UCL Institute for Sustainable Resources

Greenhouse gas removals independent review: call for evidence

Response from UCL Institute for Sustainable Resources

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Contributors

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THE BARTLETT
INSTITUTE FOR
SUSTAINABLE RESOURCES

The UCL Institute for Sustainable Resources' mission is to provide evidence, expertise and training to respond to climate change and support sustainable transitions for people and planet. The institute delivers world-leading research, teaching and enterprise in the sustainable use of global resources.

The following details the Institute's response to selected consultation questions. The full consultation text can be found online[1]. Headings relate to those highlighted in the consultation. Question numbers refer to the consultation. We do not respond to all questions but consider only those relevant to our area of expertise.

Response to consultation

Question 5: What is the potential scale of GGRs in the UK?

This could include, but is not limited to: potential scale of removals by technology type or for projects you are involved with; what assumptions that is based on, for example access to land, storage infrastructure, feedstock availability or biomass prioritisation; timelines for delivery of removals; and how the scale of removals may increase over time. Any information on the factors affecting these trajectories is also welcome.

The scale of GGR needed to reach the UK's net zero targets will depend heavily on how rapidly we decarbonise and reduce demand. Concerns about barriers to GGR scale-up and doubts about its reliability and impacts (see our response to Q7) lead us to recommend that all efforts to reduce GHG emissions should be pursued in order to reduce the need for GGRs. Under different decarbonisation scenarios, our research estimated that by 2050 the UK would require between 56 Mt CO_2/year (delivered by land-based GGRs) and 80 Mt CO_2/year (mixed basked of GGRs). In comparison, the CCC pathway for Carbon Budget 7 requires 61 Mt CO_2/y, 58% of which are engineered[2]. Importantly, the higher the scale of GGRs required, the greater the pressure on both domestic and international resource availability—from land and biomass to infrastructure and energy (Johnson et al., 2023[3]). It is very difficult to provide robust estimates of the potential scale of GGRs in the UK, both at the level of individual GGR approaches and combinations of GGRs. Factors including maturity of GGR supply chains, uncertainty over GHG storage permanence, competition for land and other resource, all present uncertainties in assessing both technical and realistically achievable potentials. While demonstration trials are ongoing, there is still substantial uncertainty over local impacts on soil, water and biodiversity for many GGRs, meaning challenges for setting sustainability criteria/regulations. For some, the lack of financial incentives, standardised MRV framework and liability framework lead to uncertainty in how and when private sector actors will get involved.

To address this uncertainty, our work focuses on demonstrating the potential for ambitious emissions reduction in order to reduce the scale of GGR required. Collaborative research between

[1] Greenhouse gas removals independent review: call for evidence - GOV.UK

[2] CCC Seventh Carbon Budget, Figure 3. https://www.theccc.org.uk/publication/the-seventh-carbon-budget/#publication-downloads

[3] Johnson, E., Betts-Davies, S., Barrett, J., (2023) Comparative analysis of UK net-zero scenarios: The role of energy demand reduction. *Energy Policy,* 179, https://doi.org/10.1016/j.enpol.2023.113620

UCL and leading UK Universities has shown that strong demand-side action can reduce final energy consumption by 50% by 2050 compared to today, significantly lowering the volume of GGRs required, and reducing the pressure on their early delivery (Barrett et al., 2022[4]). Achieving this would be difficult, would require strong and cross-sectoral policy action, and imply drastic changes in consumption practices. Yet this transformative change to our way of considering the energy system cuts the root cause of emissions, and crucially, this can be achieved without compromising future quality of life. In comparison, moderate policies that just "steer" the system to lower demands would require 76 MtCO_2e GGR by 2050. Importantly, considering additional mitigation needs could add up to 83 Mt CO_2/y CCS, implying up to ~160 Mt CO_2/y in T&S infrastructure (Sharmina et al., 2025[5]). Besides the **additional pressure on scaling up T&S infrastructure**, mixing CO_2 flows from mitigation (fossil- and process-CCS) with removal CO_2 (biogenic and DAC captured) may lead to overestimation of removals.

The future scale of GGR is intrinsically linked to future changes in, and could exacerbate competition for, land use. This is true for land both in the UK and abroad. The transformative futures described in Barrett et al., 2022 show that extrapolating current dietary shift dynamics to include higher incidences of vegetarian and vegan diets would free up areas of pasture which could instead be used for land-based GGR in the UK. The annual forestry planting rates required to achieve this would need to be ramped up to 100 kha/a, which is more than a threefold increase on the historical planting rates (EAC, 2023[6]). In parallel with requirements for GGR, demands on land for other uses are also expected to increase, e.g. for food production, biodiversity, trade, climate change mitigation and adaptation; all with potential for competition on the same areas of suitable land. For instance, our research shows that just meeting future dietary goals (e.g. 'five a day' fruits and vegetables for everyone) requires land which could have potentially strong biodiversity impacts both in the UK and overseas, where the majority of UK supplies are sourced (Chapman et al., accepted[7]). Further analysis is needed on our key trade routes, and any ways that scaling-up GGR could increase our reliance on imports.

