3RD INTERNATIONAL CONFERENCE ON

NEGATIVE CO_2 EMISSIONS

18 - 21 June 2024

CONFERENCE PROCEEDINGS

CORE THE GREENHOUSE GAS REMOVAL HUB

UK Research and Innovation

UNIVERSITY OF OXFORD

These conference proceedings contain extended abstracts submitted to the *3rd International Conference on Negative CO_2 Emissions*. While these abstracts were all selected for presentation at the conference, the contents have not undergone formal peer review.

Suggested citation: Lutz, N. & Smith, S.M. (Eds.). (2025). *3rd International Conference on Negative CO_2 Emissions Conference Proceedings*. Oxford. https://doi.org/10.5287/ora-o1yjzd6vx.

Acknowledgements

We extend our sincere thanks to all participants of the *3rd International Conference on Negative CO_2 Emissions* for their valuable contributions. We are especially grateful to the authors of the abstracts included in this proceedings document for sharing insightful summaries of their research.

Our appreciation goes to the members of the Scientific Committee for their expert guidance in shaping the conference themes: Dr Steve Smith, Dr Roger Aines, Professor Myles Allen, Dr Holly Jean Buck, Dr Annette Cowie, Dr Habiba Ahut Daggash, Professor Dr Sabine Fuss, Dr Oliver Geden, Professor David Ho, Dr Jo House, Professor Rob Jackson, Dr Jasmin Kemper, Professor Anders Lyngfelt, Professor Jaime Palter, Dr Glen Peters, Dr Phil Renforth, Professor Ros Rickaby, Professor Colin Snape, Dr Nem Vaughan, and Professor Detlef van Vuuren.

We are also deeply thankful to the Organising Committee for their tireless efforts in bringing the vision of this conference to life: Professor Myles Allen, George Hope, Umme Imani, Mikal Mast, Dr Steve Smith, Anna-Marie Sturrock, Dr Philippa Westbury, and Heather Waller.

Special thanks to Natasha Lutz for compiling this document.

Foreword

The *3rd International Conference on Negative CO_2 Emissions* brought together a global cohort of experts from academia, industry, and policy to share the latest knowledge on negative emissions technologies and practices (NETPs). Held in Oxford from 18–21 June 2024, the hybrid event hosted 360 in-person attendees and 150 online participants.

The conference addressed a breadth of NETPs. Principally these focussed on carbon dioxide removal (CDR), including biochar, Bioenergy with Carbon Capture and Storage (BECCS), coastal ecosystems (blue carbon), Direct Air Carbon Capture and Storage (DACCS), enhanced weathering, forestry, ocean alkalinity enhancement, ocean fertilisation, peatland and wetland restoration, and soil carbon sequestration. Other NETPs aimed at removing non-CO_2 greenhouse gases such as methane were discussed as well.

Technical sessions discussed the developments in the fundamental science and technology underpinning NETPs, as well as approaches for robust and transparent monitoring, reporting, and verification. Analysis of emerging policies to incentivize or regulate NETPs were presented, as well as the economic costs or benefits of these interventions. Other themes included the social and ethical dimensions of NETPs, the need for lifecycle and techno-economic assessments, and systems integration. The climate system effects of negative emissions, impermanent removals and overshoot, and strategies for removing non-CO_2 greenhouse gases were also explored.

This proceedings document presents a collection of extended abstracts from a range of presentations at the conference. They reflect the diversity of work currently being undertaken on the frontier of negative emissions research. The abstracts span engineering, economics, environmental science, and policy, offering insights into both technical innovation and systems-level approaches to climate change mitigation. This document serves as a reflection of the rich discussions held and knowledge shared.

Reducing emissions of greenhouse gases remains essential to limit climate change. Alongside, technologies and practices to generate negative emissions are also increasingly important if the goals of the Paris Agreement are to be met. One particularly noteworthy – and encouraging – theme throughout the conference was the importance of a holistic view of NETPs, carefully considering their integration with decarbonisation and with broader environmental and social goals.

The University of Oxford and the CO_2RE project were proud to host the *3rd International Conference on Negative CO_2 Emissions*, taking on the mantle from colleagues at Chalmers University in Gothenburg, Sweden, who envisioned and hosted the first two of these conferences. The relevance of negative emissions and the vitality of this research community continue to grow. We look forward to future editions of the conference in new locations and with new contributors.

