



Research article

A country-level assessment of the deployment potential of greenhouse gas removal technologies

Jude O. Asibor, Peter T. Clough^{*}, Seyed Ali Nabavi, Vasilije Manovic

School of Water, Energy and Environment, Cranfield University, Bedfordshire, MK43 0AL, UK



ARTICLE INFO

Keywords:

Greenhouse gas removal

GGR

BECCS

DACCS

Climate change mitigation

ABSTRACT

The deployment of greenhouse gas removal (GGR) technologies has been identified as an indispensable option in limiting global warming to 1.5 °C by the end of the century. Despite this, many countries are yet to include and promote this option in their long-term plans owing to factors such as uncertainty in technical potential, deployment feasibility and economic impact. This work presents a country-level assessment of the deployment potential of five GGR technologies, including forestation, enhanced weathering (EW), direct air carbon capture and storage (DACCS), bioenergy with carbon capture and storage (BECCS) and biochar. Using a multi criteria decision analysis (MCDA) approach consisting of bio-geophysical and techno-economic factors, priority regions for the deployment of these GGR technologies were identified. The extent of carbon dioxide removable by 2100 via these technologies was also estimated for each of the 182 countries considered. While the obtained results indicate the need for regional cooperation among countries, it also provides useful evidence on the need for countries to include and prioritise GGR technologies in their revised nationally determined contributions (NDCs).

1. Introduction

The deployment of greenhouse gas removal (GGR) technologies is a major requirement in limiting global warming to 1.5 °C by the end of the century (IPCC, 2022, 2018). Under this mitigation scenario, between 100 and 1000 Gigatonnes of global net anthropogenic CO₂ emissions is expected to be removed from the atmosphere before 2100 (Maher and Symons, 2022). Despite the importance of this pathway, the nationally determined contributions (NDCs) submitted to the United Nations Framework Convention on Climate Change (UNFCCC) by countries indicate a low intent to deploy these technologies, with the exclusion of forestation measures (Pozo et al., 2020), thus falling short of the 1.5 °C target (Roe et al., 2019; Rogelj et al., 2016; Schiermeier, 2015). This low level of inclusion is on account of several factors such as uncertainty about the technical potential, especially with some of the technologies at low-to-mid levels of technological readiness (Haszeldine et al., 2019; The Royal Society, 2018), uncertainty about socio-political factors (Buylova et al., 2021; Maher and Symons, 2022). Another major factor is the lack of robust country-level bio-geophysical and techno-economic feasibility assessments to ascertain national GGR deployment potential. It is this latter factor that this study aims to address.

Thus far, only a handful of countries, majorly of the Organisation of

Economic Co-operation and Development (OECD) bloc, have carried out local assessments to ascertain the deployment potential of these technologies in their respective territories by considering their bio-geophysical, technical and socio-economic resources (Alcalde et al., 2018; Baik et al., 2018; Donnison et al., 2020; Element Energy and UKCEH, 2021; Haszeldine et al., 2019; Jiang et al., 2018; Mulligan et al., 2020; Pour et al., 2018; Thoni et al., 2020). Given the global nature of the emission mitigation challenge, there is, therefore, a great need for assessment of the GGR deployment potential of the other countries.

On the global country-level front, some major efforts have also been reported. Griscom et al. (2020) assessed the country-level potential of natural climate solutions for countries in the tropical region. Roe et al. (2019) and Roe et al. (2021) assessed the contribution of the land-based activities (agriculture, forestry, land use change and BECCS) to attaining the mitigation target and identified priority regions/countries with high mitigation potentials using a combined review of modelled pathways and literature on mitigation strategies. In another study, Pozo et al. (2020) allocated carbon dioxide removal (CDR) quotas globally based on responsibility, capability and equality principles. Country-level analysis on the mitigation potential was however only carried out for the European Union on account of data availability, with the GGR technology options limited to BECCS, reforestation and DACCS.

^{*} Corresponding author. Cranfield University, Cranfield, MK43 0AL, UK.

E-mail address: P.T.Clough@cranfield.ac.uk (P.T. Clough).

<https://doi.org/10.1016/j.jenvman.2022.116211>

Received 29 April 2022; Received in revised form 31 August 2022; Accepted 5 September 2022

Available online 13 September 2022

0301-4797/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

With options ranging from the natural climate solutions to the engineered options, GGR methods not only present an opportunity to address historical and current emissions, but they also confer other co-benefits if efficiently deployed. Forestation which collectively refers to afforestation and reforestation is associated with co-benefits such as food and fuels production, air quality regulation, habitat for biodiversity and erosion control among others. Though constrained by environmental factors, it is one of the cheapest carbon sequestration options. Enhanced Weathering (EW) involves the grinding of rocks of calcium or magnesium content and spreading the resulting small grain sized rock over land or ocean surfaces to serve as storage sites for the CO₂ removed from the atmosphere. Though a capital and energy intensive option, its co-benefits include soil productivity improvement, ocean acidity reduction and reduced usage of fertilisers. In DACCS, atmospheric CO₂ is removed by exposing sorbents with a high CO₂ affinity to air. While DACCS is also characterised by high energy requirement, it enjoys advantages of minimal competition for land, water, and nutrients. BECCS which has featured in many Integrated Assessment Models (IAMs) scenarios (IPCC, 2022) has the co-benefit of generating bioenergy while simultaneously removing atmospheric CO₂. Biochar is produced when organic material such as biomass is thermally decomposed in the absence of oxygen. It is more stable than soil organic matter and thus ensures a longer sequestration time of carbon. Co-benefits of biochar deployment include energy production from the pyrolysis process (syngas), pollution remediation, soil improvement and waste treatment. Robust reviews on the operation, impact, and potential of these GGR technologies have been reported in the literature (Asibor et al., 2021; Fuss et al., 2018).

This study assessed the deployment potential of five GGR technologies for 182 countries using a multi-criteria decision analysis (MCDA) approach. This was carried out to estimate the maximum cumulative amount of carbon dioxide removable by 2100 via these technologies. The five GGR technologies considered are forestation, enhanced weathering (EW), direct air carbon capture and storage (DACCS), bio-energy with carbon capture and storage (BECCS) and biochar. The criteria for assessment were based on associated variables of the bio-geophysical and techno-economic factors that affect the performance of these technologies (Asibor et al., 2021; Fuss et al., 2018; Hepburn et al., 2019; Rueda et al., 2021). A sensitivity analysis was also carried out to assess the uncertainties of the applied weighting system.

2. Methods

2.1. Multi-criteria decision analysis (MCDA)

Fig. 1 presents the framework of the method applied in this study.

