lancashire residents perceived that information was being withheld, including potential risks to health and the environment, by planning officials and industry [62]. Residents described that in public hearings, opposition experts were often treated unfairly and their opinions dismissed [62].

5.4.4. Accountability

Rules and penalties need to be clearly communicated and understood by all stakeholders to acquire social license to operate. The UK's system of regulation for fracking was highly complex, including new provisions added such as the traffic light system, with arguably inadequate explanation of accountability. There was the perception that government relied on industry self-regulation without clear rules and with inadequate policing mechanisms. Failures ranging from slowness in decommissioning and site restoration to inadequate emergency procedures were identified [85,86].

5.4.5. Inclusiveness

In Lancashire there was the perception that decisions were made by the UK government with inadequate participation of local community members [62]. Bradshaw & Waite [25] emphasize that the community perceived the benefits to be at the national scale, while risks were to be borne at the local level. Cotton [65] argued that public concerns over trespass law amendments were ignored and local council decisions overturned 'under the rubric of *nationally significant* infrastructure decision-making rather than locally significant environmental protection.' Despite the stated aim of increasing local responsibility in decision-making (such as through the Localism Act 2011), Short et al. [87] highlight the contradiction that the national government overrode local decisions to favour shale production.

5.4.6. Integration

The plan to integrate shale gas within the NSIP process reduced authority at the local planning level and, according to Cotton [65] is a 'national interest' justification for removing local decision-making. This is opposed to decision-making that shares power between national and local levels to ensure that benefits and objectives are shared and equitable.

5.4.7. Capacity

Decision-making on issues affecting community and environmental health requires access to accurate and complete information. In response to the 'lengthy' time it took the Lancashire County Council to act on Cuadrilla's permit application, the UK government mandated enforcement of a 16-week deadline for decisions [88]. This policy change, under the guise of streamlining the process, arguably reduced assurance that full consideration would be given to impacts of permit requests. Additionally, Short and Szolucha [62] argue that the report produced by the Planning Officer in Lancashire was '…suggestive of a pro-fracking bias' and failed in its responsibility to provide an accurate and reasoned summary of evidence, limiting the Council's capacity to judge the merits of the request for permit approval.

5.4.8. Adaptability

The ability to adapt to new research and findings on benefits and risks is critical in deployment of a new technology. The UK government's approach to fracking emphasized improving the environment for technical development rather than responding to potential risk, as regulatory reform was arguably focused on improving acceptability and easing development [58]. A UK CCC report contended that ramped-up fracking operations would breach the UK's emissions targets unless stricter regulations were enacted [89]. The government refuted the finding, claiming that the existing regulatory regime was 'strong' [90].

5.4.9. Human rights

Human rights include access to energy, with potential conflicting rights that need to be addressed in frameworks. Rights include protection from risk to human and environmental health, such as water use and pollution, seismicity, air quality, noise levels, as well as risks to mental health [62]. If environmental and health risks within a community are not addressed, there is the potential to violate rights such as access to clean water, clean food, shelter, health and more, as defined under such documents as the UK 1998 Human Rights Act that includes the right to life and protection of property, and the UN's 2021 recognition of the human right to a clean, healthy and sustainable community [91,92]. Short & Szolucha [62] describe symptoms of 'collective trauma' in Lancashire, with damage to individuals and community. Short et al. [93] contend that the close relationship between government and extractive industries means the need to enact specific human rights assessments to ensure protections - assessments were not included in the fracking approval process.

6. The UK governance gap for Greenhouse Gas Removal and Anticipatory Regulation

Work undertaken by Heap et al. [13], conducted in Yorkshire, provides insights on identifying the non-financial values, map value chains, and insights into local business models. The perspectives identified came from within the local communities and a range of interested and concerned parties. Applying the lessons learned to the principles of Anticipatory Regulation provides valuable learning as to how the deployment of new technologies, such as GGR, should be approached and the gaps in the current mechanisms filled - based on the UK's experience in establishment of a fracking sector [94].

Many of the financial and non-financial aspects will be contested by developers and commercial interests. Achieving legitimacy and gaining approval to deploy these new GGR techniques and transform the landscape will depend on *how* these values are negotiated and how fair and socially acceptable outcomes are derived. These will need to balance national, local and commercial interests.