Steve Smith
University of Oxford
2025

Overview of papers

Attributional and consequential GHG life cycle assessment of bioenergy supply chains with carbon capture and storage 8
Alvarado Cummings SC., Duden, A., Junginger, M., van de Hilst, F.

Assessing life cycle methods for scalable carbon dioxide removal 10
Butnar I., Lynch J., Vetter S., Gamaralalage D., Tang Y., McKechnie J., Foteinis S., Rodway-Dyer S., Röder M., Sogbesan M., Hastings A., Renforth P., Brander M., House, J.

Feeling the "pulse": long-term studies are key to understanding carbon dynamics in EW 12
Boito L., Steinwidder L., Rijnders J., Vienne A., Roussard J., Frings P.J., Vicca S.

Life cycle assessment and techno-economic assessment of two CDR processes based on the storage of CO_2 as bicarbonates in seawater 14
Campo F., van der Spek M., Grosso M., Caserini S.

Engineering challenges of storing CO_2 as bicarbonates in seawater for CO_2 storage and removal ... 16
Caserini S., Macchi P., Raos G., Varliero S., Campo F., Bisters V., Cappello S., Cappello G., Grosso M.

Representing the demography of the UK forest diversity using a process-based land surface model 18
Chou H.-K., Harper A.B., Argles A.A., Duran Rojas M.C., Littleton E.W., Betts R.A., Cox P.M.

Direct air capture by monoethanolamine absorption with heat pump enhancements 21
de Joannis P., Castel C., Kanniche M., Favre E., Authier O.

Surge in tropospheric methane concentrations: new analysis and development of new NETs 23
de Richter R., Ming T., Li W.

Coupled uncertainty in NETs and transient climate response to cumulative CO_2 emissions 25
Di Natale C.M., Schaber T., Tran G.T., Keller D.P., Susiluoto J., Ekholm T., Partanen A.-I.

Measures of efficiency to compare the carbon sequestration potential of forestation and BECCS . 27
Egerer S., Falk S., Mayer D., Nützel T., Obermeier W.A., Pongratz J.

Managing intermittency of renewable power in sustainable production of methanol, coupled with direct air capture 29
Fulham G.J., Mendoza-Moreno P.V., Marek E.J.

The importance of distinguishing between natural and managed tree cover gains in the moist tropics. 31
Gao X., Reich P.B., Vincent J.R., Fagan M.E., Chazdon R.L., Fritz S., Schepaschenko D., Potts M.D., Hansen M.C., Jung M., Brancalion P.H.S., Uriarte M., Keenan T.F., Crowther T.W., Dubayah R.O., Lesiv M., Liang S., Wang D.

Assessing current and future CDR potentials for Germany using a multistep assessment framework 33
Gulde F., Witting M., Winkler K., Neuber F., Baatz C., Garschagen M.

Impacts of CO_2 loading on the stability of aminopolymer sorbents for direct air capture 35
Guta Y., Li S., Calegari Andrade M.F., Hunter-Sellars E., Maiti A., Pang S., Sievers C., Jones C.W.

Quantifying persistent aromatic carbon (PAC) in biochar 37
Hagemann N., Leifeld J., Wolf R., Kamra V., Herdegen V., Vosswinkel S., Schmidt H.-P., Meredith W., Uguna C., Snape C.E.

Public perceptions and socially responsible direct air capture in Teesside 39
James M., Carter N., Brown R.

Feasible deployment of carbon capture and storage and the requirements of climate targets 41
Kazlou T., Cherp A., Jewell J.

Does Europe need carbon dioxide removals? A large portfolio of negative emissions technologies and practices in scenario modelling for carbon neutrality 43
Koponen K., Markkanen J., Lehtilä A., Similä L., Koreneff G., Koljonen T.

Policies to incentivise the efficient use of CDR in agriculture: Economic assessment and stakeholder perception of policy instrument strategies 45
Korte K., Strauss V., Gawel E., Markus T., Paul C., Schaller R.