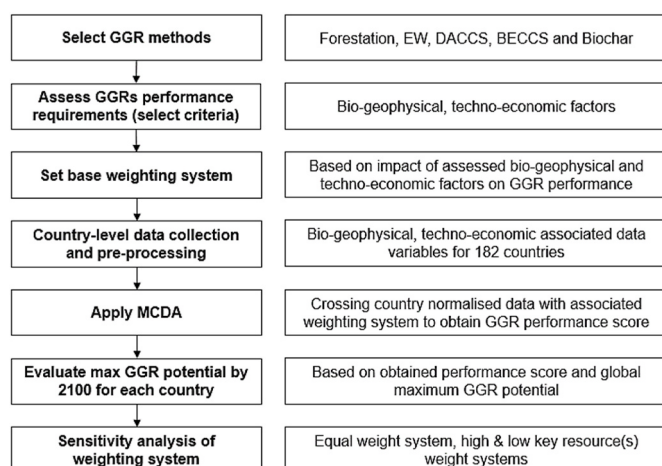


Fig. 1. Method framework for MCDA analysis.

The method was based on the typical MCDA process employed in negative emissions technologies portfolio (Rueda et al., 2021) and sustainable energy (Wang et al., 2009). MCDA is an integrated operational evaluation and decision support approach that is suitable for addressing complex problems with high uncertainty, conflicting objectives, different forms of data and information, multi-interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems (Wang et al., 2009). It provides an integrated result (performance scores) for competing alternatives (or options) based on an assessment of selected multi-criteria or attributes. It typically involves; alternatives m (182 countries), criteria n (bio-geophysical and techno-economic factors), criteria weights (impact weight of selected factors on respective GGR technology performance) and the evaluating result (performance scores) from the decision matrix ($m \times n$). For each GGR technology, the performance score of each country which is an indication of their ability to deploy the respective technology was obtained.

2.2. Criteria selection

The five GGR methods considered in this study (forestation, EW, DACCS, BECCS and biochar) were selected based on their carbon dioxide removal potential and technological readiness levels (Fuss et al., 2018; Haszeldine et al., 2019). In addition, major bio-geophysical and techno-economic factors necessary for the sustainable and efficient performance of these GGR methods were identified from the literature (Asibor et al., 2021). These identified factors which formed the criteria upon which the MCDA assessment was carried out is presented in Table 1.

2.3. Setting the criteria weighting system

Weights were assigned to the selected criteria based on the impact of these factors on the performance of the respective GGR methods. This obtained weight system (base wt) was adapted from the impact ranking of GGR factors developed by Asibor et al. (2021). This ranking which was done on a scale of 0–5, was based on a comprehensive assessment of the impact of bio-geophysical and techno-economic factors on the performance of various GGR methods. To get a unit sum of weight of criteria for each GGR method, this ranking was then scaled down proportionately. The obtained base weight system is presented in Table 2.

2.4. Country-level data collection and pre-processing

Country-level data of associated indicators for the selected criteria were obtained for 182 countries. For climate, average monthly temperature and precipitation (World Bank, 2022) was adopted. For land use (CIA, 2022), land availability for forestation (FLu) consisted of a combination of the countries' forest land use (reforestation potential) and agricultural land use (afforestation potential). For the latter, arable land suited for growing crops was not considered to ensure that the growing of trees did not negatively impact on food production. For

Table 1
Selected criteria.

GGR technologies	Selected criteria
Forestation	Temperature (temp) and precipitation (ppt), Forestation land availability (FLu), Water availability, Vegetation type.
EW	Temperature and precipitation, Cost, Energy requirement, Agricultural land availability (AgLu).
DACCS	Cost, Geological storage potential, Water availability, Energy requirement.
BECCS	Biomass availability, Cost, Geological storage potential, Water availability.
Biochar	Biomass availability, Temperature and precipitation, AgLu, Cost.

Table 2
Applied criteria weights.

	Temp	ppt	Land avail. (FLu)	Land avail. (AgLu)	Biomass avail.	Water req.	Geological Storage	Cost	Energy req.	Vegetation type
Forestation	0.133	0.2	0.267	0	0	0.133	0	0.067	0	0.2
EW	0.1	0.1	0	0.134	0	0	0	0.333	0.333	0
DACCS	0	0	0	0.067	0	0.067	0.333	0.267	0.267	0
BECCS	0	0	0	0	0.333	0.134	0.333	0.2	0	0
Biochar	0.018	0.164	0	0.182	0.454	0	0	0.182	0	0

water availability, the level of water stress (FAO, 2022a) was adopted. Cost factor was indicated by GNI per capita (World Bank, 2021). For energy availability, the percentage share of each countries' energy that is generated from low carbon energy sources (IEA, 2020; Ritchie et al., 2020) was adopted. This is to ensure that the deployment of energy-dependent GGR methods does not result in additional CO₂ emissions. Data for the other selected criteria were obtained as follows; geological CO₂ storage potential (IEAGHG, 2011; Kearns et al., 2017), biomass availability (IRENA, 2021) and Vegetation type (FAO, 2022b).

The obtained raw data was pre-processed into a useable form by numerical encoding of string type data and analytical determination of incomplete data. Data normalisation was also carried out between 0 and 1 for the entire dataset to eliminate any potential bias brought about by differences in range of values among the variables.

2.5. Maximum cumulative GGR potential

Using the simple additive weighting (SAW) or weighted sum method (WSM), the performance score for each country in deploying each of the

five GGR technologies was obtained. This method was applied because of its convenience in calculation and the requirement of attributes (variables) to be independent. Using the obtained performance score as a fraction of the total scores, the share of each country's maximum cumulative carbon removal potential for each GGR technology was then evaluated from the projected global maximum cumulative potential by 2100 reported by Rueda et al. (2021) based on their review of the literature. Fig. 2 presents the curves of the global potential of GGR technologies, with the area under the curve indicating the maximum cumulative potential by 2100 (total) as shown.

3. Results and discussion

3.1. Global GGR potential

Using the MCDA approach, the maximum cumulative CDR potential by 2100 via five technologies was obtained for 182 countries on the basis of their bio-geophysical and techno-economic characteristics. The GGR technologies considered are forestation, EW, DACCS, BECCS and

