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COMMENTARY:

Investing in negative emissions

Guy Lomax, Timothy M. Lenton, Adepeju Adeosun and Mark Workman

Methods of removing CO_2 from the atmosphere add vital flexibility to efforts to tackle climate change. They must be brought into mainstream climate policy as soon as possible to open up the landscape for innovation and development, and to discover which approaches work at scale.

To achieve the widely held policy target of limiting average temperature change to 2 °C, integrated assessment models (IAM) increasingly depend on massive-scale 'negative emissions' through biomass energy with carbon capture and storage (BECCS), deployed in the second half of this century[1–6]. Yet this key technology is technically immature today, and it is far from clear whether such large-scale deployment several decades in the future would be either feasible or desirable[1]. Hence a recent Commentary by Fuss *et al.* has branded BECCS a potentially "dangerous distraction"[1]. But before anyone dismisses what doesn't yet exist, we argue that the best way to determine "how safe it is to bet on negative emissions in the second half of this century"[1] is to instigate a policy framework for greenhouse-gas removal (GGR) and invest in research and development innovation now.

Two dimensions of flexibility

Scalable GGR approaches bring unique flexibility to the mitigation toolbox. BECCS, along with other methods for removing greenhouse gases from the atmosphere, offer two key dimensions of flexibility; they decouple abatement opportunities from emissions sources in both space and time[7–9].

Decoupling in space allows GGR to indirectly mitigate emissions from areas of the energy system that are most difficult or expensive to decarbonize. Such 'project-level' negative emissions can in principle bring many benefits as a complement to conventional mitigation efforts, depending on the direction and efficacy of climate policy and GGR deployment. Possibilities include (i) buying time for the development of clean technologies, the replacement of locked-in sources, and changes in societal attitudes; (ii) reducing the total costs of meeting climate targets by displacing the most challenging and expensive emissions sources; (iii) making more aggressive emissions cuts feasible by simply adding new mitigation options; or (iv) allowing continuing use of fossil fuels in certain key sectors such as aviation[7,9].

Decoupling in time raises the idea that GGR theoretically could be deployed at massive scale to generate global 'net-negative' emissions later this century, allowing us to recover from emitting too much earlier this century and overshooting CO_2 concentration targets[1,4,9]. The negative emissions capacity outlined in the IPCC's Fifth Assessment Report[3] implies BECCS input of up to 10 gigatonnes of CO_2 abatement per year with global net negative emissions from around 2070.

It is this second dimension of flexibility — decoupling in time — that Fuss *et al.* rightly caution against as "betting" on negative emissions[1]. They argue that our ability to reach or even assess the feasibility of a late-century, massive-scale BECCS scenario is severely constrained by (at least) four main groups of uncertainties surrounding: (i) access to sufficient biomass supply and storage space for captured CO_2; (ii) the uncertain response of the global carbon cycle; (iii) relative costs and viability of untested technology; and (iv) social and political factors. Similar uncertainties face other GGR technologies. For example, estimates of the cost of direct air capture range from below US$100 to more than US$1,000 per tonne of CO_2 abated[10], and approaches based on interactions with natural systems such as soils and ocean alkalinity raise concerns over potential environmental impacts that are not yet fully understood[11–13].

Responses to uncertainty

In the face of such uncertainties it can seem premature to commit to long-term policy support. A natural, scientific response is to call for a substantial interdisciplinary research agenda to explore and try to constrain the uncertainties[1], so that we can best assess the future potential of GGR and guide policy through the remaining uncertainties. But at such vast scales of global deployment, and over such long timescales of technological, political and societal development, many of the uncertainties are inherent, and can only ever be loosely constrained by modelling and research[9]. This is well illustrated by, for example, existing estimates of global sustainable biomass resource in 2050 to 2100, which range from around 30×10^{18} J (30 EJ) per year to over 600 EJ yr^{-1} depending on assumed trends in diet, crop yields, land use and population[14]. The call to try to constrain the unconstrainable instead may lead to 'analysis paralysis', losing valuable time and helping to self-fulfil the prophecy that GGR cannot be realized at scale.

A central problem is the framing of GGR as a large-scale, late-century approach that would inevitably entail major environmental and social consequences[7]. This presents multiple issues for policy, and immediately polarizes rather than nuances the debate. It risks both over-emphasizing the need