Atmospheric CO_2 removal deposits (ACORDs) – a policy tool designed to fulfil the 1.5-degree target 47
Lyngfelt A., Fridahl M., Stenström O.

The state of innovation in carbon dioxide removal 49
Müller-Hansen F., Minx J.C., Probst B., Nemet G., Edwards M., Toetzke M., Lück S., Repke T., Greene J., Thomas Z., Surana K., Kennedy K., Zaiser A., Hoffmann V., Diaz Anadon L., Engelmann T.

Tightening the 'net': fair and legitimate mechanisms for matching removals and residuals 52
McLaren D.P.

Earth system trade-offs and responses to large-scale carbon dioxide removal portfolio deployment 54
Moustakis Y., Wey H.-W., Nuetzel T., Oschlies A., Pongratz J.

The economics of carbon dioxide removal technologies using equilibrium modelling 55
Presty R., Massol O., da Costa P.

Spatial analysis of CDR implications for global biodiversity refugia 57
Prütz R., Rogelj J., Fuss S., Price J., Forstenhäusler N., Warren R., Augustynczik A.L.D., Havlík P., Kraxner F.

Monitoring, reporting and verification of greenhouse gas removals: untangling the web 59
Rodway-Dyer S., House J., Martirosian N., Mouchos E., Thoppil M., Newport B.

Carbon dioxide removal: A source of ambition or of delays? 61
von Rothkirch J., Ejderyan O., Stauffacher M.

Current rates of carbon dioxide removal through afforestation and reforestation 64
Schwingshackl C., Gasser T., Houghton R.A., Pongratz J.

Achieving BECCS with chemical looping combustion 66
Staničić I., Mattisson T., Brorsson J., Hellman A., Rydén M., Fortret Casabella J., Surywanshi G.D., Gastaldi J., Lyngfelt A.

Preconcentration of methane by vacuum-temperature swing adsorption for removal from air 69
Subraveti S.G., Mondino G., Blom R., Anantharaman R.

Sequencing carbon dioxide removals into the EU ETS 71
Sultani D., Osorio S., Günther C., Pahle M., Sievert K., Schmidt T.S., Steffen B., Edenhofer O.

Assessing a complex biochar system with circular economy principles 74
Sundberg C., Tibbetts H., Zakrisson L., Njenga M., Ndinda C., Kozyatnyk I.

Spatially analysis identifies the potential for biochar production in Great Britain 76
Tang Y., Gamaralalage D., McKechnie J., Cockerill T.T.

But when? Temporal compression in life cycle accounting for carbon dioxide removal.....................78
Tanzer S.E.

Attributional and consequential GHG life cycle assessment of bioenergy supply chains with carbon capture and storage

Conference session: Life Cycle Assessment (LCA)

Susan Alvarado Cummings[1,*], Anna Duden[1], Martin Junginger[1], Floortje van de Hilst[1]

[1] Utrecht University, Copernicus Institute of Sustainable Development, Department of Energy & Resource, Vening Meinesz building, Princetonlaan 8a, 3584 CB Utrecht, The Netherlands.

**Corresponding author - Email address: s.c.alvaradocummings@uu.nl*

Introduction

Bioenergy with Carbon Capture and Storage (BECCS) holds promise for achieving a negative GHG emission balance while generating power. Few studies examine GHG emissions through the whole supply chain during the transition from operational coal-biomass power plants to BECCS, especially concerning alternative feedstock uses and carbon stocks and flows over time.

Methods

This study conducts an attributional and consequential GHG life cycle assessment (LCA) for biogenic and fossil carbon in BECCS supply chains. The assessments use data from actual coal-biomass combustion plants, biomass suppliers, and CCS under-development projects. For the attributional LCA, we assess the coal-wood plants in 2021. Then, we compare them to BECCS projections for 2030, using wood pellets sourced from Louisiana, USA, for two facilities in the Netherlands (Plant 1 and Plant 2).

This study innovatively estimates GHG emissions of different fates for the feedstock. The consequential analysis compares in-forest decomposition, no thinning, alternative products, and wood pellet electricity to BECCS. The estimations include the replacement of a marginal electricity mix in 2030. Furthermore, we incorporate the calculation of carbon parity times, which signify how long it takes for BECCS to have the same cumulative GHG emissions compared to the alternatives.