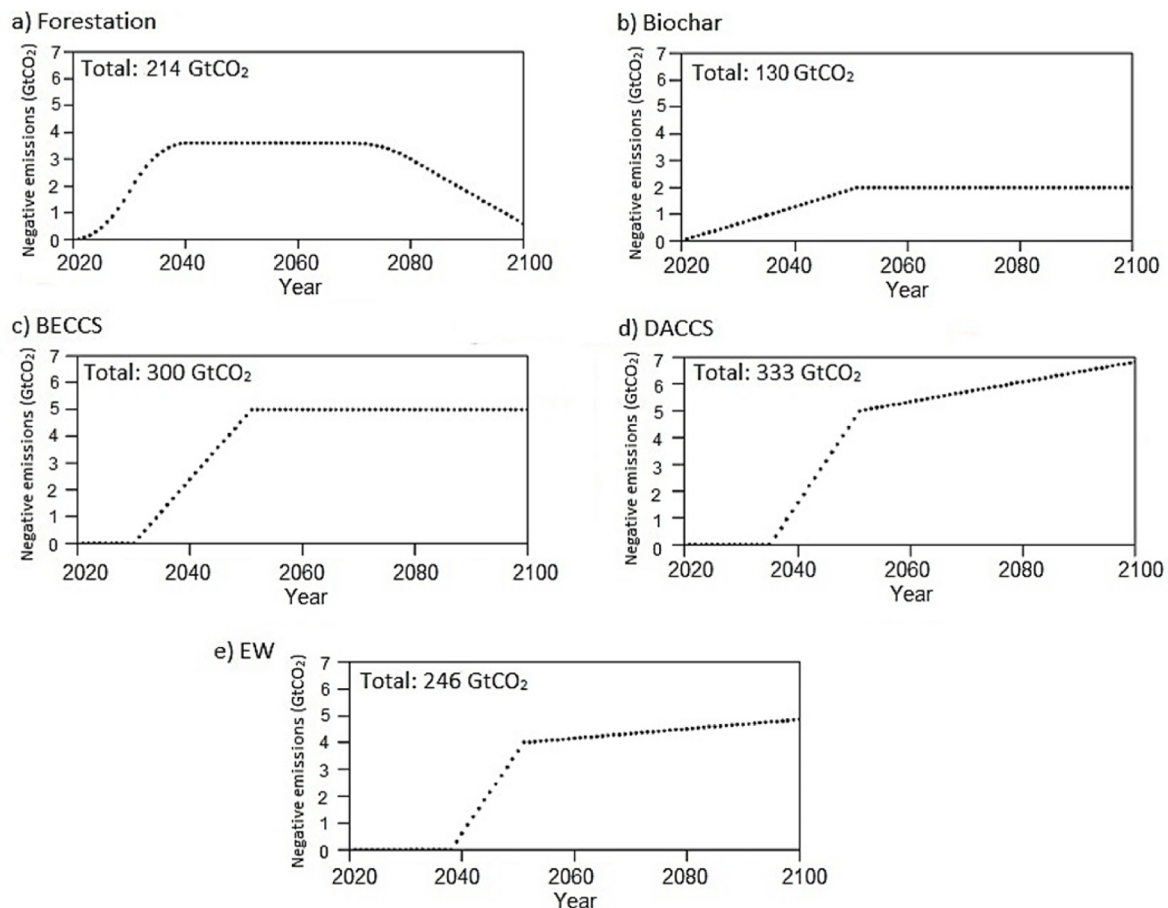


Fig. 2. Curves of GGR technologies potential for 2020–2100. a) forestation, b) biochar, c) BECCS, d) DACCS, e) EW (reprinted with permission from Rueda et al. (2021), Copyright 2021 Elsevier).

Biochar. Fig. 3 presents global maps showing the CDR potential of these countries for the five GGR methods considered.

According to Fig. 3a, countries in LAM, SSA as well as South East Asia were found to have the highest CDR potential via forestation accounting for about 60% of the global potential. This is mainly because of their favourable tropical climatic conditions and vegetation characteristics. These countries, including Brazil, Brunei, Malaysia, Colombia, Costa Rica, Venezuela, Panama and the Democratic Republic of Congo, are largely in agreement with the priority regions identified by Roe et al. (2021). Countries in MNAF had the lowest CDR potential (5%) because of their arid climatic conditions. The OECD and REF countries accounted for about 27% on account of low land availability and less favourable climatic characteristics.

The assessment for EW was based on the assumed scenario of available rock resources for all countries, due to lack of available data. From Fig. 3b, OECD and LAM countries had the highest potential for this technology (21% each) with major countries including Australia, New Zealand, Brazil, USA, Canada, Costa Rica and EU countries among others. This is as a result of their high GNI per capita (high financial capability) and available agricultural land for spreading the weathered rocks. Asian countries such as Singapore, China, Japan and Malaysia, as well as Middle Eastern countries like Saudi Arabia and Qatar were also identified as areas with high EW deployment potential. Parts of Central and Southern Africa were also identified as priority areas largely on account of the availability of low carbon energy. Given the high capital and energy requirement for this technology, most countries within MNAF, and parts of Asia and SSA were found to have a low potential for deploying this technology largely due to their low financial capability and development.

As shown in Fig. 3c, OECD and REF countries with appropriate geological storage sites jointly accounted for 40% of the global DACCS potential. This is majorly because of their high financial capability given the high-cost requirement of deploying DACCS. This was closely followed by SSA and LAM which jointly accounted for 38% of the global potential. This is because of the availability of low carbon energy in these regions. Major countries identified include USA, Canada, Australia, Norway, Brunei, Saudi Arabia, the Netherlands, New Zealand, Russia and the UK. Developing countries (especially in SSA) and those without appropriate geological storage sites such as Azerbaijan, Haiti, Burkina Faso, Moldova, and Malawi had the lowest DACCS deployment potential.

With the CDR potential of BECCS greatly hinged on the availability of biomass and appropriate geological storage sites, the same countries that had the low potential to deploy DACCS deployment were also found to have low BECCS CDR potential on account of the latter factor. Given that some of these countries are characterised by available biomass, they might still play a key role in BECCS deployment through collaboration with neighbouring countries with geological storage sites. From the BECCS CDR potential map shown in Fig. 3d, major countries for this GGR technology include Brazil, Russia, USA, Canada, Australia, and the other tropical countries in LAM (18%), SSA (21%) and South-East Asia. These identified countries are in agreement with the priority regions identified by Roe et al. (2019). Though the BECCS potential of the EU is limited by the availability of biomass, its relatively high financial capacity is expected to play a major role in enhancing its potential through options such as biomass importation.

For biochar (Fig. 3e), countries in LAM (25%) and OECD (21%) were found to have higher CDR potential with the major ones, including Brazil and the USA. Other countries with relatively high potential include Russia, Costa Rica, Malaysia, Brunei, Indonesia and Venezuela. However, it is important to note that the impact of soil characteristics was not considered in this assessment because of the complexity of interacting factors (Lorenz and Lal, 2014; Nair et al., 2017) and inadequate country-level data availability. Hence, this assessment was based on the generally accepted fact that biochar effects on soil are biochar-, soil-, and plant-specific, thus all countries were assumed to meet the soil

characteristics requirement. MNAF countries, however had low CDR potential (7%) on account to their arid climate and low biomass availability.

This study builds on previous studies which have been largely limited to natural climate solutions (NCS) including Forestation, BECCS and Biochar. Our identified areas of high potential to deploy these technologies are broadly in line with previous studies with Griscom et al. (2020); Roe et al. (2021, 2019) reporting tropical countries of LAM, SSA and Asia to have the highest NCS mitigation potential estimated at 6.51 GtCO₂e yr⁻¹. Beyond these NCS-based technologies, novel country-level assessment of two other mitigation pathways (EW and DACCS) have also been presented. Given the maturity of forestation, lots of progress has been made with regards to large-scale deployment. While most countries have included forestation and other land-use related measures in their NDCs (Roe et al., 2021), other international programmes such as the Bonn Challenge, New York Declaration on Forests (NYDF) have also been set up to drive the deployment of this method. While encouraging more actions in the restoration of forests, it is also important to ensure that efforts are made by governments to address the challenges of degradation and deforestation. This is very key because the 1.5 °C roadmap requires deforestation to decline 70% by 2030 and 95% by 2050 (Roe et al., 2019). While all five technologies are at varying technological readiness levels (TRLs) (Haszeldine et al., 2018; The Royal Society, 2018) with their projected timeline of deployment captured in Fig. 2, the need for increased investment in R&D cannot be over-emphasised if the mitigation target is to be met.