Besides competing for land with other land-uses, **different types of GGRs can compete for the same land**. Cronin et al., 2020[8] investigated potential trade-offs between using land for energy crops as BECCS feedstock vs. afforestation. Their findings suggest that prioritising afforestation over BECCS using energy crops increases the CO_2 removal, while increasing co-benefits from increased forest area. The study also highlights key uncertainties related to both afforestation and BECCS, which should be investigated further to establish the best use of land, and thus understand how much *and where* different GGRs should be prioritised. Studies are needed on (i) the dependency of removal rates on forest management practices, (ii) the social, technical and economic factors that affect the potential for converting abandoned agricultural land to energy crops or new forest.

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[4] Barrett, J., Pye, S., Betts-Davies, S. *et al.* Energy demand reduction options for meeting national zero-emission targets in the United Kingdom. *Nat Energy* **7**, 726–735 (2022). https://doi.org/10.1038/s41560-022-01057-y

[5] Sharmina, M., Broad, O., Barrett, J.; Brand, C., Garvey, A.; Kennard, H.; Norman, J.; Price, J.; Pye, S.; Snape, J.; and White, E. (2025) Net zero society scenarios: Co-creation with policy and public stakeholders can increase buy-in for a demand side focused analysis. *Nature Energy (under review).*

[6] https://committees.parliament.uk/publications/40938/documents/199465/default/

[7] Chapman, A.S.A. et al., accepted for publication in People & Nature. 'Measuring trade-off risk between food crops and vertebrate biodiversity in three African countries'.

[8] Cronin, J., Pye, S., Price, J., Butnar, I. 2020. Biomass, afforestation and energy demand reduction: trade-offs in the route to decarbonisation. UKERC Report. Available at: http://www.ukerc.ac.uk/publications/afforestation-energy-demand.html

Question 6. What are the co-benefits of GGRs?

This could include, but is not limited to: GGR co-products, non-carbon environmental benefits, and supporting the Government's Growth and Clean Energy Superpower Missions. Any information on the size and determinants of these co-benefits is helpful, either at an economy-wide or project level.

Land-based GGRs usually provide more co-benefits as compared to engineered solutions. Our research suggests that these co-benefits are location, time and management practice specific. Without adequate governance and MRV in place, expected positive co-benefits may be replaced by negative impacts. More UK-based demonstration is needed to build reliable data and methods for quantifying these co-benefits and/or impacts.

Depending on how CDR is implemented, **the environmental side-effects can be either positive or negative**, e.g. tree planting using diverse tree types will deliver removals whilst increasing biodiversity, water retention, flood mitigation (EAC, 2023[9]). On the flip side, which trees, where and how they are planted have significant implications for climate mitigation benefits from afforestation scale-up in the UK (Bateman et al., 2024[10]). If well placed and well managed, energy crop grown for BECCS can provide additional ecosystem services. For example, miscanthus plantations can act as flood defence (Kam et al, 2019[11]), while integrating a perennial grass into a rotational farming system could improve soil and water quality (Hodgson et al, 2024[12]). However, if energy crops are planted in areas with relatively high amounts of natural vegetation, they may substantially reduce local biodiversity (Tudge et al., 2024[13]).

While several co-benefits could be achieved by GGR implementation, the current evidence suggests that there is a predominance of evidence on negative effects compared to positive ones (Prütz et al., 2024[14]). Our own research (Butnar et al., in preparation[15]) suggests that co-benefits and trade-offs of GGR deployment are two faces of the same coin, as they are site specific, highly dependent on how the project is implemented and maintained, and on the scale of the infrastructure. For instance, afforestation trials and scenario modelling show that when afforestation is driven targeting natural capital growth, it can deliver both removals and improved biodiversity (Bateman et al 2024).

[9] https://committees.parliament.uk/publications/40938/documents/199465/default/

[10] Bateman, I. J., Binner, A., Addicott, E. T., Balmford, B., Cho, F. H. T., Daily, G. C., De-Gol, A., Eisenbarth, S., Faccioli, M., Ferguson-Gow, H., Ferrini, S., Fezzi, C., Gannon, K., Groom, B., Harper, A. B., Harwood, A., Hillier, J., Hulme, M. F., Lee, C. F., … Day, B. H. (2024). How to make land use policy decisions: Integrating science and economics to deliver connected climate, biodiversity, and food objectives. *Proceedings of the National Academy of Sciences of the United States of America*, *121*(49), e2407961121.