Results

The preliminary attributional LCA shows that by 2030, transitioning to BECCS transforms both analysed plants from net positive to net negative CO_2 emitters (Figure 1). Using average values from the supply chain configurations for the plants, the cumulative emissions over 100 years indicate that wood pellet BECCS consistently achieves negative emissions. BECCS is favourable from the first year compared to alternative products and no thinning, and by the eighth year, it outperforms in-forest decomposition of harvest residues and commercial thinnings (Figure 2).

Conclusion

Our preliminary findings confirm that BECCS supply chains achieve negative emissions from an attributional and consequential perspective. This research highlights carbon trade-offs and offers insights to inform upcoming EU legislation on negative emissions and BECCS supply chains.

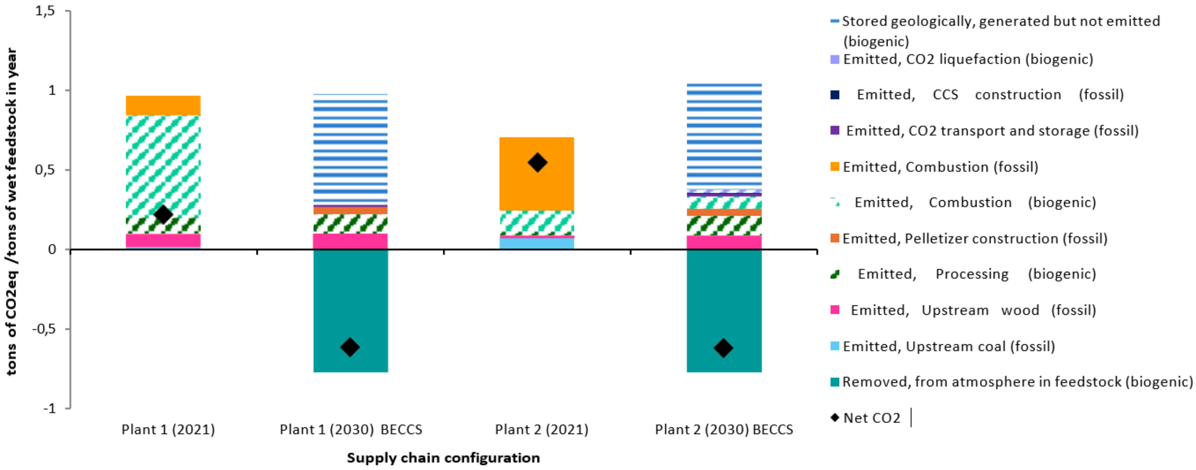


Figure 1. *Preliminary attributional LCA comparing CO_2 emissions of 2021 coal-biomass plants to 2030 BECCS plants.*