This study has explored the domestic potential of nations to deploy these technologies based on their respective available in-country resources. While this is aimed at enabling countries identify the suite of GGR technologies they can sustainably and efficiently deploy, it will also provide insight on areas they will require collaborations to boost their potentials. The actual decision making will require a consideration of resource sharing opportunities such as geological storage sites, as well as importation of resources such as biomass and low carbon energy. A consideration of how the deployment of potential GGR options will impact on existing resources will also influence the decision-making process. This is to ensure that adopted GGR options do not create a competition for resources such as land, water, and renewable energy, and compromise other societal objectives such as the Sustainable Development Goals which includes food security and biodiversity conservation (Batalini de Macedo et al., 2022; Fajardy et al., 2019; Förster et al., 2022).

3.2. Assessing the CDR quotas

Having obtained the cumulative CDR potential for 5 GGR technologies for the 182 countries considered, a comparative assessment was carried out on the basis of the work of Pozo et al. (2020), who allocated the global CDR quota of 687 GtCO₂ (IPCC SR1.5 'middle-of-the-road' P3 scenario (IPCC, 2018)) to 176 countries. This allocation of the CDR burden was carried out under 3 equity sharing principles of Responsibility (based on historical emission liability of countries); Capability (based on the financial ability of countries) and Equality (based on the population size of countries). Using their findings, we compared the obtained domestic CDR potential for each country with the quotas allocated under the 3 equity sharing principles. This was done to identify countries that will be able to meet up with their allocated quotas domestically using these five GGR methods as well as areas that will require regional partnerships and collaborations. Fig. 4 presents the country-level cumulative CDR quotas and potential by 2100.

For Asia (Fig. 4a), most member countries can domestically meet their respective CDR quotas under the three principles. The exceptions are China, India, Indonesia, and Pakistan, who cannot meet their Equality-based quota brought about by their relatively high population. For Singapore and South Korea, their respective CDR potential did not meet up with their Capability-based quota brought about by their high

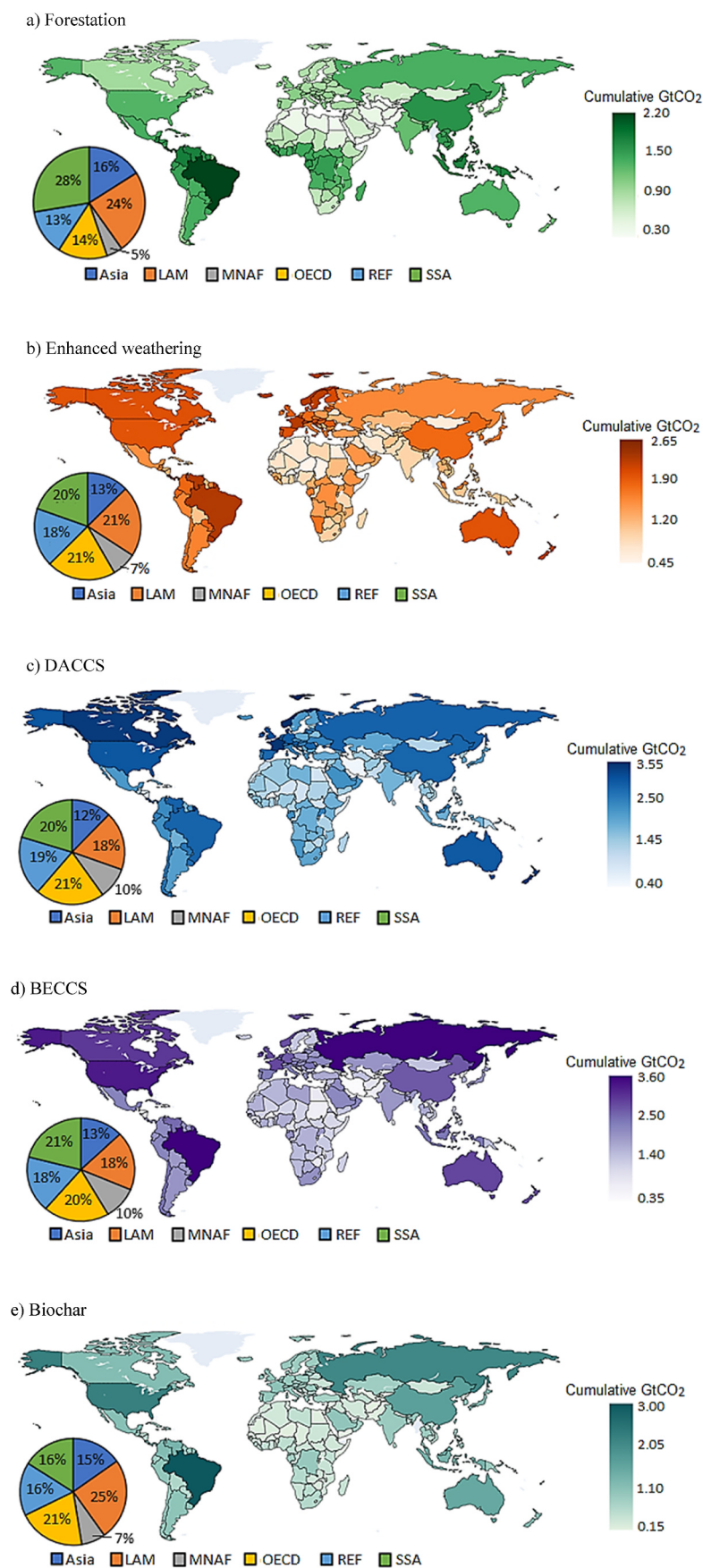


Fig. 3. Maximum cumulative carbon dioxide removal (CDR) potential by 2100: Forestation (a), Enhanced weathering (b), DACCS (c), BECCS (d) and Biochar (e). Countries are coloured according to their potential so that the darker the shade, the larger the CDR potential. Pie charts show the results aggregated into six regions (OECD, includes the countries in the OECD as of 1990; REF, reforming economies of Central and Eastern Europe and the Former Soviet Union; ASIA, Asian countries with the exception of the Middle East, Japan and Former Soviet states; MNAF, countries of the Middle East and North Africa; LAM, Latin America and the Caribbean; SSA includes Sub-Saharan countries; see the full list of countries in each region in [Supplementary Table S1](#)). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