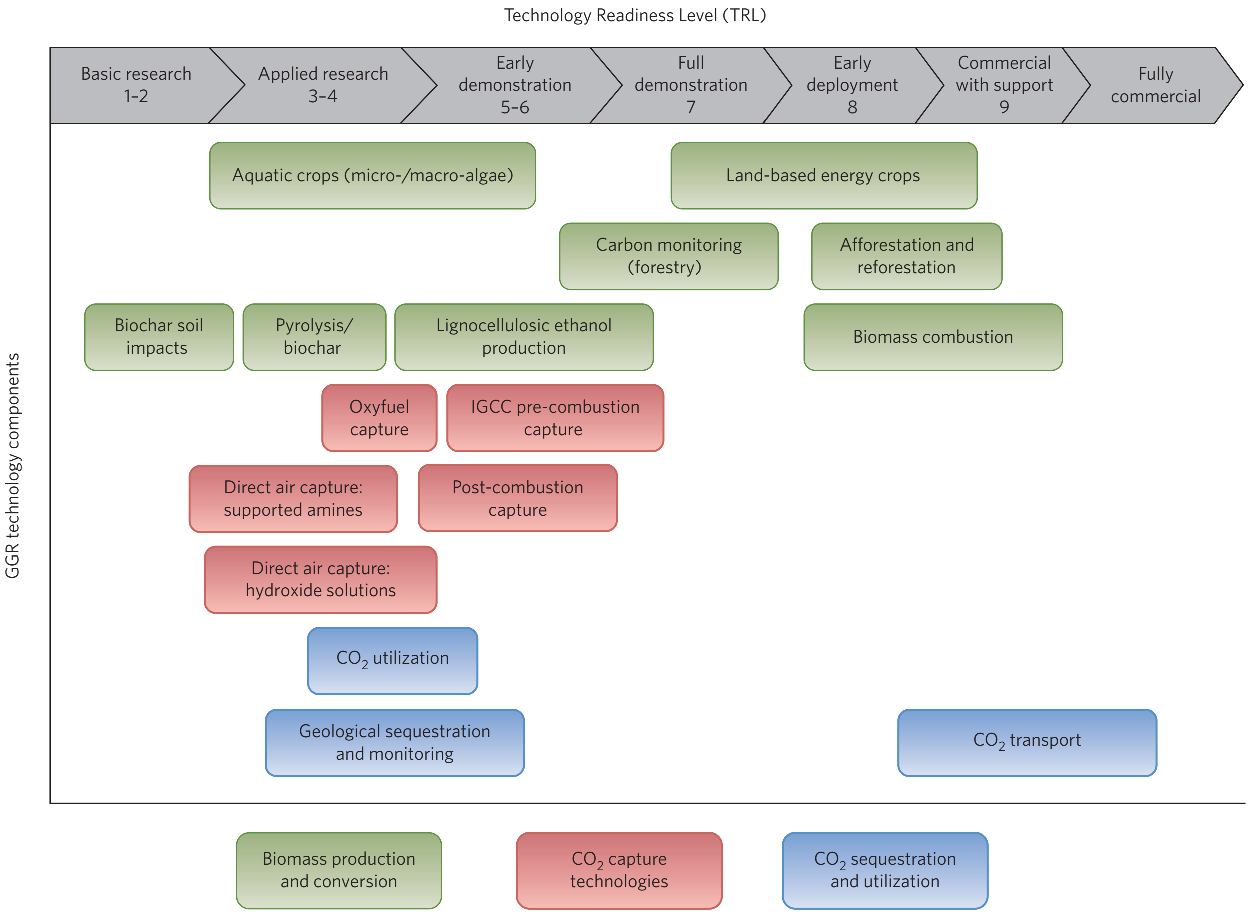

Figure 1 | Schematic diagram showing the Technology Readiness Levels (TRLs) of key science and technology components relevant to leading GGR approaches of afforestation, BECCS, biochar (from biomass pyrolysis) and direct air capture, according to the authors' assessment. IGCC, integrated gasification combined cycle. TRLs are a method of characterizing technological maturity from the most basic research (TRL 1) through to full-scale real-world operation (TRL 9). Many important elements of all GGR technologies are still in research and early demonstration. Technologies often take decades to advance from this stage to commercial deployment (TRL 9) and widespread scale-up, even with continuous R&D support (see text).

for precaution and regulation over the possible advantages, and portraying reliance on these highly uncertain scenarios as an economically optimal policy. By concentrating on events more than 50 years in the future, it takes the debate away from current scientific knowledge, global experience and policy planning horizons, giving the false impression that effective policy engagement with GGR in the near term is of little value or urgency. This distracts attention from the nearer-term value that BECCS and other GGR could offer in supplementing ongoing mitigation efforts at more modest scales, and the urgency of the early technical and policy groundwork necessary to enable future scale-up[7].

Thus, although research to try to constrain long-term uncertainties is undoubtedly important, these uncertainties should not be used to justify inaction on more pressing near-term technology development and policy support needs. Indeed, an alternative response to such uncertainty is to start learning by doing. BECCS and its component technologies are at a relatively early stage of technical development, as are many other GGR options (Fig. 1). Individually, bioenergy and CCS technology and industries are themselves at an early stage, and integrating them poses further challenges to technical viability and achieving attractive economics[7,15,16].

Advancing from the current state of technical readiness to maturity and widespread deployment is a process that takes many decades. For example, one oft-cited example of successful scale-up of a new energy technology is the United Kingdom's 'Dash for Gas', the development and nationwide roll-out of combined-cycle gas turbine power plants in the 1990s. Even with heavy, sustained R&D programmes by both industry and government, it took 30 years to move from the first plants to a competitive energy technology[17]. Given the widespread remaining research and development challenges, and the large-scale need for GGR anticipated several decades from now, timely research and demonstration of the technologies are themselves priorities.