The approach taken and processes used to negotiate the outcomes will be as important as the issues. This procedural justice, and the need for participatory engagement, needs to be embedded within the development processes, and planning legislation. This focus on procedural justice will help build trust and enable social legitimacy. In July 2021 the UK government issued a revised National Planning Policy Framework that incorporated elements of anticipation into the development of local planning, which look 15–30 years ahead [95]. The goal of the framework is to develop a sustainable approach to the planning system, with a major focus on expediting house building. Although it encourages engagement with publics particularly around aspects of local neighbourhood plans, the extent of engagement and how it is undertaken is unclear. It emphasizes the inclusion of factors such as biodiversity net gain, preservation of natural beauty, and climate action. While it encourages plans to include expected nationally and regionally strategic infrastructure, it is unclear what mechanisms need to be in place to accommodate emergent infrastructure that might present challenges outside the bounds of existing local and regional plans. It will be important to ensure that local planning mechanisms are appropriately resourced to allow them to remain participatory and adaptive to innovation and changing societal attitudes.

As such it can be stated that the current governance frameworks therefore make little provision for engaging stakeholders in the planning and development of GGR. Embedding procedural justice will require modifications to planning law to make its requirement more explicit, including Environmental Impact Assessments, expanding engagement, and ensuring well-informed participation. The current specifications allow developers to adopt a narrow interpretation of engagement, with consultations becoming mere 'tick box' exercises, with little indication of how and if stakeholder concerns have been addressed [11,13].

Table 3
Anticipatory Regulation requirements for GGR and what we learned from fracking.

Anticipatory Regulation	Requirement for GGR	Lessons from the fracking discourse	The governance gap
Inclusive and collaborative	Deploying the various GGR options will impact local communities and stakeholders in a variety of ways. Early expansion of the framing of projects and proposals means issues and opportunities can be identified so that solutions can be developed and incorporated into deployment. Participation and collaboration build trust, which is required for social legitimacy. At a national level, there are gaps in understanding of the impacts of this new sector, including on CO_2 emitters, other policy areas and sectors, and the wider social and environmental priorities. An inclusive and collaborative approach can bring these issues forward and develop the pathways to determine acceptable interventions.	Lack of meaningful engagement of wide and diverse stakeholders, notably local communities and missed opportunities to identify issues of concern at the local level. Lack of transparency and access to information by local stakeholders combined with limited and unsatisfactory opportunities to discuss proposed operations led to a 'framing out' of the public. Inadequate engagement led to decisions made without understanding or acknowledging needs of communities and undermined justice issues. Early lack of inclusion arguably led to a 'hardened' community position against fracking, and perceptions that decision-making excluded their input. The imposed regulatory regime reduced the potential for vertical and horizontal integration. Result was a lack of community acceptance of hydraulic fracturing	Current planning regulations are largely treated as a 'tick box' exercise, rather than as an opportunity to build trust, manage risks and stimulate innovation. Narrow framing of local consultations and national policy considerations can exclude valuable perspectives meaning that important issues are missed, and possible solutions and trade-offs are not considered. Inclusion means issues can be anticipated, and planned for, rather than being revealed unexpectedly during deployment. It is important to acknowledge at a national level the need for strategic understanding of the extent of possible interactions and the impact of this new and diverse sector.
Future facing	Deploying GGR will create local impacts and add another tool for CO_2 emitters to tackle climate change. However, there are many factors that will determine how it is eventually used and the relevant scale is reached. It is being deployed at a time of huge upheaval both in response to climate change but also technological, societal, and economic change. Understanding how things are changing or might change, both at a national and local level, will inform how GGR options are deployed and determine the policies and regulation that will be required to stimulate and manage them.	Regulation of fracking in the UK was conducted under an existing web of policies and laws designed to manage conventional hydrocarbon extraction and exploration. Thus, new risks, such as seismicity or impacts of large-scale developments, were not anticipated. The Traffic Light System (TLS) that would trigger operational slow-downs or cessations was initiated *after* unexpected incidents of seismicity were tied to fracking. Seismicity created public trauma that further hardened positions against fracking. Climate change impacts arguably were not fully considered in Secretary of State for Community & Local Government's overturning of Lancashire CC's decision to deny planning permission to Cuadrilla, although the likelihood of stronger climate action was recognised and therefore could have been anticipated from the outset. There was a lack of consideration of the risk of carbon lock-in, as regulatory modifications to address hydraulic fracturing assumed future hydrocarbons extraction [96]. The UK's decision to leave the EU may have implications for climate objectives and regulatory schemes that need to be understood and acknowledged in frameworks.	Environmental and social issues can have a significant impact on the outcomes of technical transitions. There is a need for foresight and futures tools to explore how these will impact infrastructure and policy decisions, more widely. Tools include horizon scanning and using future scenarios to explore the possible impacts. This will allow non-financial values, including environmental and social, to be integrated into decision-making.
Outcomes based	There are diverse opinions about what the expected outcomes that GGR, and the various specific techniques that are being developed, could achieve. This means the potential for companies to set or 'game' rules. A lack of agreement is leading to polarisation over which options are acceptable and therefore which should be deployed. This is creating uncertainty about the future scale of each option. An outcomes-based approach would allow more flexibility in response. This can allow companies room to be innovative in delivering the outcomes. The outcomes themselves will be commonly agreed and therefore resilient to change. Defining acceptable outcomes will shape the interventions and the institutions needed to oversee delivery.	Regulation focused on fracking, without considering the problem the technology was designed to solve. The UK's rule-based approach emphasized permitting procedures and regulation to speed up application of the technology, rather than equitable and socially acceptable *outcomes*. Additionally, the existing framework for conventional extraction was considered adequate to control risk. The framework did not begin with an overarching outcomes-based approach that would place resource extraction within larger-scale energy policy.	Processes are lacking to identify and define the outcomes desired from implementing and utilising GGR and from each of the various techniques that are being developed. This will help define what the regulator will expect to see. Participants can also define the actions should the outcomes be achieved or not achieved. An outcomes-based approach requires developing a new relationship between the regulator and regulated firms, requiring new supervisory and compliance processes. Developing an outcomes-based approach requires new skills to enable the processes.
Proactive	A wide range of options are being proposed and developed to deliver GGR. Innovators and developers need to be able to have open access to regulators to access advice and explore the existing or potential regulatory landscape. The novel challenges and cross-sector nature of many of the GGR value chains cross existing regulatory frameworks. Regulatory implications may not be apparent to innovators and developers, or it may not be clear who is the regulator.	Regulation was reactive rather than proactive, playing 'catch-up' to the technology, which led to risks that were not anticipated. Additionally, regulatory modifications were directed toward supporting fracking's development, with the assumption that existing regulatory structures were adequate to manage fracking that was viewed as analogous to conventional extraction [58].	Regulators need to engage proactively and continuously with innovators to understand the innovations and track emerging issues. Regulators should be able to think and act beyond the existing frameworks. This will enhance the support but also help identify gaps and anticipate the types of intervention that might be required to manage any risks. There is a need to develop creative approaches to addressing issues and identifying regulatory response. Regulation can be used to stimulate innovation where challenges persist.