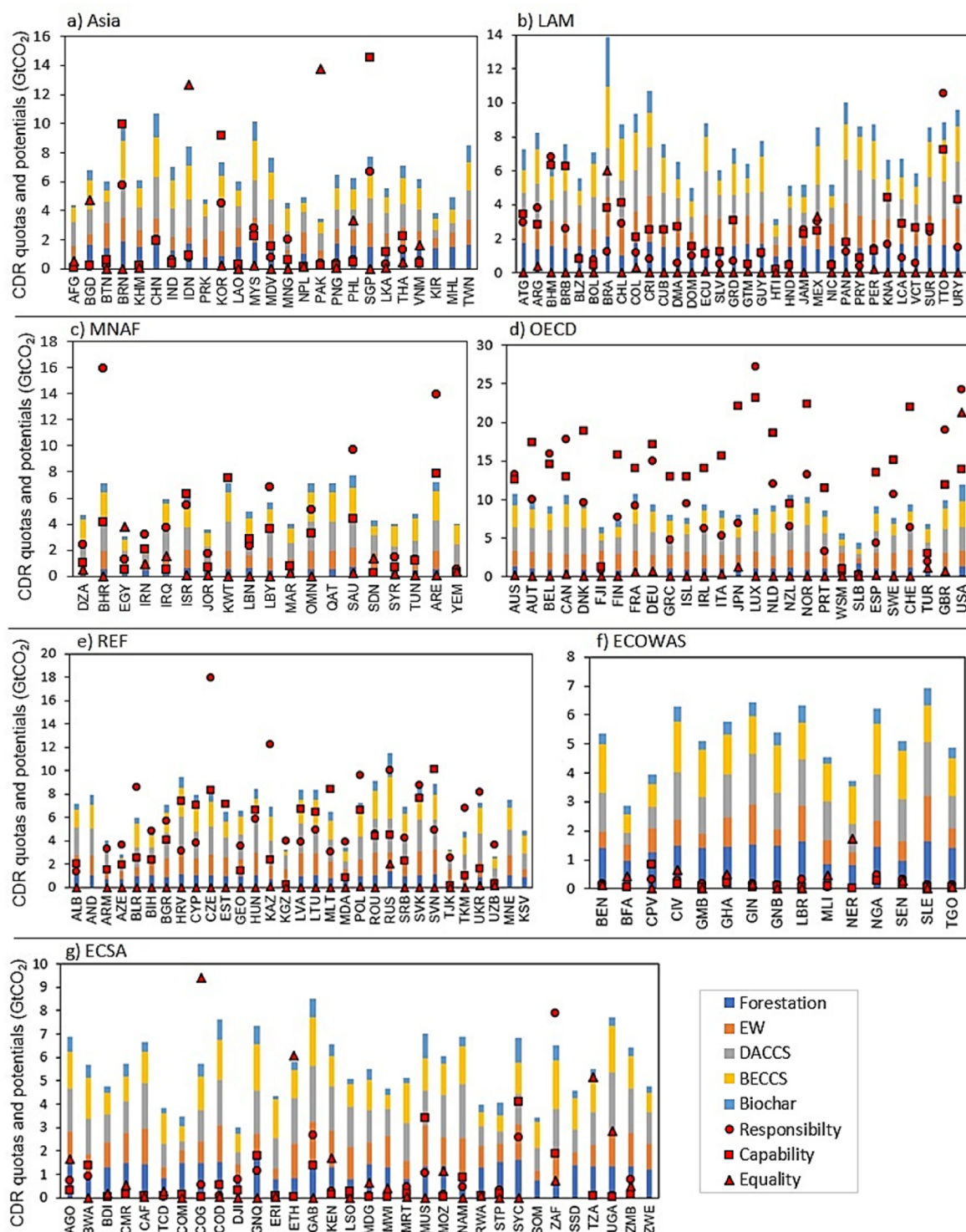


Fig. 4. Comparison of Country-level cumulative CDR quotas (Poza et al., 2020) and the obtained potential by 2100: a) Asia, b) LAM, c) MNAF, d) OECD, e) REF, f) ECOWAS, and g) ECSA. (The CDR quota by equality for China (CHN), India (IND) and Nigeria (NGR) are not featured on the map on account of the relatively large value. SSA was split into ECOWAS (West African countries) and ECSA (East, Central and Southern Africa) for better visualisation).

GDP per capita. CDR quota data for Kiribati, Marshall Islands and Taiwan were unavailable.

While all the LAM countries (except Trinidad and Tobago) were able to meet their quotas under the three principles (Fig. 4b), Bahrain, Saudi Arabia and the United Arab Emirates were the only exceptions for the MNAF region (Fig. 4c) as their CDR potential did not meet their Responsibility based quotas. For the OECD group (Fig. 4d), only four

member-countries (Fiji, Samoa, Solomon Islands and Turkey) met their quotas under all principles. This is largely because most of the other countries were allocated relatively higher CDR quotas under Responsibility and Capability principles as they constitute the bulk of the most industrialised (high historical emissions) and wealthiest nations of the world. They all, however, met their Equality-based quotas, with the only exception being the USA.

All the REF countries (Fig. 4e) met their quotas under the three principles except for Belarus, Czech, Estonia, Kazakhstan, Turkmenistan, Poland and Ukraine, which did not meet their Responsibility-based quotas. Malta, Estonia and Slovenia did not also meet their respective Capability-based quotas. CDR quota data for Kosovo and Montenegro were unavailable. For ECOWAS (Fig. 4f), only Nigeria did not meet its CDR quota for all three principles, with the Equality-based quota being the outstanding one on account of its high population. For East, Central and Southern Africa (ECSA), countries whose CDR potential did not meet their quota include the Republic of Congo, Ethiopia and South Africa.

Though this assessment has evaluated the maximum cumulative CDR potential by 2100, it is important to note that actual deployment is expected to be lower on account of factors such as deployment delay, the scale of deployment, and discount rate (Rueda et al., 2021) as well as socio-political considerations. While this may result in many countries not being able to meet up with one or more of their principle-assigned quotas (responsibility, capability, equality) domestically, a look at the regional comparison (Fig. 5) presents very useful evidence on the need for regional co-operation in the attainment of the emission mitigation target. As shown, all the regions except Asia, MNAF and OECD can meet up with all their quotas under the 3 principles. For SSA and LAM, which are majorly developing countries, it can be observed that a combination of the cheaper GGR options (Forestation, biochar and BECCS) will be sufficient to meet up with their respective quotas. While the high population of China and India presents a high quota burden for Asia by the Equality principle, the high level of industrialisation and wealth of the OECD members presents a higher CDR burden beyond their CDR potential. Given the impact of bio-geophysical constraints and with the OECD expected to drive the development and deployment of these technologies, one major way to address their potential deficit will be to collaborate with regions having surplus CDR potentials such as LAM and SSA through the provision of the needed financial support and investments, especially in the deployment of the more expensive engineered solutions (DACCS, EW and BECCS).

3.3. Sensitivity analysis of weight

In order to minimise the impact of probable subjectivity in the applied criteria weighting system (base wt) and account for uncertainties, a sensitivity analysis was carried out to evaluate the robustness and stability of the obtained output (CDR potential and regional share) by assessing the impact of other weighting systems. For each GGR method, four criteria weight allocation scenarios (weighting systems) were considered: Equal weight scenario and three dominant variables scenarios (50%, 60%, 70%). While the same weights were assigned to all the variables under the Equal weight scenario, the dominant variables scenario involved assessing the impact of assigned weights (50%, 60%, 70%) on key factors (criteria) that influence the

performance of the respective GGR methods. For forestation, land availability & vegetation type (LV) was considered; for EW, cost and low carbon energy availability (CE); for DACCS, cost and geological storage potential (CS); for BECCS, geological storage potential and biomass availability (SB); and for biochar, biomass availability (B). Details of the various weighting systems for the five GGR methods are presented in Tables S2–S6 in Supplementary Information.