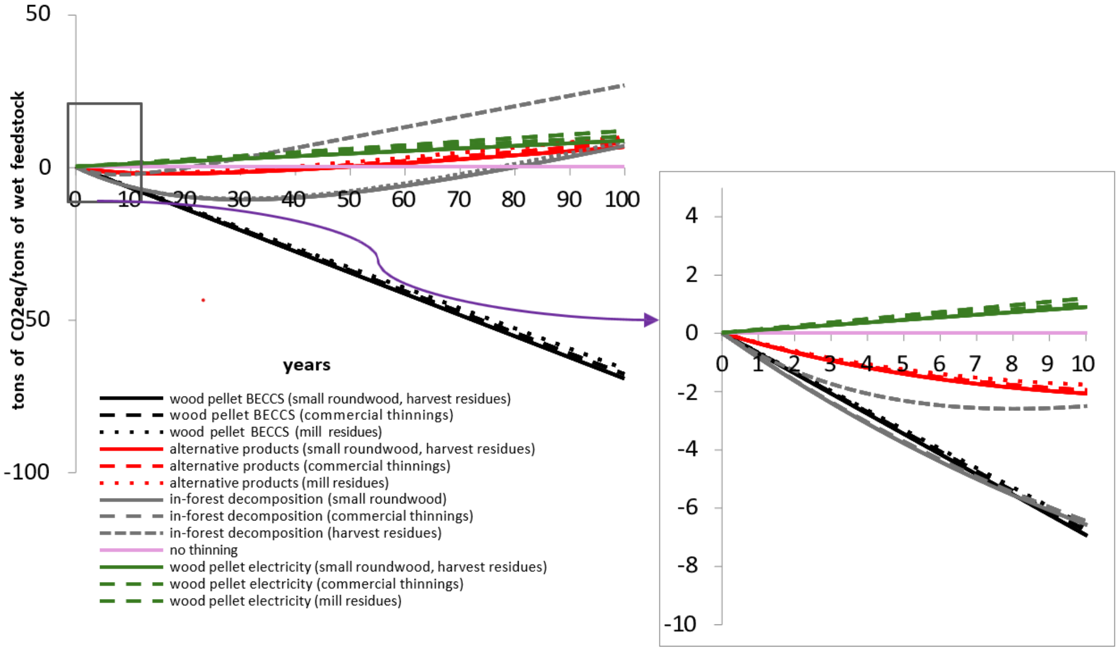


Figure 2. *Preliminary consequential LCA comparing cumulative emissions over 100 years for three wood feedstocks (commercial thinnings, harvest residues, and mill residues) and four alternative scenarios (wood pellet electricity, alternative products, in-forest decomposition, and no thinning).*

Assessing life cycle methods for scalable carbon dioxide removal

Conference session: Life Cycle Assessment (LCA)

Isabela Butnar[1], John Lynch[2], Sylvia Vetter[3], Disni Gamaralalage[4], Daolin Tang, Yuzhou Tang[5], Jon McKechnie[4], Spyros Foteinis[6], Sue Rodway-Dyer[7], Mirjam Röder[8], Samuel Sogbesan[8], Astley Hastings[9], Phil Renforth[6], Matthew Brander[10], Jo House[7]

[1] *University College London, Institute for Sustainable Resources, London, UK, WC1H 0NN, i.butnar@ucl.ac.uk*

[2] *University of Oxford, Department of Biology, Oxford, UK, OX1 3RB, john.lynch@biology.ox.ac.uk*

[3] *University of Aberdeen, Institute of Biological and Environmental Sciences*

[4] *University of Nottingham, Faculty of Engineering*

[5] *University of Leeds, School of Mechanical Engineering*

[6] *Heriot-Watt University School of Engineering and Physical Sciences,* [7] *University of Bristol, School of Geographical Sciences*

[8] *Aston University, EBRI*

[9] *University of Aberdeen*

[10] *University of Aberdeen, Business School*

Introduction

Life Cycle Assessment (LCA) has been historically used to investigate potential environmental impacts related to products and services. Given the increased visibility of Carbon Dioxide Removal (CDR) in the global policy arena, CDR-related LCA research increased exponentially in the last decade, addressing critical questions such as the quantification of removal potential[1], and the environmental consequences of deploying CDR.[2,3] However, the diversity of CDR approaches and the variety of LCA methods employed led previous LCA practitioners to conclude that these results should be interpreted with caution.[4,5] This work critically reviews LCA features which are of particular importance when informing the scaling-up of CDR approaches, exploring potential gaps and identifying best practices in using LCA methods to inform policy decision making.

Methods

We conducted a focused literature review of CDR LCA case-studies through the lenses of three key aspects relevant to policy decision-making on CDR scale-up: (1) comparability of results across CDR LCA assessments, (2) assessment of the climatic merit of a CDR intervention across its full life cycle, and (3) consideration of wider co-benefits and trade-offs associated with CDR interventions. From the initially identified 324 studies, we undertook in-depth review of 26 LCA studies selected for the completeness of their coverage, i.e. all stages from cradle-to- grave.

Results

Our findings reveal that whilst providing critical life cycle understanding, current practices utilise a mix of methods, usually attributional in nature, which are CDR and time specific. As a result, they do not allow comprehensive cross-comparison between CDRs, nor reveal potential consequences of scaling up CDRs in the future, e.g. negative impacts of CDR can be far greater when they are scaled-up. We suggest and discuss key criteria any LCA aimed at informing sustainable scaling-up of CDR should meet in terms of scope and goal definition, functional unit choice, system boundaries and baseline definitions, see Figure 1. This would allow for robust assessments, comparison with other CDR, and evidencing net climate benefits.