(*continued on next page*)

Table 3 (*continued*)

Anticipatory Regulation	Requirement for GGR	Lessons from the fracking discourse	The governance gap
			There is a need to address issues early to encourage acceptability and reduce investment risks.
Iterative	Many of the GGR techniques that are being developed are novel, which brings a range of uncertainties such as their impacts, the market mechanisms needed, and science and technology gaps. The implications may be hard to bound. The novelty of the sector and the pace of change may lead to further innovation and unknowns. The development of GGR options means new issues may emerge. Ongoing engagement is needed to address issues and to test and develop responses and solutions either virtually or physically. Solutions that have been co-developed need to be tested. This allows experimentation on how to address issues and uncertainties. Transparent presentation of the findings of the test to the community for review is needed for granting or withholding of social license to operate [25].	Much of the strategy that concluded existing frameworks were adequate quoted the 2012 Royal Society Report, that fracking was 'safe', without incorporating new data and perspectives meaningfully [3]. There was a lack of updated and comprehensive baseline data of both environmental and social issues. The approach was not iterative to solve new and evolving problems such as changing community dynamics and changing environmental conditions.	Developing regulations and governance for novel techniques can be difficult as the uncertainties make it hard to capture and accommodate all possible outcomes. Mechanisms to support and manage the emerging GGR sector need to be iterative to accommodate new issues as they emerge. Many of the options are still in development and their wider impacts have not been fully explored. As new techniques emerge, they may bring uncertainties. Clarity is needed over the processes involved and how emerging issues will be managed. This includes the criteria for review and for closing off issues. Without this it will create additional uncertainty for the stakeholders and parties involved.
Experimental	GGR techniques often have few existing regulatory parallels, and in many cases, their value chains cross several sectors. Existing regulation and governance may be inadequate to address the range of issues, or not applicable. New governance and regulatory frameworks will be needed. An iterative and collaborative approach should allow experimentation to identify novel solutions to be explored and developed.	The government's approach relied on regulation of *conventional* oil and gas with a focus on permitting and planning, which prevented development of more robust and diverse regulatory responses. The strategy did not encourage or *imagine* alternatives to fossil fuels. Lack of transparency and data sharing between industry and academia meant limited experimental approaches.	The current governance frameworks for GGR are fragmented or non-existent. Opportunities might be missed, and risks emerge if the options are segmented so as to allow existing policies to be applied or to avoid wider assessment of the technology being deployed. The wider context and implications of a technology can have significant impact on its legitimacy.