[11] https://link.springer.com/chapter/10.1007/978-3-030-13068-8_115

[12] https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.13177

[13] Tudge, S.F R. Murphy, Z. M. Harris, A. De Palma, 2024. Balancing bioenergy expansion and restoration: Global shifts in biodiversity intactness. https://doi.org/10.1111/1365-2664.14695

[14] Prütz, R., Fuss, S., Lück, S. et al. A taxonomy to map evidence on the co-benefits, challenges, and limits of carbon dioxide removal. Commun Earth Environ 5, 197 (2024). https://doi.org/10.1038/s43247-024-01365-z

[15] Butnar, I., J. House, M. Thoppil, N. Martirosian, E. Mouchos, J. Lynch, S. Vetter, D. Gamaralalage, Y. Tang, J. McKechnie, S. Foteinis, S. Rodway-Dyer, M. Röder, S. Sogbesan, A. Hastings, P. Renforth, M. Brander, R. Brown, C. Price, G. Hodgins, F. Deng, B. Emmett, J. Hatton, C. Pearce, R. James, S. Robinson, K. Gannon, J. Thornton, I. Bateman., 2025. Evidencing carbon removals and environmental co-benefits and impacts of Carbon Dioxide Removal interventions. In preparation.

However, when afforestation is driven only for carbon storage, then it can create local impacts and even economic losses.

It is important to note that measuring co-benefits and ecosystem health improvements linked to GGR expansion is strongly related to the counterfactual use of the land, i.e. what would happen in the absence of that GGR deployment. For instance, small biodiversity gains garnered from planting energy crops in areas with limited natural vegetation might be comparatively lower than those that could be obtained by instead leaving the land to recover naturally (Tudge et al., 2024[16]). Our own research shows that assessments of GGR scale up usually do not report environmental co-benefits and trade-offs, and that when they do, these co-benefits/trade-offs reports tend to disregard the counterfactual scenario (Butnar et al., 2024[17]). Furthermore, the data availability and quality around the co-benefits and trade-offs related to GGR deployment and scale up is patchy, e.g. very good quality soil data are available for a limited number of afforested sites, but these are very heterogeneous and management dependant, reducing the degree of confidence in the data (Butnar et al., in preparation[18]). This is an area which needs further research and harmonisation.

Some GGR approaches can deliver co-products to the energy system. Any concept of BECCS (for power, for hydrogen, for FT fuel production) is thus expected to produce useful energy outputs alongside a stream of CO_2. This could offer clear benefits to the energy system, and is a key reason why BECCS technologies feature so strongly in future net zero energy system pathways. However, real system design will imply trade-offs between maximising carbon, flexible co-product output, or energy system support with ancillary services. Lehtveer and Emanuelsson (2021)[19] assess the comparative roles of BECCS and DACCS in a flexibility energy system, highlighting the complexity and dynamic nature of this relationship, implying that a clear concept of what GGR are designed to prioritise and how market and governance systems are expected to interact with them is fundamental.

Another co-benefit of CO_2 removal could materialise as **durable carbon capture and usage** (CCU) with permanent storage, e.g. utilisation of wood in construction, carbonation of concrete. Note that while some models suggest a role for CCU in decarbonisation scenarios, CCU is usually not included in national to global scale integrated assessment models informing transitions (Butnar et al, 2020[20]). This omission may reduce their visibility in some national plans. For instance, the French carbon

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[16] Tudge, S.F R. Murphy, Z. M. Harris, A. De Palma, 2024. Balancing bioenergy expansion and restoration: Global shifts in biodiversity intactness. https://doi.org/10.1111/1365-2664.14695

[17] Butnar, I., Lynch, J., Vetter, S., Gamaralalage, D., Tang, Y., McKechnie, J., Foteinis, S., Rodway-Dyer, S., Röder, M., Sogbesan, S., Hastings, A., Renforth, P., Brander, M. and House, J. (2024), A Review of Life Cycle Assessment Methods to Inform the Scale-Up of Carbon Dioxide Removal Interventions. WIREs Energy Environ, 13: e540. https://doi.org/10.1002/wene.540

[18] Butnar, I., J. House, M. Thoppil, N. Martirosian, E. Mouchos, J. Lynch, S. Vetter, D. Gamaralalage, Y. Tang, J. McKechnie, S. Foteinis, S. Rodway-Dyer, M. Röder, S. Sogbesan, A. Hastings, P. Renforth, M. Brander, R. Brown, C. Price, G. Hodgins, F. Deng, B. Emmett, J. Hatton, C. Pearce, R. James, S. Robinson, K. Gannon, J. Thornton, I. Bateman., 2025. Evidencing carbon removals and environmental co-benefits and impacts of Carbon Dioxide Removal interventions. In preparation.

[19] Lehtveer, M. and A. Emanuelsson, 2021. BECCS and DACCS as Negative Emission Providers in an Intermittent Electricity System: Why Levelized Cost of Carbon May Be a Misleading Measure for Policy Decisions. Frontiers in Climate, volume 3, https://doi.org/10.3389/fclim.2021.647276

[20] Butnar, I., Cronin, J., Pye, S. 2020. Review of Carbon Capture Utilisation and Carbon Capture and Storage in future EU decarbonisation scenarios. Report for the CCS Association. CCS and CCU in future EU decarbonisation scenarios

accounting guidelines[21] recognise the delayed emission benefit of carbon stored in wood and bio-based materials over the time of the building, but it is assumed that this biogenic carbon is largely released back into the environment at the end of the product's life (according to the assumptions of the underlying environmental databases). If this could be strengthened by policy instruments designed to ensure that biogenic carbon will not simply be released upon the end of a building's or building component's lifetime but then be stored, potentially more carbon storage in buildings could be recognised as removal and scaled-up. (Ministère de la Transition Énergétique, 2024[22], p. 61).

