GREENHOUSE GAS REMOVAL
RESEARCH PROGRAMME

UK GGR Research Programme
Policy Brief

Comparative assessment and region-specific optimisation of GGR

Summary

Achieving the ambition of the Paris Agreement will require greenhouse gas removal (GGR) at a large scale, particularly to address residual emissions from those sectors that are difficult to decarbonise.

Conceptually greenhouse gas removal (GGR) has become an important part of the integrated assessment models (IAMS) that predict and inform how we can remain within the 1.5°C global temperature rise target. In reality there is some way to go to put GGR into practice effectively to meet these goals.

Countries vary in their GGR portfolios and their resources to deploy GGR. The ways that different GGR pathways work together in different regions in the context of evolving energy systems and policy landscapes need to be assessed and incorporated into IAMs.

The 'Comparative assessment and region-specific optimisation of GGR' project has researched the feasibility of the more mature GGR approaches and assessed how the balance of cost, CO_2 removal and environmental impact will influence the capacity to scale GGR nationally and regionally.

Researchers have explored options for allocating the responsibility for GGR and assessed the role of collaboration in GGR deployment. Results show that full inter-regional collaboration would lead to the highest chance of meeting global GGR targets at lowest cost.

By assessing the implications of delaying action on GGR, the project has estimated that each year of inaction in the EU would cost an additional 120 to 190 billion EUR2015 to remove 50 billion tonnes of net CO_2.

The ways that different GGR pathways work together in different regions in the context of evolving energy systems and policy landscapes need to be assessed and incorporated into Integrated Assessment Models

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There is need to inject more reality into the portrayal of GGR in current integrated assessment models and for the models to reflect the dynamics of how GGR will evolve with energy and policy systems over time.

The use of equality principles to frame responsibility for undertaking GGR is in line with current messaging around reaching net zero and provides a framework for collaboration which will be essential to deploy effective and efficient GGR.

Relatively mature GGR approaches such as Bioenergy with Carbon Capture and Storage (BECCS) can make important contributions to net zero emissions but require international supply chains to be feasible, efficient and sustainable. Trade-offs do and will exist between environmental impacts, CO_2 removal and energy production but these are not impossible to navigate and demonstrator projects can help establish what these routes will look like.

Time is of the essence: the longer we delay the deployment of GGR the more intensive it will need to be to remove the necessary amount of CO_2 within a required timeframe and this will make it more costly. There will always be uncertainty surrounding the effectiveness and efficiency of GGR and scientific research will not be able to eliminate this completely. What could help is some indication from policy makers on what is essential for them to know before they can take action to deploy and scale-up these technologies.

Trade-offs do and will exist between environmental impacts, CO_2 removal and energy production but these are not impossible to navigate and demonstrator projects can help establish what these routes will look like

1. Integration of GGR into global models and national targets

1.1 Definition of GGR

GGR must be understood and adopted in the same way across research, policy and practice, and across different countries. GGR differs from carbon dioxide removal (CDR) in that it refers to the removal of all greenhouse gases, but the terms are interchangeable when focussing on CO_2.

According to the Zero Emissions Platform (ZEP) carbon dioxide removal is the physical removal of CO_2 from the atmosphere in a manner intended to be permanent (see box 1) (Zero Emissions Platform, 2020). Key to this definition is that the CO_2 is not avoided or displaced but physically removed and that strategies should be in place to prevent and account for CO_2 returning to the atmosphere.

1.2 How has GGR been incorporated into IAMs so far?

Recent assessments by the Intergovernmental Panel on Climate Change (IPCC) highlight a key role for large-scale carbon dioxide removal to achieve net zero emissions targets. Scenarios with negative emissions technologies (NETs) were included in IPCC's fourth assessment report and large-scale NETs are part of the fifth and sixth reports.

The models informing these reports have focussed on relatively mature forms of GGR such as BECCS (Minx et al., 2018). GGR approaches such as Direct Air Carbon Capture and Storage (DACCS), ocean fertilisation and enhanced weathering still have to find their way into scenario literature (Fuss et al., 2018).