Fig. 6 presents the sensitivity analysis of the weights. Variation in the obtained CDR potential ranged from less than 3%–15%, with overall changes in regional share less than 5% for forestation, EW, DACCS and BECCS. For biochar, the four modified weighting scenarios returned similar and consistent outputs (robust) for OECD, REF and SSA that varied with those obtained for the applied base wt. Based on changes in regional share, the uncertainty in the applied weighting system for forestation, EW, DACCS and BECCS is set to 5%, while that of biochar is set to 20%.

3.4. Limitations and recommendations

The deployment potential of five GGR technologies has been obtained for 182 countries. In this section we highlight limitations and recommendations to guide and ensure best use of the obtained results. Given that the study is based on MCDA, it consequently inherits the strengths and limitations of this methodology. While the MCDA has proven to be a valuable approach in solving problems with multiple objectives, a key limitation lies in the subjective nature of some of its crucial components such as the criteria weighting (Kujawski, 2003; Wang et al., 2009). To ascertain the robustness of the results and examine the impact of the criteria weights, sensitivity analysis was carried out using alternative weightings (section 3.3).

Another critical aspect is the availability of country-level data which was a key factor in the selection of criteria. All the major indicators of bio-geophysical and techno-economic factors required to assess the five GGR methods were selected as criteria and applied in the study. The only exception was in the case of EW in which availability of rock resources (basalt) was excluded because of unavailability of country-level data. An assumed scenario of available rock resources for all countries was however adopted for the EW assessment. This assumption is based on the widespread abundance of basalt which accounts for about 6.8 million km² of the earth's surface (about 4.56% of the world's land mass), with significantly more beneath the surface and under the oceans (Kantola et al., 2017).

While the study evaluated the cumulative GGR potential by 2100 based on bio-geophysical and techno-economic characteristics, it is important to note that the prevailing socio-political systems of the various countries will play a major role on the extent of deployment and choice of GGR options that will be eventually adopted from these outcomes. With this assessment largely based on estimates of currently available data, it is therefore recommended that the outcomes should be updated when new estimates are available.

4. Conclusions

A country-level assessment of the deployment potential of five GGR technologies, including forestation, enhanced weathering (EW), direct air carbon capture and storage (DACCS), bioenergy with carbon capture and storage (BECCS), and biochar, has been carried out. Using a multi criteria decision analysis (MCDA) approach consisting of bio-geophysical and techno-economic factors, priority regions for the deployment of these GGR technologies have been identified. The extent of carbon dioxide removable by 2100 via these technologies has also been estimated for each of the 182 countries considered. An assessment of the CDR quotas identified LAM, SSA and REF as the only regions with sufficient potential to meet their allocated quotas domestically under the three equity sharing principles. For the OECD, addressing their potential deficit will involve collaborating with regions having surplus CDR

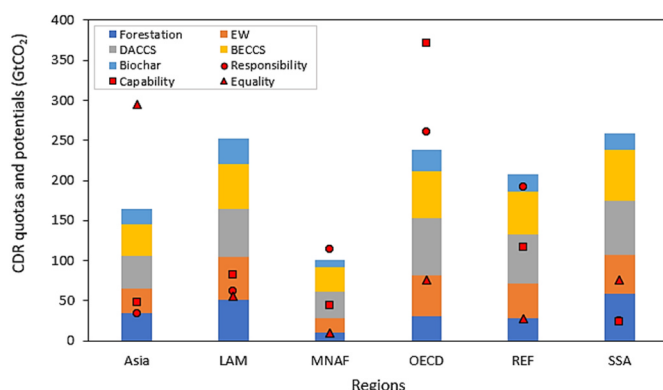


Fig. 5. Comparing regional cumulative CDR quotas and potential by 2100.