Question 7. What are the barriers to and enablers of GGR deployment in the UK?

This could include, but is not limited to: evidence or information about what makes the UK an attractive place, or not, in which to invest and deploy GGRs; the strengths and limitations of the current scientific evidence base of effectiveness and environmental impacts; policy and regulatory environment; availability and prioritisation of resources; costs and constraints of access to storage; and public perceptions. In each case we would like any evidence on the determinants and impacts.

A critical barrier to scaling up GGRs is their perceived credibility—are they delivering *genuine* removals, at acceptable cost, with public and investor trust? Currently, trusted quantification methods and high-quality data remain nascent, undermining confidence in the integrity of removal claims. Credibility also hinges on recognising that GGRs are not single-point technologies but complex, multi-actor supply chains. Governance must evolve accordingly to address fragmentation, ensure accountability, and support responsible scaling-up.

To address the issue of **GGR credibility**, we led the CO_2RE Hub process to co-develop a **holistic evaluation framework**[23] with various stakeholders to inform the sustainable scaling up of GGRs in the UK. Besides revisiting carbon accounting for GGRs to allow assessing the credibility of removals and cross-comparison across different type of GGRs, i.e. compare tonne CO_2 removed by afforestation with tonne removed by DACCS, the framework navigates other dimensions critical to sustainable delivery of GGR, namely environmental co-benefits and impacts, public acceptability, and competition for decarbonised energy, materials, and infrastructure (Butnar et al., in preparation[24]). Three key cross-dimensions are needed to govern sustainable GGR delivery, namely MRV, legal, and business models. A data mapping across the seven dimensions shows data gaps for assessing the environmental dimension, in particular environmental co-benefits, which are strong contributors to the resilience of the GGR and the wider systems supporting them.

In terms of credibility of **methods used for appraising removals**, our research shows that current Life Cycle Assessment methods are fit for purpose for appraising small CDR demonstrator projects but are not adequate for assessing scaling-up of CDR, nor large-scale CDR deployment in the future

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[21] RE 2020 offers *biogenic carbon stored* (*Carbone biogénique stocké (StockC)*) as a dedicated supplementary indicator (in kg of carbon per m^2), without direct regulatory relevance (Ministère de la Transition Énergétique, 2024, p. 15). This refers to the quantity of biogenic carbon stored in the building. An explicit example of biogenic storage is carbon stored in the wooden frame of the construction (Ministère de la Transition Énergétique, 2024, p. 59).

[22] Ministère de la Transition Énergétique, 2024. Guide RE2020.

[23] https://co2re.org/ggr-evaluation/

[24] Butnar, I., Cox, E., Lynch, J., Strubelj, L., Brophy, A., House, J., Westbury, P.S., Workman, M., Waller, L., Patrizio, P., Ragazzi, I., Macinante, J., Richardson-Barlow, C., Rodway-Dyer, S., Ghaleigh Singh, N., Bogojević, S., Bellamy, R., Haszeldine, S., Smith, S., Martirosian, N., Mouchos, M., 2025. Scaling up Credible Carbon Dioxide Removals: CO_2RE Indicators and Evaluation Framework. Manuscript in preparation.

(Butnar et al., 2024[25]). As GGR learning advances and their supply chains change and grow, the amount of removal GGRs can provide will change, so it is important to be transparent on what assumptions (in the GGR intervention itself or wider system conditions) give rise to the LCA estimates, both current scale and how these may change upon scaling-up. This research has fed into the draft Flexi-standards for BECCS and DACCS currently in preparation by the British Standard Institute, commissioned by the UK Department for Energy Security and Net Zero. This UK initiative in standardising methods for appraising GGRs increases credibility in GGR delivery. However, this needs to be expanded to include other GGRs and to also include quantitative environmental assessment.

Whilst important progress has been made over the last 5 years of CDR demonstration, important uncertainties remain, affecting the scaling up rate. Some are CDR-specific (see forestry and BECCS examples below), others, such as **market drive and robust supply chains**, apply across all CDRs (e.g. Prütz et al., 2024[26]). For instance, notwithstanding highs of 30 kha/a in the 1980s, recent **tree planting** has struggled with average values below half the expected rate (EAC, 2023[27]). Comparatively, current policy expects afforestation to reach 30 to 50 kha/a by 2050. This is further complicated by uncertainties around which trees, where and how they are planted, as all these choices will have significant implications for climate mitigation benefits from afforestation scale-up in the UK (Bateman et al., 2024[28]). Regarding **BECCS**, it is unclear whether biomass can be produced sustainably without displacing food crops or other GGRs (Bateman et al., 2024[4]; Cronin et al., 2020[29]), and whether complex BECCS supply chains can deliver full life-cycle removals (Fajardy & Mac Dowell, 2018[30], Broad et al., 2021[31]) while generating energy at an appropriate scale (Fajardy et al., 2019[32]). In the UK, dependency on imported biomass is also a concern, with current trends likely to cause energy and CDR security challenges.