There is variation in the estimates of the amount of cumulative CO_2 removal that is required to meet temperature targets by 2100 and they range from a few hundred to over a thousand $GtCO_2$ depending on pace and extent of efforts to mitigate climate change (Fajardy & MacDowell, 2020). It is unlikely a single approach can achieve this level of removal, meaning that portfolios of NETs will be necessary (Fuss et al., 2018). Further efforts are needed to integrate a wider range of GGR options into models (Pozo et al., 2020).

1.3 Is there a way to allocate responsibility for GGR?

The process of allocating responsibility to undertake GGR amongst regions will be important in acceptance of quotas.

Taking BECCS as an example not all regions are equally endowed to sequester CO_2 or produce

Zero Emissions Platform principles for defining Carbon Dioxide Removal

1. Carbon dioxide is physically removed from the atmosphere.
2. The removed carbon dioxide is stored out of the atmosphere in a manner intended to be permanent.
3. Upstream and downstream greenhouse gas emissions, associated with the removal and storage process, are comprehensively estimated and included in the emission balance.
4. The total quantity of atmospheric carbon dioxide removed and permanently stored is greater than the total quantity of carbon dioxide emitted to the atmosphere.

BOX 1

sustainable biomass. North America, Latin America and Russia have the highest potential for energy crop production on land that has been set-aside from agricultural production. Regions also vary in their capacity to store CO_2 underground in geological formations: it is estimated that the US has over 8000 $GtCO_2$ storage whilst in India there is 50 $GtCO_2$ storage (Fajardy & MacDowell, 2020). Uncertainty exists around the estimations for storage capacity and there is variation in the level of uncertainty.

The distribution of the burden for GGR to different regions and nations will depend on the rationale behind removing CO_2. If a more retrospective perspective is taken to offset past emissions this will skew the position of the responsibility towards more developed countries. If the proposed rationale behind GGR is to compensate for today's increasing emissions then responsibility to undertake GGR will be more equally allocated. Nationally determined contributions to the Paris Agreement do not mention CDR targets, leaving open the question of how and by whom CDR will be delivered (Pozo et al., 2020).