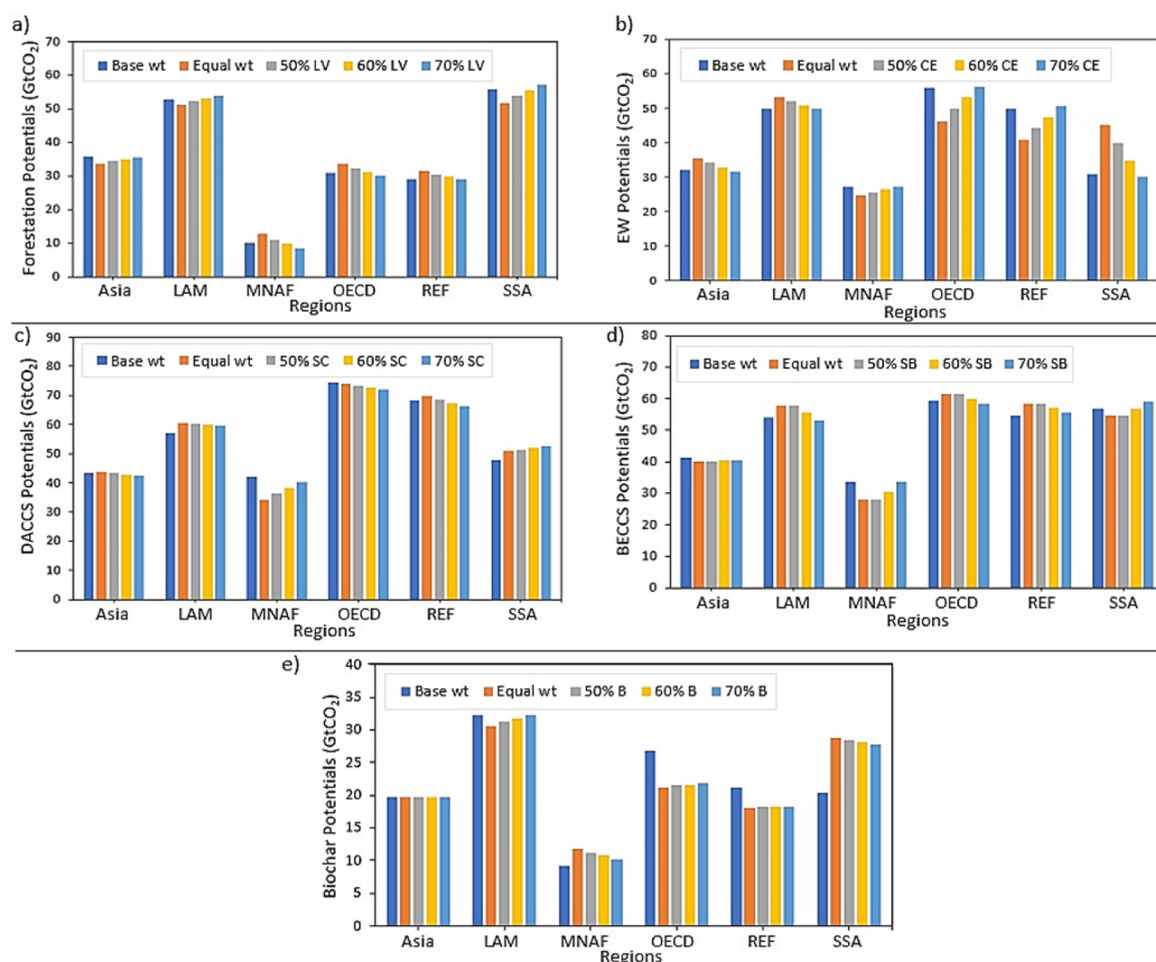


Fig. 6. Sensitivity analysis of weighting system: Forestation (a), Enhanced weathering (b), DACCS (c), BECCS (d) and Biochar (e). (Key: LV- Land availability & Vegetation type; CE- Cost & Energy availability; SC- Cost & Geological storage potential; SB- Geological storage potential & Biomass availability; B- Biomass availability).

potentials, especially LAM and SSA, through the needed financial support and investments. Sensitivity analysis of the criteria weighting system indicates the certainty of the obtained CDR potential to range from 80 to 95%. While the obtained results indicate the need for regional cooperation among countries, it also provides useful evidence on the need for countries to include and prioritise GGR technologies in their revised nationally determined contributions (NDCs).

Credit author statement

J.O. Asibor: Conceptualisation, Methodology, Software, Formal Analysis, Investigation, Writing - Original Draft. **P.T. Clough** - Conceptualisation, Writing - Review & Editing, Supervision, Project administration. **S.A. Nabavi** - Conceptualisation, Writing - Review & Editing, Supervision. **V. Manovic** - Conceptualisation, Writing - Review & Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data underlying this study can be accessed through the Cranfield

University repository (CORD) at: <https://doi.org/10.17862/cranfield.rd.20427804>.

Acknowledgement

Jude O. Asibor is grateful to the Petroleum Technology Development Fund (PTDF), Nigeria, for doctoral study scholarship, award number: PTDF/ED/OSS/PHD/JOA/077/19 and the University of Benin, Benin City, Nigeria.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2022.116211>.

References

- Alcalde, J., Smith, P., Haszeldine, R.S., Bond, C.E., 2018. The potential for implementation of negative emission technologies in Scotland. *Int. J. Greenh. Gas Control* 76, 85–91. <https://doi.org/10.1016/j.ijggc.2018.06.021>.
- Asibor, J.O., Clough, P.T., Nabavi, S.A., Manovic, V., 2021. Assessment of optimal conditions for the performance of greenhouse gas removal methods. *J. Environ. Manag.* 294, 113039. <https://doi.org/10.1016/j.jenvman.2021.113039>.
- Baik, E., Sanchez, D.L., Turner, P.A., Mach, K.J., Field, C.B., Benson, S.M., 2018. Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States. *Proc. Natl. Acad. Sci. U. S. A.* 115, 3290–3295. <https://doi.org/10.1073/pnas.1720338115>.
- Batalini de Macedo, M., Nóbrega Gomes Júnior, M., Pereira de Oliveira, T.R., H. Giacomoni, M., Imani, M., Zhang, K., Ambrogi Ferreira do Lago, C., Mendiondo, E.