The perceptions, values and priorities of land managers will play an important role in the scale-up of land-based GGRs, as ultimately these are the actors who decide who which techniques are implemented. As several GGRs will take place on agricultural land, their scale-up must be considered

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[25] Butnar, I., Lynch, J., Vetter, S., Gamaralalage, D., Tang, Y., McKechnie, J., Foteinis, S., Rodway-Dyer, S., Röder, M., Sogbesan, S., Hastings, A., Renforth, P., Brander, M. and House, J. (2024), A Review of Life Cycle Assessment Methods to Inform the Scale-Up of Carbon Dioxide Removal Interventions. WIREs Energy Environ, 13: e540. https://doi.org/10.1002/wene.540

[26] Prütz, R., Fuss, S., Lück, S. et al. A taxonomy to map evidence on the co-benefits, challenges, and limits of carbon dioxide removal. Commun Earth Environ 5, 197 (2024). https://doi.org/10.1038/s43247-024-01365-z

[27] https://committees.parliament.uk/publications/40938/documents/199465/default/

[28] Bateman, I. J., Binner, A., Addicott, E. T., Balmford, B., Cho, F. H. T., Daily, G. C., De-Gol, A., Eisenbarth, S., Faccioli, M., Ferguson-Gow, H., Ferrini, S., Fezzi, C., Gannon, K., Groom, B., Harper, A. B., Harwood, A., Hillier, J., Hulme, M. F., Lee, C. F., … Day, B. H. (2024). How to make land use policy decisions: Integrating science and economics to deliver connected climate, biodiversity, and food objectives. *Proceedings of the National Academy of Sciences of the United States of America*, *121*(49), e2407961121.

[29] Cronin, J., Pye, S., Price, J., Butnar, I. 2020. Biomass, afforestation and energy demand reduction: trade-offs in the route to decarbonisation. UKERC Report. Available at: http://www.ukerc.ac.uk/publications/afforestation-energy-demand.html

[30] Fajardy, M., & Mac Dowell, N. (2018). The energy return on investment of BECCS: is BECCS a threat to energy security? *Energy & Environmental Science*, *11*(6), 1581–1594. https://doi.org/10.1039/C7EE03610H

[31] Broad O., Butnar I., and Watson J., 2021. The role of bioenergy with carbon capture and storage (BECCS) in the UK's net-zero pathway. Report for the European Climate Foundation. https://www.ucl.ac.uk/bartlett/sustainable/files/ecfbeccsfinalreportpdf

[32] Fajardy, M., Köberle, A., Dowell, N. M. A. C., & Fantuzzi, A. (2019). *BECCS deployment : a reality check. Grantham Institute Briefing paper No 28. January 2019* (Issue 28). https://www.researchgate.net/profile/Andrea_Fantuzzi/publication/330774659_BECCS-deployment-_a-reality-check/links/5c539d81a6fdccd6b5d87347/BECCS-deployment-a-reality-check.pdf

as highly integrated with farming activities, so the current **stalling of the new Environmental Land Management subsidy scheme** presents a barrier.

In addition to economic drivers, **farmers' perception of GGRs and their own land are key**. For example, Helliwell (2018[33]) found that while the focus on placing energy crops on marginal land can resolve sustainability concerns, this can be understood as 'energy crops are for marginal land' but farmers often do not consider their land marginal enough.

Question 8. What is the economic cost of deploying GGRs?

This could include, but is not limited to: information, project-level or sector-wide, on the per-tonne costs of GGR technologies in 2030, 2040 and 2050 in the UK or overseas; evidence on the reasons for differences in domestic and overseas deployment; factors affecting deployment costs; and how costs are expected to evolve over time.

Providing a clear and widely scoped definition of what is meant by "the economic cost" of GGRs is essential to ensuring that future UK pathways towards our Net Zero goals look beyond single technology "techno-economic" cost per tonne metrics. Our institute has developed leading work in the recent development of the UK's natural capital accounts. Our research has highlighted that applying a natural capital lens to decision making reveals gaps and systemic bias in how the value of different characteristics of the natural environment are evidenced, leaning towards well understood activities over ecosystemic, natural, or spiritual values (Fairbrass et al. 2025[34]). What is meant by "economic costs" should therefore go beyond traditional CAPEX and OPEX considerations and scope more widely to understand GGRs' total economic including social costs and ecosystem value.