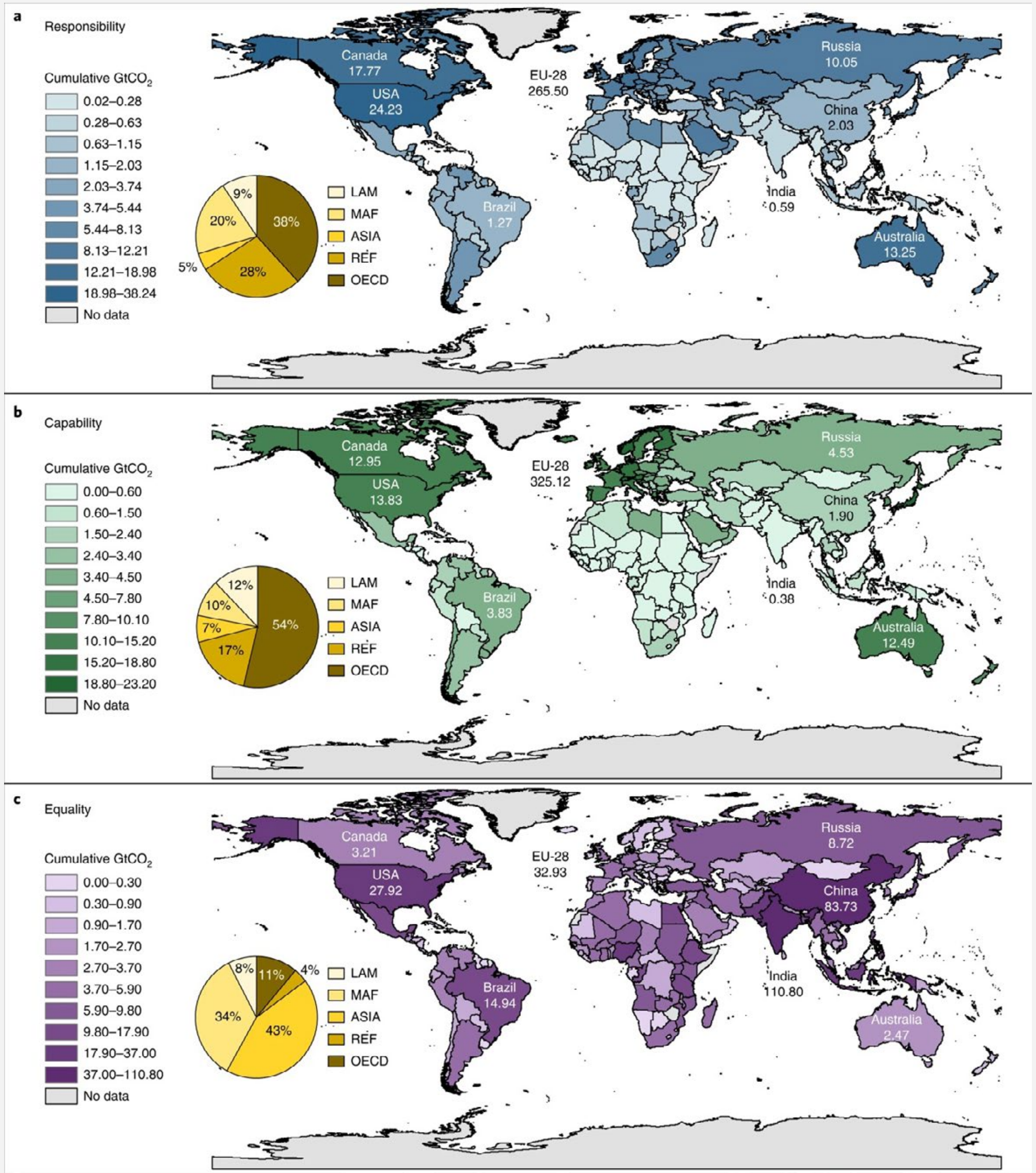
The allocation of CDR quotas can draw on burden-sharing principles that have already been used to allocate mitigation efforts and burdens among UNFCCC parties from 2017 – 2019. The principles revolve around Responsibility, Capability and Equality (see box 2) (Pozo et al., 2020).

Principles of allocation

BOX 2

1. The responsibility (or proportionality) principle relates liability for climate change damage with responsibility for its solution. CDR efforts would increase with greater accumulated historical emissions.
2. The Capability (or ability-to-pay) principle establishes that countries better able to solve a common problem should contribute more, which implies wealthier countries are assigned a greater share of CDR efforts.
3. Under the Equality (or environmental justice) principle, every individual should have the same right to be protected from pollution. Hence, equal CDR per capita is here enforced across countries irrespective of current (or past) emission levels and economic capability.

If the proposed rationale behind GGR is to compensate for today's increasing emissions then responsibility to undertake GGR will be more equally allocated



Taking a mid-range global target of 687 $GtCO_2$ removal by the end of the century and considering DACCS, reforestation and BECCS as the modes of removal, research has estimated how each of these principles would allocate responsibility of GGR to 176 countries.

Using the responsibility principle seven countries would shoulder a quarter of global CDR effort whilst for the capability principle it would be six of the wealthiest countries accounting for 21% of the cumulative CDR efforts. Under the equality principle, five of the most populated countries would be allocated 41% of the cumulative CDR (see figure 1).

FIGURE 1: **Cumulative CDR quotas by 2100 for UNFCCC countries according to the three principles of allocation:**

a) responsibility
b) capability
c) equality.

Countries are coloured according to their quota so that the darker shade, the larger the quota and more CO_2 removal is needed (countries in grey no data available). Pie charts show results aggregated into five regions: OECD countries as of 1990, REF (reforming economies of Eastern Europe and Former Soviet Union), ASIA (Asian countries with exception of Middle East, Japan and Former Soviet states, MAF (Middle East and Africa), LAM (Latin America and the Caribbean) (Pozo et al., 2020).