- M., 2022. Low impact development practices in the context of united nations sustainable development Goals: a new concept, lessons learned and challenges. *Crit. Rev. Environ. Sci. Technol.* 52, 2538–2581. <https://doi.org/10.1080/10643389.2021.1886889>.
- Buylova, A., Fridahl, M., Nasiritousi, N., Reischl, G., 2021. Cancel (out) emissions? The envisaged role of carbon dioxide removal technologies in long-term national climate strategies. *Front. Clim.* 3 <https://doi.org/10.3389/fclim.2021.675499>.
- CIA, 2022. The World Factbook 2022 [WWW Document]. URL: <https://www.cia.gov/library/publications/resources/the-world-factbook/index.html>. (Accessed 10 June 2020).
- Donnison, C., Holland, R.A., Hastings, A., Armstrong, L.M., Eigenbrod, F., Taylor, G., 2020. Bioenergy with Carbon Capture and Storage (BECCS): finding the win-wins for energy, negative emissions and ecosystem services—size matters. *GCB Bioenergy* 12, 586–604. <https://doi.org/10.1111/gcbb.12695>.
- Element Energy, UKCEH, 2021. Greenhouse Gas Removal Methods and Their Potential UK Deployment.
- Fajardy, M., Köberle, A., Dowell, N.M.A.C., Fantuzzi, A., 2019. BECCS Deployment: A Reality Check. Grantham Institute Briefing paper No 28.
- FAO, 2022a. FAO-AQUASTAT database [WWW Document]. URL: <http://www.fao.org/g/nr/water/aquastat/data/query/results.html>. (Accessed 15 July 2020).
- FAO, 2022b. Global Ecological Zones (GEZ) mapping. Global Forest Resources Assessments [WWW Document]. URL: <https://www.fao.org/forest-resources-assessment/remote-sensing/global-ecological-zones-gez-mapping/en/>. (Accessed 1 March 2022).
- Förster, J., Beck, S., Borchers, M., Gawel, E., Korte, K., Markus, T., Mengis, N., Oschlies, A., Schaller, R., Stevenson, A., Thoni, T., Thrän, D., 2022. Framework for assessing the feasibility of carbon dioxide removal options within the national context of Germany. *Front. Clim.* 4 <https://doi.org/10.3389/fclim.2022.758628>.
- Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., De Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente, J.V., Wilcox, J., Del Mar Zamora Dominguez, M., Minx, J.C., 2018. Negative emissions - Part 2: costs, potentials and side effects. *Environ. Res. Lett.* 13 <https://doi.org/10.1088/1748-9326/aab9f9>.
- Griscom, B.W., Busch, J., Cook-Patton, S.C., Ellis, P.W., Funk, J., Leavitt, S.M., Lomax, G., Turner, W.R., Chapman, M., Engelmann, J., Gurwick, N.P., Landis, E., Lawrence, D., Malhi, Y., Murray, L.S., Navarrete, D., Roe, S., Scull, S., Smith, P., Streck, C., Walker, W.S., Worthington, T., 2020. National mitigation potential from natural climate solutions in the tropics. *Philos. Trans. R. Soc. B Biol. Sci.* 375 <https://doi.org/10.1098/rstb.2019.0126>.
- Haszeldine, R.S., Flude, S., Johnson, G., Scott, V., 2018. Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* 376 <https://doi.org/10.1098/rsta.2016.0447>.
- Haszeldine, S., Cavanagh, A., Scott, V., Sohi, S., Mašek, O., Renforth, P., 2019. Greenhouse Gas Removal Technologies-Approaches and Implementation Pathways in Scotland Executive Summary. ClimateXChange.
- Hepburn, C., Adlen, E., Beddington, J., Carter, E.A., Fuss, S., Mac Dowell, N., Minx, J.C., Smith, P., Williams, C.K., 2019. The technological and economic prospects for CO₂ utilization and removal. *Nature* 575, 87–97. <https://doi.org/10.1038/s41586-019-1681-6>.
- IEA, 2020. IEA Energy Atlas [WWW Document]. URL: <http://energyatlas.iea.org/#/te/llmap-1118783123/1>. (Accessed 15 September 2020).
- IEAGHG, 2011. Global Storage Resources Gap Analysis for Policy Makers.
- IPCC, 2022. Summary for policymakers. In: Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J. (Eds.), *Climate Change 2022: Mitigation of Climate Change*. Cambridge University Press, Cambridge, UK, pp. 1–30.
- IPCC, 2018. Global warming of 1.5°C an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. In: *The Context of Strengthening the Global Response to the Threat of Climate Change*.
- IRENA, 2021. Statistical Profiles [WWW Document]. URL: <https://www.irena.org/Statistics/Statistical-Profiles>. (Accessed 10 December 2020).
- Jiang, K., He, C., Dai, H., Liu, J., Xu, X., 2018. Emission scenario analysis for China under the global 1.5 °C target. *Carbon Manag.* 9, 481–491. <https://doi.org/10.1080/17583004.2018.1477835>.
- Kantola, I.B., Masters, M.D., Beerling, D.J., Long, S.P., DeLucia, E.H., 2017. Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. *Biol. Lett.* 13 <https://doi.org/10.1098/rsbl.2016.0714>.
- Kearns, J., Teletskiy, G., Palmer, J., Thomann, H., Khesghi, H., Chen, H., Paltsev, S., Herzog, H., 2017. Developing a consistent database for regional geologic CO₂ storage capacity worldwide. *Energy Proc.* 114, 4697–4709. <https://doi.org/10.1016/j.egypro.2017.03.1603>.
- Kujawski, E., 2003. Multi-criteria decision analysis: limitations, pitfalls, and practical difficulties. *Lawrence Berkeley Natl. Lab.* 13, 1169–1176. <https://doi.org/10.1002/j.2334-5837.2003.tb02692.x>.
- Lorenz, K., Lal, R., 2014. Biochar application to soil for climate change mitigation by soil organic carbon sequestration. *J. Plant Nutr. Soil Sci.* 177, 651–670. <https://doi.org/10.1002/jpln.201400058>.
- Maher, B., Symons, J., 2022. The international politics of carbon dioxide removal: pathways to cooperative global governance. *Glob. Environ. Polit.* 22, 44–68. https://doi.org/10.1162/glep_a.00643.
- Mulligan, J., Rudee, A., Lebling, K., Levin, K., Anderson, J., Christensen, B., 2020. CarbonShot: Federal Policy Options for Carbon Removal in the United States. World Resources Institute.
- Nair, V.D., Nair, P.K.R., Dari, B., Freitas, A.M., Chatterjee, N., Pinheiro, F.M., 2017. Biochar in the agroecosystem-climate-change-sustainability Nexus. *Front. Plant Sci.* 8 <https://doi.org/10.3389/fpls.2017.02051>.
- Pour, N., Webley, P.A., Cook, P.J., 2018. Opportunities for application of BECCS in the Australian power sector. *Appl. Energy* 224, 615–635. <https://doi.org/10.1016/j.apenergy.2018.04.117>.
- Pozo, C., Galán-martín, Á., Reiner, D.M., Dowell, N. Mac, Guillén-Gosálbez, G., 2020. Equity in allocating carbon dioxide removal quotas. *Nat. Clim. Change*. <https://doi.org/10.1038/s41558-020-0802-4>.
- Ritchie, H., Roser, M., Rosado, P., 2020. Renewable Energy - Our World in Data [WWW Document]. URL: <https://ourworldindata.org/renewable-energy>. (Accessed 14 June 2022).
- Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J., Emmet-Booth, J., Engelmann, J., Fricko, O., Frischmann, C., Funk, J., Grassi, G., Griscom, B., Havlik, P., Hanssen, S., Humpenöder, F., Landholm, D., Lomax, G., Lehmann, J., Mesnildrey, L., Nabuurs, G.J., Popp, A., Rivard, C., Sanderman, J., Sohngen, B., Smith, P., Stehfest, E., Woolf, D., Lawrence, D., 2021. Land-based measures to mitigate climate change: potential and feasibility by country. *Global Change Biol.* 1–34. <https://doi.org/10.1111/gcb.15873>.
- Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., Fricko, O., Gusti, M., Harris, N., Hasegawa, T., Hausfather, Z., Havlik, P., House, J., Nabuurs, G. J., Popp, A., Sánchez, M.J.S., Sanderman, J., Smith, P., Stehfest, E., Lawrence, D., 2019. Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Change* 9, 817–828. <https://doi.org/10.1038/s41558-019-0591-9>.
- Rogelj, J., Elzen, M. Den, Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., 2016. Paris Agreement climate change proposals need a boost to keep warming well below 2 °C. *Nature* 534. <https://doi.org/10.1038/nature18307>.
- Rueda, O., Mogollón, J.M., Tukker, A., Scherer, L., 2021. Negative-emissions technology portfolios to meet the 1.5 °C target. *Global Environ. Change* 67. <https://doi.org/10.1016/j.gloenvcha.2021.102238>.
- Schiermeier, Q., 2015. Combined climate pledges of 146 nations fall short of 2 °C target. *Nature* 2–4. <https://doi.org/10.1038/nature.2015.18693>.
- The Royal Society, 2018. Greenhouse Gas Removal. PostNote 1–5.
- Thoni, T., Beck, S., Borchers, M., Förster, J., Görl, K., Hahn, A., Mengis, N., Stevenson, A., Thrän, D., 2020. Deployment of NETs at the national level: a need for holistic feasibility assessments. *Front. Clim.* 2, 12.
- Wang, J.J., Jing, Y.Y., Zhang, C.F., Zhao, J.H., 2009. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renew. Sustain. Energy Rev.* 13, 2263–2278. <https://doi.org/10.1016/j.rser.2009.06.021>.
- World Bank, 2022. World Bank Climate Change Knowledge Portal [WWW Document]. URL: <https://climateknowledgeportal.worldbank.org/>. (Accessed 21 July 2020).
- World Bank, 2021. GNI Per Capita, Atlas Method (current US\$). Data [WWW Document]. URL: <https://data.worldbank.org/indicator/NY.GNP.PCAP.CD>. (Accessed 9 October 2021).



DSPACE

<https://dspace.org/>

A country-level assessment of the deployment potential of greenhouse gas removal technologies

Asibor, Jude Odianosen; Clough, Peter T.; Nabavi, Seyed Ali; Manovic, Vasilije

2022-09-13

Elsevier

<https://doi.org/10.1016/j.jenvman.2022.116211>

Asibor JO, Clough PT, Nabavi SA, Manovic V. (2022) A country-level assessment of the deployment potential of greenhouse gas removal technologies. *Journal of Environmental Management*, Volume 323, December 2022, Article number 116211