Roadblocks to policy engagement

To support this learning-by-doing approach, early policy engagement is vital, but it is also confronted by several potential roadblocks.

The task of accounting for the removed greenhouse gases poses a considerable challenge to practical policy integration. Unlike emissions from fossil fuel combustion, the flows of greenhouse gases involved with GGR approaches are much more diverse and less well understood. Especially with approaches based on ecosystems, soils and biomass, the greenhouse-gas storage varies with time and external factors[18], making it difficult to accurately measure the amount of carbon stored. Risks of emissions through direct and indirect land-use change also threaten the effectiveness of biomass-based GGR, requiring effective ways of quantifying or minimizing such effects through policy[19].

Furthermore, GGR approaches do not completely separate the greenhouse gases from the natural carbon cycle, calling into question the permanence of the sequestration[11,20]. This problem ranges from gradual decay of biochar in soils[21], to diffuse leakage of CO_2 from geological storage[22], to catastrophic release of forest carbon in a wildfire[23]. The risks or mechanisms of this happening are often poorly understood and, as with storage itself, monitoring or quantification of any loss is often difficult.

These issues create a challenge to integrating GGR into international accounting and accreditation schemes as well as developing effective policy support for them, and these challenges need to be addressed early if the potential of BECCS and other GGR is to be realized. Indeed, developing effective and sustainable policy is likely to require co-evolution and iterative refinement of policies as GGR efforts scale up over decades, as is currently being seen in the bioenergy sector[24].

The risks of delaying policy engagement

Policy and technology development undoubtedly take time, but delaying GGR policy engagement also carries risks. First, and most practically, it risks missing out on the near-term and smaller-scale value of some more mature and economically attractive GGR options, potentially including co-firing of biomass in fossil-fuel CCS plants, sequestration through biochar production, and carbonation of mineral wastes[15,25,26]. Second, excluding GGR from near-term policy attention would reduce any incentives for businesses and research organizations to expend effort and investment on advancement of GGR technology, and to engage with policy to develop suitable support for GGR-oriented businesses. Enabling such innovation is essential to realizing the long-term opportunity.

A final risk arises from the fact that policy decisions made today will define the context in which the high rates of GGR deployment anticipated by modelling will occur in several decades' time[7]. Infrastructure, assets and technology choices in the energy system, in particular, can have a lifetime of many decades, and ongoing development of the bioenergy and the CCS sectors now with no thought for their future integration could make roll-out of BECCS difficult and costly. An effective policy approach must aim to strike a balance between the urgent need for policy support on these key issues and the high level of current uncertainty, taking low- or no-regrets steps towards integration of GGR into policy and near-term development.

A way forward

A first step forward can come from noting that the practical and conceptual difficulties in accounting, and to some extent the uncertainties, are shared to varying degrees by several emissions reduction technologies that are currently the focus of policy efforts. Life-cycle assessment methodologies, developing guidelines for carbon accounting in forestry and land-use change, approaches for reducing risks of indirect emissions from bioenergy and accounting, monitoring and liability mechanisms for geological storage are all transferable to different GGR methods, and these mechanisms can form the basis for policy integration. These ongoing overhauls of emissions accounting across all sectors represent a good opportunity to incorporate GGR.

Based on the principles of integration with mitigation policy and building flexibility, we therefore propose four principles for a high-level strategy that can be applied in order to begin to make progress towards successful GGR integration[7]:

- Fund research, development and demonstration of GGR systems, focusing on constraining uncertainties, developing practical accounting methods and bridging any other gaps between technology maturity and policy needs. Given the value of GGR in tackling the most difficult emissions sources, diverting some funding from more advanced and speculative clean energy research may pay off.
- Build up support for low-cost, early opportunities through existing or new bottom-up policy mechanisms. Examples might include subsidies for electricity generated from early BECCS opportunities such as biomass co-firing in coal CCS plants, or inclusion of soil carbon enhancement or biochar in agricultural policies. This will help to capture early opportunities as well as stimulating development and innovation.
- Commit to full integration of GGR into emissions accounting, accreditation and overall policy strategy in the longer term, including any carbon pricing mechanisms. This process will undoubtedly be complex, but the commitment will stimulate investment, research and long-term planning for GGR.
- Develop steps to lay the broader groundwork for future GGR and to keep the GGR option open, avoiding lock-out of valuable opportunities. The first three principles will go some way towards achieving this, but there may be further steps that can be taken that are specific to each technology and must be identified through close engagement with stakeholders. An example of this might be 'capture-ready' requirements for bioenergy plants to ensure that they can be retrofitted with CCS when this option becomes viable.

The challenge of meeting climate targets is huge, and we will need to make use of every tool at our disposal. GGR methods that can extract CO_2 from the atmosphere itself can add vital flexibility to the efforts and must be brought into mainstream climate policy as soon as possible to open up the landscape for innovation and development. Effectively integrating such diverse approaches into policy will be challenging and complex, and the principles proposed here only point to the first stages of the process. But they represent essential steps that must be taken if we are not to miss the opportunity that GGR provides. ❐

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