Due to biophysical limits, only a handful of countries could meet their allocations if they were acting individually and using natural afforestation and BECCS. If we are to approach targets within the frame of compensating for today's rather than yesterday's emissions then equality principles may be appropriate and this is one of several recommendations for allocation for GGR provided by researchers(see box 3).

Recommendations for allocation of responsibility for GGR

According to researchers (Pozo et al., 2020) the allocation of responsibility for GGR should:

- be transparent
- be separate to mitigation targets
- be based on common objectives
- consider technical limitations
- use equality principles
- happen soon

BOX 3

2. Assessing technical performance of GGR technologies

2. 1 Scaling-up CO_2 removal to a global level

A review of research has shown that the global upper bound estimate of annual CO_2 removal is 12, 10, 6, and 5 $GtCO_2$ per year for BECCS, DACCS, land management (such as preventing deforestation, reforestation, afforestation, and tillage practices) and weathering/mineral carbonation (see figure 2). In the case of DACCS, global data on reliable CO_2 storage opportunities were unavailable, and the potential upper bound estimate is considered conservative. Summarising across these GGR technologies, the review estimates a total value of 35 Gt of CO_2 that can be removed per year (Psarras et al., 2017).

Based on a later review of the literature (Fuss et al., 2018) the estimates appear to be more varied and conservative. Best estimates for sustainable global potential for negative emission technologies in 2050 are 0.5–3.6 $GtCO_2$ per year for afforestation and reforestation, 0.5–5 $GtCO_2$ per year for BECCS, 0.5–2 $GtCO_2$ per year for biochar, 2–4 $GtCO_2$ per year for enhanced weathering, 0.5–5 $GtCO_2$ per year for DACCS, and up to 5 $GtCO_2$ per year for soil carbon sequestration. Costs vary across technologies, as does the permanency of the removal and the cumulative potential for removal as they go beyond 2050 (Fuss et al., 2018).

There is need to consider both the strategic evidence from climate change mitigation models that project the potential for GGR based on biophysical understanding and the bottom-up evidence from engineering and social science disciplines on the practicalities around deploying technologies and public acceptance. Research is needed to bring these different disciplines together and consider the technicalities involved in different GGR approaches and the capacity for GGR at a regional level.

2. 2 Can BECCS deliver negative emissions and produce energy?

2. 2. 1 What is the energy return on BECCS?

BECCS is unique in that it has the potential to provide both carbon removal and electricity. Implicit in IAMs is the assumption that BECCS is a net producer of energy, but this may not hold at scale due to energy intensive supply chains and low power generation efficiency (Fajardy & MacDowell, 2018).