This definition should extend its geographical and timeframe boundaries, aligning with the full GGR supply chain and a robust, MRV supported, definition of permanent CO_2 removal. Any other approach risks significantly underestimating the cost of delivering true carbon removals. Current GGR cost estimates often focus on isolated technologies, not full supply chains, typically excluding the cost of data collection and reporting for Monitoring, Reporting, and Verification (MRV), a core pillar of GGR credibility. Thus, current discussions of "economic cost per tonne of carbon removed" vary widely in their scope and lack comparability. In the context of meeting our national and global Net Zero goals it is however important that these comparisons become possible and meaningful, with costs compared "per unit of carbon removed and permanently stored over the full GGR supply chain". (Butnar et al., 2024[35])

Strong precautionary principles should be applied to considering, and purchasing, overseas carbon removal credits. Assessing the diverse cost components described above, in the context of the UK, in a nascent field with a rapidly expanding knowledge base and few – usually very specific – examples

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[33] Richard Helliwell, 2018. Where did the marginal land go? Farmers perspectives on marginal land and its implications for adoption of dedicated energy crops. Energy Policy 117, 166-172, https://doi.org/10.1016/j.enpol.2018.03.011.

[34] Fairbrass, A. J.; Fradera, K.; Shucksmith, R.; Greenhill, L.; Acott, T.; and Ekins, P. (2025). Revealing gaps in marine evidence with a natural capital lens. *Philosophical transactions of the Royal Society B – Biological Sciences.* Volume 380, Issue 1917. https://doi.org/10.1098/rstb.2023.0214

[35] Butnar, I., Lynch, J., Vetter, S., Gamaralalage, D., Tang, Y., McKechnie, J., Foteinis, S., Rodway-Dyer, S., Röder, M., Sogbesan, S., Hastings, A., Renforth, P., Brander, M. and House, J. (2024), A Review of Life Cycle Assessment Methods to Inform the Scale-Up of Carbon Dioxide Removal Interventions. WIREs Energy Environ, 13: e540. https://doi.org/10.1002/wene.540

of demonstration or scaled up projects, is very challenging. Understanding what reliable costs estimates would be when including additional international stakeholders, global commodity market exposure, and considerable differences in institutional and regulatory environments, seems unreasonable. Please refer to evidence and discussions on these points in the context of Question 10 and its reference to Article 6.

Some project specific evidence is increasingly available for techno-economic assessments of GGRs, but the ranges vary widely. Examples for land based options in the UK could include: the costs of woodland establishment ranging from £3,240 to £28,000 ha/yr (Haw, 2017[36]; Valatin, 2019[37]; CCC, 2020[38]), or peatland restoration costs of £200 to £10,000 ha/yr (Moran et al, 2013[39]; Moxley et al, 2014[40]; Glenk & Martin-Ortega, 2018[41]; Artz et al, 2018[42]). European / international data for the cost of establishing energy crop can range from £170 to £7,700ha/yr (Ericsson et al, 2009[43]; El Kasmioui & Ceulemans, 2012[44]; Witzel & Finger 2016[45]). These estimates exclude any ongoing / maintenance costs or wider social costs. costs. Similar assessments have been conducted in the UK for engineered removals. One such assessment was conducted for government by Element Energy in 2021 and is summarised in the DESNZ Technology Assessment Report[46]. As part of our work with the CO_2RE Hub, we are collaborating with ERM who have been commissioned to update these cost estimates. This update will be available by the end of July 2025. The focus of this work is on engineered removals, i.e. DACCS, a range of BECCS approaches, ERW and biochar, updating TRL and cost for individual technologies. The update will follow the same methodology as the previous report, focusing on parts of the complex GGR supply chains, i.e. not covering full GGR supply chains due to data availability.

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[36] Haw, R. (2017) Assessing the Investment Returns from Timber and Carbon in Woodland Creation Projects, (August), pp. 1–8. Available at: www.forestry.gov.uk/england-wctf

[37] Valatin, G. (2019). Comparing the cost-effectiveness of forestry options for climate change mitigation. Research Note FCRN038. London: Forestry Commission. https://www.forestresearch.gov.uk/publications/comparing-the-cost-effectiveness-of-forestry-options-for-climate-change-mitigation/

[38] Climate Change Committee. (2020). Sixth Carbon Budget, The UK's path to Net Zero. London. https://www.theccc.org.uk/publication/sixth-carbon-budget/

[39] Moran D, Wreford AA, Evans N, Fox K, Glenk M, Hutchings D, et al. (2013) Assessing the preparedness of England's natural resources for a changing climate: assessing the type and level of adaptation action required to address climate risks in the 'vulnerability hotspots. Report to the Adaptation Sub Committee. Committee on Climate Change. http://www.theccc.org.uk/wpcontent/uploads/2013/07/Final-report-SRUCASC-4-July_ASC-FINAL-9-July-2013_clean.pdf

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[41] Glenk, K. and Martin-Ortega, J. (2018) The economics of peatland restoration, *Journal of Environmental Economics and Policy*. Taylor & Francis, 7(4), pp. 345–362. doi: 10.1080/21606544.2018.1434562.

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Question 10. What are the roles and options for all GGRs, domestically and internationally, to balance the UK's residual emissions?