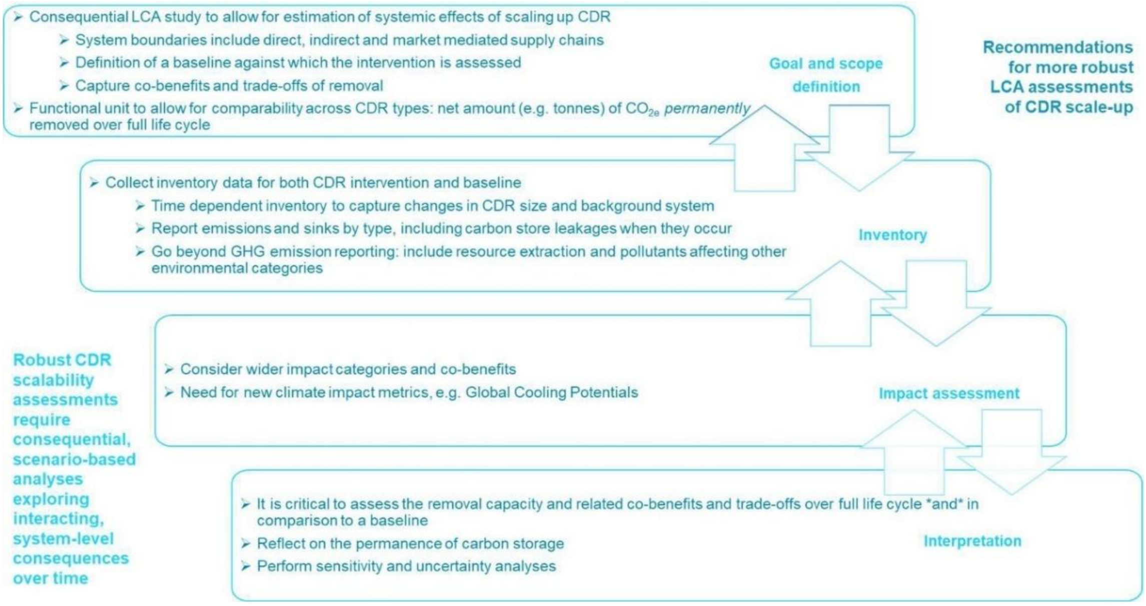


Figure 1. *Key recommendations for CDR LCA practitioners and users, split by LCA stage.*

Conclusion

This work reviews LCA features which are of particular importance when informing the scaling-up of CDR approaches, exploring potential gaps and identifying best practices in using LCA methods to inform policy decision- making. Our findings highlight that currently utilised LCA methods are not fully fit for informing scaling up of CDR. We provide 12 key recommendations to strengthen CDR LCA practices in order to provide robust CDR scalability assessment.

References

1. García-Freites, S., et al. The greenhouse gas removal potential of bioenergy with carbon capture and storage (BECCS) to support the UK's net-zero emission target. Biomass and Bioenergy, 151, 106164 (2001).
2. Terlouw, T., et al. Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources. Environmental Science and Technology, 55(16), 11397–11411 (2021).
3. Vetter, S., et al. Soil carbon sequestration and biochar. In M. D. N. Bui M (Ed.), Greenhouse Gas Removal Technologies, Royal Society of Chemistry, 194–243 (2022).
4. Goglio, P., et al. Advances and challenges of life cycle assessment (LCA) of greenhouse gas removal technologies to fight climate changes. Journal of Cleaner Production, 244, 118896 (2020).
5. Terlouw, T. Life cycle assessment of carbon dioxide removal technologies: A critical review. Energy and Environmental Science, 14(4), 1701–1721 (2021).