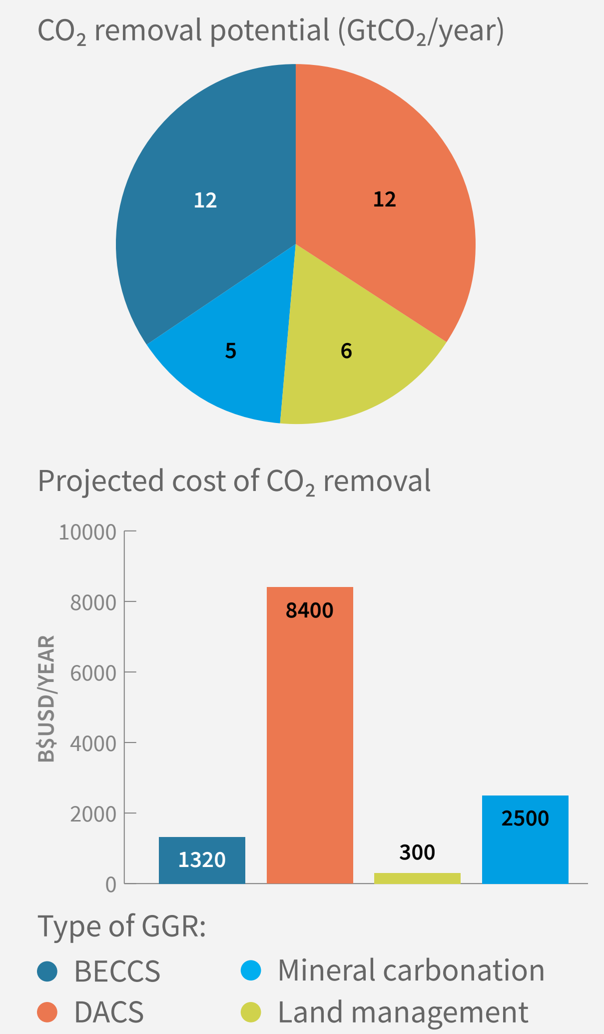


FIGURE 2: **Impact of various CO_2 removal strategies (Psarras et al., 2017). Relative CO_2 removal potential per year (above) and projected cost of removal (below) using cost estimates from National Academy of Sciences (National Academy of Sciences, 2015).**

Researchers have used the MONET framework (see box 4) to estimate energy produced by converting feedstock in a 500 MW BECCS facility in the UK using either domestic or imported biomass pellets from USA. Depending on the scenario, the energy value from BECCS could range from being negative to being competitive with renewables such as photovoltaic.

For BECCS, there is a trade-off between annual carbon removal potential and power generation so deployment will depend on which service provided by BECCS is most valued.

MONET (Modelling and Optimisation of Negative Emissions Technologies)

BOX 4

The MONET framework:

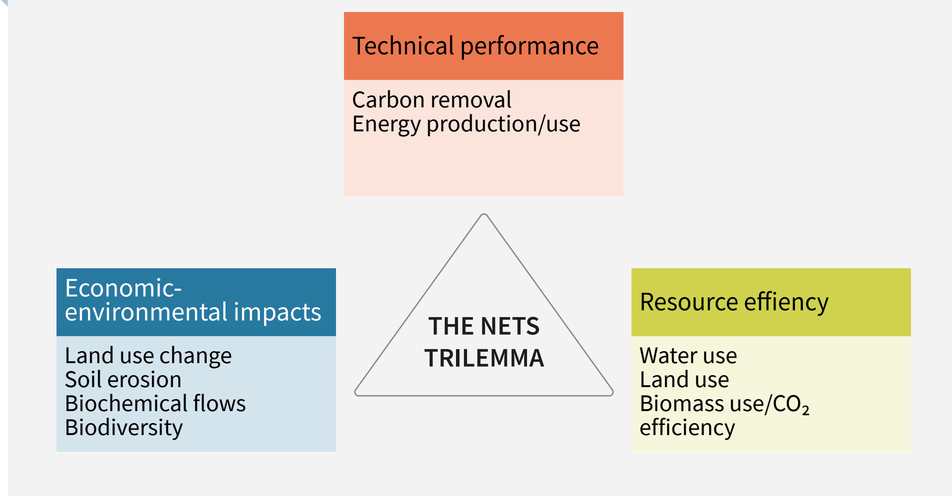
- Includes BECCS, DACCS, afforestation, biochar and enhanced weathering
- Covers different and important economies: US, Brazil, EU, India and China
- Reads in different types of crops into the model
- Considers availability of different types of land
- Utilises knowledge on CO_2 storage capacity for different regions
- Runs on a decadal time scale and using CO_2 removal levels as set out by IPCC scenarios

2. 2. 2 Optimising the international supply chain for BECCS

Using the MONET framework and focussing on BECCS, researchers investigated the best combination of feedstock type, region, land type, and transport route to a given region to remove CO_2 with 500 MW power plants based in the UK, US and China (Fajardy et al., 2018).

According to the model, the optimal structure of an international BECCS supply chain varies as the focus shifts from conserving water, land or biomass, to maximising energy (see figure 3). For example, water use increases threefold when land and biomass use are minimised (compared to the water minimisation scenario) (Fajardy et al., 2018).