This could include, but is not limited to: potential of international GGR deployment; opportunities and barriers from Article 6 framework; the role of nature-based GGRs such as afforestation, soil carbon enhancement and ecosystem restoration; the role of more novel technologies such as marine carbon dioxide removal; and alternative deployment strategies.

The size of residual emissions in the UK will be strongly dependent on the level of effort that is put into delivering transformative change at a system level with a focus on both demand and supply side options. While trajectories that look to systemically reduce energy demand are challenging and will require increased and cross-sectoral policy focus, they are increasingly prominent and require increasing attention (Johnson et al., 2023[47]). Please refer to questions 5, 6, 7, and 8 for additional discussion of these references.

Clearly ascribing roles and future scales of action to chosen GGRs is difficult in a fast-changing landscape of research and development. Rather than picking key winners at this stage, it would be preferable to maintain agile and diverse investment support across a full basket of GGR options. Our research has shown, for example, that small changes to technology characteristics around the efficiency of carbon capture can result in significantly different energy system build-outs to 2050 (Broad et al., 2023 [48]). Or that adjustments to biomass availability can affect the role of BECCS for power, and delay fossil use phase out under certain conditions (Butnar et al., 2020[49]). (Please see our response to question 11 for full discussion of this evidence). Overall, our experience so far suggests that as new GGR become available and as characteristics of more mature technologies are better understood, their corresponding roles in the energy system will change. Along with our research on low energy demand futures, this strongly suggests strategies that focus on known solutions early, e.g. end-use sector electrification, while keeping open avenues of research into GGR across a portfolio of options for when they will be required, is a more suitable strategy.

The UK should apply a very strong precautionary principle when considering the use of GGRs overseas to offset domestic emissions. Article 6 of the Paris Agreement offers mechanisms for countries to trade emissions reduction credits – bilaterally or via a market – along with guidance to ensure emissions reductions are real, measurable, and additive. This presents an opportunity for the UK government to fund GGRs abroad in exchange for credits which can be counted towards national net-zero and NDC targets. However, there are serious concerns about negative social impacts of these projects. Our research shows that, international offsetting schemes are likely to encourage funding of afforestation or other land-based GGRs by higher income countries in lower income countries (Cronin et al., 2021[50]). This is due to the perceived availability of land, the lower price of

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[48] Broad O., Butnar I., and Watson J., 2021. The role of bioenergy with carbon capture and storage (BECCS) in the UK's net-zero pathway. Report for the European Climate Foundation. https://www.ucl.ac.uk/bartlett/sustainable/files/ecfbeccsfinalreportpdf

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land, and higher carbon sequestration rates in tropical forests. It is already a matter of record that such land-deals[51] are taking place with different goals and varying levels of transparency. While this, in principle, has the potential to fund sustainable development, such schemes also risk driving large-scale land acquisitions, which overlook local rights and needs, bringing negative local economic, social and environmental impacts, and a failure to recognise procedural justice (Obergassel et al, 2017[52]; Borras Jr et al, 2019[53]). Importantly, these market mechanisms are not new. The CDM mechanism established under the Kyoto Protocol sets a clear precedent for Article 6 but has been poorly reviewed suggesting that it "has fundamental flaws in terms of environmental integrity (Cames et al., 2016[54]). The involvement of international actors in land acquisitions, and the exclusion of local voices in decision-making, presents strong risks of a new form of colonialism (Eberle et al, 2019[55]; Redvers et al, 2025[56]). Strong institutional commitment and engagement of local communities may be able to mitigate such risks. It is not clear that there are sufficient incentives for certification schemes and standard setting organisations to engage communities in this way, as these organisations require improved social safeguards, better transparency, and stronger governance structures. If engaging in international offsetting, the UK must therefore take responsibility for ensuring the social integrity of any projects. This should be additive to life-cycle carbon and environmental impact considerations, and should not be taken for granted.

Question 11. How can GGRs contribute to security of supply, with respect to the UK's energy system?

This could include, but is not limited to: the relative prioritisation of biomass use; the energy consumption of GGR technologies; and the potential contribution of GGR technologies to security of supply in line with the different GGR deployment pathways.

"Security of supply" is understood here to refer to "Energy security" in the context of the whole energy system. This concept is multifaceted, complex, and widely researched with many different frameworks proposed to assess how pathways "contribute" or "affect" security. One example of such a framework can be found in Cox, 2018[57], with an adaptation of this concept applied in our

[51] https://www.theguardian.com/environment/2023/nov/30/the-new-scramble-for-africa-how-a-uae-sheikh-quietly-made-carbon-deals-for-forests-bigger-than-uk

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research to assessing energy futures in for the UK in Watson et al. (2018[58]). We reference this work to highlight (1) that security of supply encompasses much wider considerations than physical security – i.e. access to a given commodity or resource – and (2) that analyses can be developed to combine qualitative and quantitative metrics that help to assess these wider considerations. Hereafter, we discuss evidence from our work that helps to quantify different areas where GGRs interact with aspects of Energy Security in the context of the Whole UK Energy System.