Feeling the "pulse": long-term studies are key to understanding carbon dynamics in EW

Conference session: Enhanced Rock Weathering (ERW) 2

Lucilla Boito[1], Laura Steinwidder[1], Jet Rijnders[1], Arthur Vienne[1], Jasper Roussard[1], Patrick Frings[2], Sara Vicca[1]

[1] *Biobased Sustainability Engineering (SUSTAIN), Department of Bioscience Engineering, University of Antwerp, Antwerp, Belgium, 2020, email: lucilla.boito@uantwerpen.be*

[2] *Earth Surface Geochemistry, GFZ German Research Centre for Geosciences, Potsdam, Germany, 14473*

Introduction and Methods

Enhanced silicate weathering (EW) applied on croplands is a promising technology for Carbon Dioxide Removal (CDR). So far, most research focused on lab-based weathering and sequestration rates, but these might differ substantially in field settings, where biota may have a strong effect on EW processes. Additionally, these studies are mostly short-term, thus limiting our knowledge on the long-term effects of silicate addition on croplands.

Here, we set up a mesocosm experiment (n = 44 pots) to quantify the carbon (C) sequestration of EW and how this is affected by biota. The experiment consisted of sandy-loam soils applied with basalt (n = 22, 50 ton/ha) and combinations of corn and/or earthworms (corn n = 32, corn + worms n = 16). It spanned over two growing seasons, for a total duration of 16 months. We measured i) Soil CO_2 Efflux (SCE) , ii) porewater and leachate water Dissolved Inorganic Carbon (DIC), pH and other elemental chemistry, and iii) soil pH and elemental chemistry in order to determine weathering rates.

During the growing seasons, SCE was measured every week with a portable EGM-5 infrared gas analyser (PP Systems, Hitchin, UK), and porewater samples were collected every other week with rhizon samplers (Rhizon Flex, Rizosphere Research Products B.V., Wagening, NL). During the fallow period, SCE measurements and porewater collection were performed monthly. Leachate waters were regularly collected and analysed. The aboveground biomass was harvested from all pots at the end of each growing season. At the end of the first growing season, half of the pots (n = 22) were harvested and soil samples were collected for pH and elemental analysis. At the end of the second growing season, the remaining pots were harvested and soil samples were collected.

Results

The porewater DIC indicates that, especially in the first growing season, the weathering process is active and there is an effect of plants emerging over time in basalt-amended pots (Figure 1). Hence, plants might play a crucial role in EW.

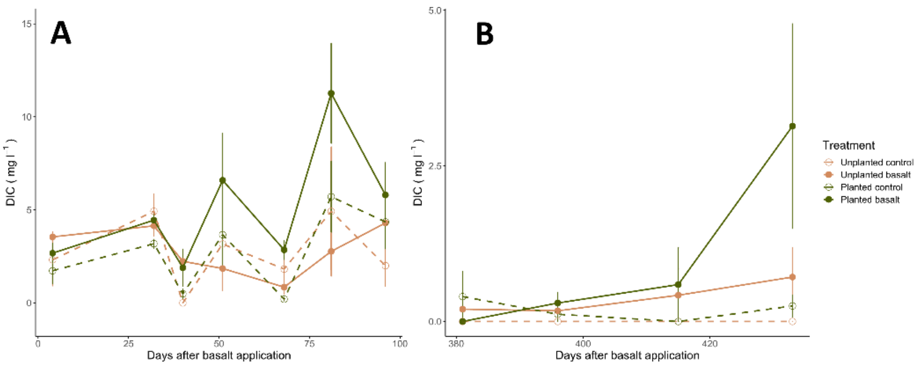


Figure 1. *Porewater DIC concentrations ± se during the experiment. (A) First growing season, showing a plant effect on DIC emerging over time in pots amended with basalt. (B) Second growing season. Here, there is also an effect of plant on DIC in basalt-amended pots, but it is emerging only at the end of the season. Note that the two y-axes (A, B) are not on the same scale.*

However, the weathering process is not directly reflected in the SCE fluxes. Our data shows that basalt had a different effect on SCE in the two growing seasons (Figure 2). In both seasons, the effect of basalt depended on plant presence, though in two different directions. In the first growing season, basalt increased emissions significantly compared to controls, but only when plants were present ($p=0.002$). In contrast, during the second growing season basalt almost-significantly decreased SCE over time compared to controls, but only in absence of plants ($p=0.066$). Here, there was no effect of basalt on SCE whenever plants were present.