FIGURE 3: **Schematic of the NETS trilemma. NETs key performance indicators are reassembled into three categories: technical performance, resource efficiency and economic-environmental impacts (Fajardy et al., 2018).**



To meet regional targets, imported biomass (from Brazil, China, the EU or the US depending on the country) was consistently chosen in all three countries over domestic biomass in the land and water minimisation scenarios. This confirms the importance of yield, carbon intensity in the electricity grid and precipitation, over transport distance.

In spite of these environmental trade-offs, BECCS could meet its electricity production objective while remaining inside safe boundaries of land use within which humanity can continue to thrive in the future. Building a research approach that can assess the optimal reconciliation of BECCS performance and environmental impact, while accounting for regional variation, is a key research challenge to be addressed.

Scaling a diversity of GGR technologies is challenging and a gap exists between diffusion of NETs implied in models and the actual level of progress in innovation and deployment

3. Scaling up GGR and minimising environmental cost

3. 1 What do we need to know to scale?

Scaling a diversity of GGR technologies is challenging and a gap exists between diffusion of NETs implied in models and the actual level of progress in innovation and deployment (Minx et al., 2018).

The work of demonstrator projects should help bridge this gap. Research teams setting up this type of project can apply learning from technologies that have been successfully diffused, taking into account the need to appeal to a range of users, to manage of policy risk, and understand and address public concerns (Nemet et al., 2018).

Knowledge around the impact of GGR on climate stability is also essential. Decisions around location of facilities, transportation and flows of materials and energy all have implications for the environmental impact (Fuss et al., 2018).

3. 2 Meeting national UK CDR expectations sustainably with BECCS

Researchers (Zhang et al., 2019) have conducted the first bottom-up study using data on CO_2 removal and energy generation from a range of biomass feedstocks to present a BECCS design capable of meeting UK CO_2 removal expectations of 47 Mt CO_2 per year by 2050 as set out by UK's Committee on Climate Change n 2018 (UK Committee on Climate Change, 2018)

The study found that waste and residues (secondary biomass sources) such as straw and leftover wood provided a valuable supplement to primary biomass in the UK.

The research showed that, in the initial phases of deployment, the optimal location of CDR infrastructure of biomass power plants tends to be near cities and sources of low cost, waste biomass. However, as GGR levels are increased, the optimal location of infrastructure moves closer to areas where biomass can be grown. Storage infrastructure was not considered in the study. The study suggests that the UK can be self-sufficient in biomass supply by utilising available indigenous biomass to remove up to 50 MtCO_2 per year but, for economic reasons, it may be preferable to import biomass when removal is scaled up (Zhang et al., 2019).

3. 3 Realising BECCS supply chains and models of collaboration

Researchers have explored the complexity of infrastructures involved in large-scale BECCS in Europe (Negri et al., 2021). Assuming co-operation among the 28 EU countries (now EU-27 and UK) to reach a removal target of 0.61 $GtCO_2$ per year and taking a life cycle assessment (LCA) approach to consider impact on cost, health and environment, the study showed that, by focussing on minimum cost to reach targets, removal of each tCO_2 would cost 117 Euros. If instead environmental impacts were minimised the costs would increase by 45% but environmental performance would improve by 23%.

In an exploration of collaboration at a global scale in delivering CO_2 removal from BECCS, researchers (Fajardy & MacDowell, 2020) considered five regions of the world – US, Brazil, China, India and the UK. The research found significant differences in life cycle removal cost via BECCS among regions. Costs became much greater when sustainable boundaries of the biomass were pushed. Not all regions are equally endowed in sustainable biomass and CO_2 storage assets so researchers investigated three approaches to collaboration – full, partial and no collaboration – and modelled what would happen to global CO_2 removal.

Full inter-regional collaboration in the trading of biomass and negative emissions led to the highest chance of meeting global targets at lowest cost (see figure 4). With less collaboration the total cost of removal can increase by up to 14 % and cumulative CO_2 removal can decrease by 65 $GtCO_2$.