While BECCS systems have the potential to contribute to delivering both reliable CO_2 removal and secure energy supply, it is not currently on track to do either. As such, they present both opportunities and risks for energy security. Following current trends, BECCS will scale up by relying, as it does today, on imported biomass. Supplying alternative domestic feedstock will require significant increases in both forestry and energy crop planting rates – targets for which have been systematically missed in recent years with average values below half the expected rate (EAC, 2023[59]). It is likely then that the UK will, in the medium term at least, continue to be highly dependent on international markets for biomass supply. Importantly, our research in global pathways stabilising global temperature under 2C (Butnar et al., 2020[60]) suggests that this market, and the number of actors interacting on it, are set to grow. In the short term (to 2030), biomass is seen replacing coal in electricity generation and industrial heat production, with China and the US emerging as major importers of solid biomass. This has direct implications for UK access to international biomass feedstock – affecting the energy system's physical security of supply.

GGR technology characteristics are still uncertain. Our research shows that small changes in key assumptions about GGR availability, timing, or carbon efficiency, have deep implications for energy system design. This, in turn, impacts infrastructure needs, and investments in other parts of the energy system. In Broad et al. (2023) [61], UK system pathways with small shifts in carbon capture efficiency across both GGR and mitigation options display a knife's edge modelling result with biomass alternately used for power and higher electrification of end use services, over alternatives with BECCS for hydrogen, and higher levels of direct biomass use in end use sectors. These two futures have starkly different infrastructure investment requirements, both of which would need to start very early to be successful. Choosing the wrong pathway, or diverting from one to another, will inherently imply both significantly higher costs and potential delays. Similarly, Butnar et al. (2020[62]) highlights global analysis where varying assumptions on the availability of different GGR technologies deeply influences system design, including the demand and application of bioenergy. When BECCS is available, biomass is diverted to electricity generation with CCS to increase the delivery of removals. This perceived "win-win" of carbon and electricity output displaces cheaper variable renewables, likely affecting end use electricity consumer cost. Both these examples highlight the intrinsic link between GGR and the "affordability" aspect of UK security of supply.

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[59] https://committees.parliament.uk/publications/40938/documents/199465/default/

[60] Butnar I., Broad, O., Solano Rodriguez, B., & Dodds, P. E. (2020). The role of bioenergy for global deep decarbonisation: CO 2 removal or low-carbon energy? GCB Bioenergy, 2020;00: 1–15. https://doi.org/10.1111/gcbb.12666

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Strategic rebalancing of policies and support structures could make better use of existing UK resources in the context of developing GGR technologies. We focus here on land and biomass as an example where evidence exists, but it is likely similar arguments for differentiating "national, regional, and local" policy support will apply to novel GGR as they develop. The UK biomass resource is distributed, and making efficient use of it with lower infrastructure costs and environmental impacts requires that domestic biomass is used where it is produced (Albanito et al., 2020[63]). Recent work with the UK Energy Research Centre[64] has considered the value of this distributed resource and its current use for flexibility purposes. Linking local and national scales, domestic targets for biomass production (mentioned earlier) highlight the need for a shift in policy perspective. Over 2018-2023, average energy crop output increased by 0.25 kha/a, including both miscanthus and SRC willow or poplar, whereas the Government's Net Zero Strategy assumes planting needs between 9 and 17 kha/a by 2038. While some reasons for limited uptake are well understood (Clifton-Brown et al., 2023[65]), many are not addressed and any scale up will require **varied policy support, better farming practices and stable feedstock markets.**

Large scale reliance on GGR in technology ambitious futures can affect physical and affordability aspects of security of supply. Here we focus on the example of Direct Air Capture. A review of recent research has highlighted that total energy needs for solid and liquid sorbent DACS technologies range respectively from 1-1.83 MWh/tCO_2 and 1.8-2.7 MWh/tCO_2 (Ozkan et al. 2022[66]). Our research (Sharmina et al. 2025), using values within this range, has demonstrated that technology centric future UK pathways that do not have a strong energy demand reduction focus combine energy system cost levels between 25% and over 200% higher than they need to be (see Question 8), and require large volumes DACCS. Running these systems in these futures would require between 38.3 and 83 TWh of energy. In electricity terms, this would be 12% and 26% of the electricity we produce today (based on 316.8 TWh, (DUKES 2024)[67]). Additionally, it is expected that large BECCS power plants will support electricity system balancing and provide flexibility, an important dimension of security of supply. However, until plants are built, it will remain unclear how flexible such systems may be, and whether flexible operation will be traded off against emissions reductions via carbon capture.

Considering the diversity of facets to Energy Security, alongside the nascent and rapidly advancing field of GGRs, it is essential to maintain agile and diverse investment support across a full basket of GGR options. Keeping options open, monitoring and adapting will help mitigate the risk of non-delivery, manage costs, and pivot towards options that are delivering (CO_2RE Hub, 2024[68]).

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[64] https://ukerc.ac.uk/project/biomass-as-a-strategic-energy-store/

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