Procedural justice is based on interested parties having access to information that allows them to make an informed response. This needs to be based on wider awareness of GGR in order to allow a more informed response to potential impacts. This requires a strategic co-productive approach that convenes the various interests and explicitly addresses these issues face to face to build trust, social legitimacy, and new institutional capabilities. By working across sectors and interests, a co-production approach will raise understanding, inform the development and design of the proposals, and help identify and operationalise any opportunities it can bring to the communities and overcome the perceived barriers to GGR establishment and scaling.

An Anticipatory Governance approach to developing the necessary frameworks will ensure the breadth of issues are captured early. Participatory engagement will promote recognition of the different needs, allowing responses to be co-produced and fairness in the solutions ensured, engendering the trust that underlies social legitimacy.

There is additionally the potential for commercial opportunities and innovation to emerge from the process as local business and industry are engaged. Therefore, rather than being a hurdle to deployment such an approach can add value to the proposals, promoting social legitimacy and opening new opportunities. Understanding the opportunities and challenges and how to enable or resolve them will give a clearer picture of the potential role that GGR will play in addressing climate change and meeting net-zero targets.

The table below describes the key elements critical for developing Anticipatory Regulation and highlights the lessons drawn from the experience with fracking relevant to GGR regulation (Table 3).

7. Conclusions and policy implications

Climate change will require substantial modification to our infrastructure and the deployment of a suite of new technologies, such as carbon removal, that will require technical, policy and regulatory innovation to take place at the same time. These will all have an impact on local communities. The experience of the UK's regulatory approach to hydraulic fracturing highlights that a technology may be deemed to be important on a national need and economic basis, but failure to engage early with the local communities and accommodate their concerns could lead to delays and ultimately jeopardize any form of deployment.

The UK's experience with shale gas highlights the implications of perceived reliance on industry self-regulation rather than clearly defined and understood rules and penalties. Furthermore, assumptions that existing legislation could be used and adapted to support the introduction of the new technology of fracking proved flawed, as implications of new risks were not anticipated adequately. The top-down approach adopted to support the development of fracking meant that the concerns and decisions of local authorities were disregarded. This failure to take a proactive approach to inclusion and collaboration, undermined trust and led to a loss of social legitimacy.

Early research evidence indicates that the deployment of GGR will raise a wide range of issues among the local communities and interested parties that will likely require regulatory interventions. The uncertainties and complexity presented by the deployment of novel GGR technologies means new regulatory frameworks will need to be developed. The scale at which GGR will need to be deployed to meet our net-zero targets will raise environmental and distributional justice issues. A proactive and inclusive approach will be necessary to anticipate the issues that arise so that they can be addressed early. This requires a participatory approach to enhance the ability to anticipate issues and to co-develop solutions. Adopting an iterative and experimental approach will help accommodate the uncertainties and address the issues that arise. These issues will be substantive as GGR approaches range from solutions that are nature-based to those that require chemical infrastructure - each having its own specific requirements with differing levels of emphasis depending on the distinctive local context within which it is deployed. The very nature of the application of bottom-up insights will systemise the revealing of these requirements as GGR value chains are deployed. The approach identified for Anticipatory Regulation provides a valuable framework for how this could be achieved.

There are indications that the need for a more forward looking, participatory approach is being recognised within government, but when applied to emerging technologies the process needs to remain

dynamic, iterative, and able to adapt to accommodate new scientific findings and knowledge, and respond to changing societal perspectives and attitudes.

Declaration of competing interest

The authors, Miriam Aczel, Richard Heap, Mark Workman, Stephen Hall, Harry Armstrong and Karen Makuch declare that there is no conflict of interest.

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