Full inter-regional collaboration in the trading of biomass and negative emissions led to the highest chance of meeting global targets at lowest cost

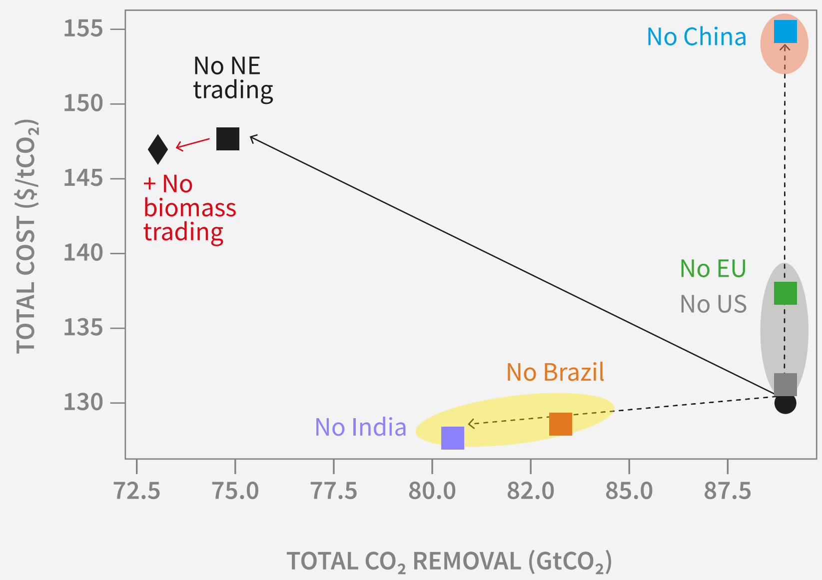


FIGURE 4: **The impact of collaboration on global CO_2 removal via BECCS (Fajardy & MacDowell, 2020). Total cost of removal and cumulative CO_2 removal are presented under full collaboration (circle), negative emissions trading constraints (squares), biomass trading constraints (crosses), or both constraints (diamonds) under a low target scenario.**

Next steps

So far 1.5 million tonnes of CO_2 per year has been removed via BECCS (Bui et al., 2018) and around 0.01 million tonnes of CO_2 per year with DACCS technologies (Fasihi et al., 2019).

Research focussed on BECCS and DACCS in the EU (Galán-Martín et al., 2018) has shown that each year of carbon dioxide removal inaction could increase the removal costs from about 120 to 190 billion EUR2015 to remove 50 Gt of net CO_2 emissions by 2100.

There is a need to start GGR deployment soon but this will require substantial resources, collaboration and knowledge. The next stage of trialling GGR techniques is crucial to interrogating how these technologies will perform in the real world and establishing the nature of the interactions between different approaches and regions.

Portfolios of GGR technologies are necessary to reach climate change targets and more research is needed to assess the less mature technologies and how they will fit with the more established approaches. Impacts beyond climate change must be considered in the scale-up of GGR technologies and must be integrated into assessments.

Trade-offs exist between environmental impacts, CO_2 removal and energy production but these are not impossible to navigate. How to regulate systems where biomass is imported from a productive region A, CO_2 is stored in region B with abundant storage, to meet the CO_2 removal target of a region C, as well as how to allocate credits among these actors, are key research and policy questions to be investigated.

Questions for next generation of research projects to address

BOX 5

- How will different GGR techniques interact in the real world? And how will the less mature approaches fit with those that are more established?
- How can we weigh up the environmental impacts, the CO_2 removal potential and the energy production of GGR approaches to produce the best results?
- To enable collaboration how best can we incentivise different actors involved in different stages of the supply chain?

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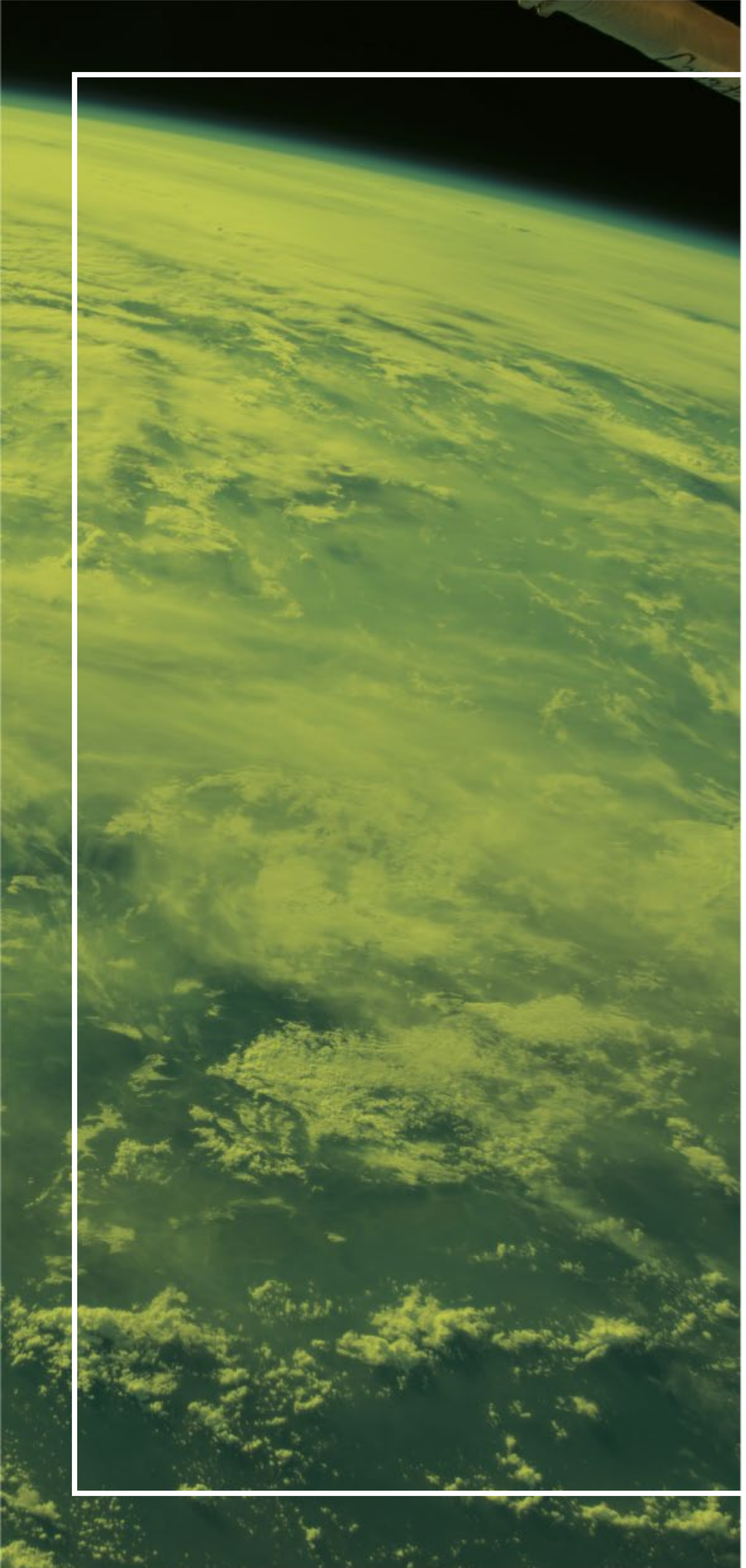

About the programme

The Greenhouse Gas Removal research programme aims to improve our knowledge of the options for removing carbon dioxide and other greenhouse gases from the atmosphere. Through eleven component research projects it addresses the environmental, technical, economic, governance and wider societal aspects of such approaches on a national level and in an international context to inform implementation of climate policy pathways that include large scale removal of carbon dioxide.

The Comparative Assessment and Region-Specific Optimisation of GGR project is one of eleven components. This policy brief was created in collaboration with Prof. Niall MacDowell.

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