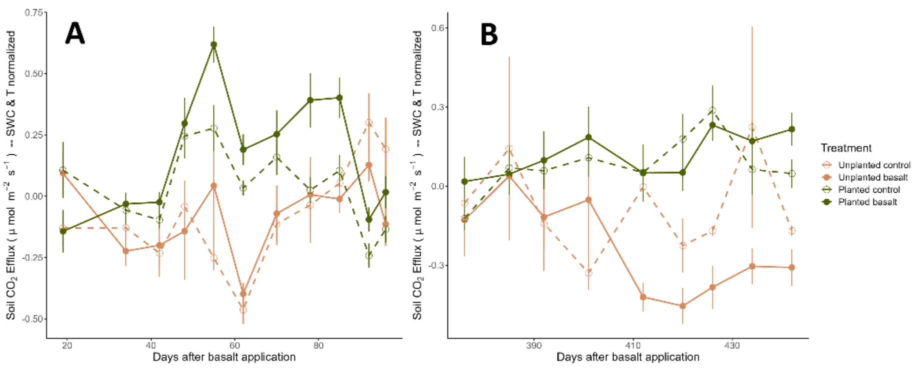


Figure 2. *Residual SCE ± se after normalizing for soil water content (SWC) and temperature (T). (A) First growing season, showing significantly higher SCE with basalt compared to control, for planted treatment. (B) Second growing season, showing SCE of unplanted pots with basalt decreasing over time compared to the control.*

Conclusion

These contrasting results suggest an initial stimulation of SCE ("pulse") due to basalt application, especially prominent in the presence of plants and possibly involving changes in soil organic carbon dynamics. These findings highlight the need for long-term studies that outlast this initial "pulse" and elucidate the fate of organic carbon in order to accurately quantify the CDR potential of EW.

Life cycle assessment and techno-economic assessment of two CDR processes based on the storage of CO_2 as bicarbonates in seawater

Conference session: Poster session

Francesco Campo[1,2], Mijndert van der Spek[3], Mario Grosso[1], Stefano Caserini[4]

[1] Dipartimento di Ingegneria Civile ed Ambientale, Politecnico di Milano, Milan, Italy, 20133, email: francescopietro.campo@polimi.it; mario.grosso@polimi.it

[2] Limenet s.r.l. Benefit Corporation, Lecco, Italy, 23900, email: francesco.campo@limenet.tech

[3] Research Centre for Carbon Solutions, School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, United Kingdom, EH14 4AS, email: M.Van_der_Spek@hw.ac.uk

[4] Dipartimento di Ingegneria e Architettura, Università di Parma, Parma, Italy, 43100, email: stefano.caserini@unipr.it

The storage of CO_2 in seawater through the discharge of a solution rich in bicarbonates at the same pH as the seawater has been proposed in the literature.[1,2] Here, we discuss the potential environmental impacts and costs of two configurations[3] for using this storage option for the CO_2 removed from the atmosphere to achieve negative CO_2 emissions.

The first one is an Ocean Alkalinity Enhancement (OAE) process, where a bicarbonates-rich marine solution obtained from the dissolution of external atmospheric CO_2 and slaked lime is released into seawater at the same pH as the sea. The process uses renewable electricity for limestone calcination, storing the CO_2 produced in the form of bicarbonates using a part of the slaked lime produced. The second is a mix of OAE and Bioenergy and Carbon Capture and Storage (BECCS) process, where biomass is grown and then gasified to produce the hot syngas needed for limestone calcination. The biogenic CO_2 released during the gasification is captured and stored in the form of bicarbonates in a pH-equilibrated solution discharged in the ocean, together with the CO_2 from the limestone calcination. The decarbonized slaked lime that is not used for buffering the CO_2 could be used for OAE.

The potential environmental impacts of the two CDR (Carbon Dioxide Removal) approaches are assessed using the Life Cycle Assessment methodology. In addition to the climate change impact that measures the efficiency of the process in removing CO_2, other 15 impact categories are analyzed according to the Environmental Footprint method implemented in Simapro software. The impacts are referred to a functional unit that is 1 tonne of atmospheric CO_2 removed and stored in the form of bicarbonates in the sea. The results for climate change impact show a potential for net CO_2 removal - on a lifecycle basis - of the two processes, about 931 and 876 kg of negative CO_2 emissions per tonne of CO_2 removed for biomass and renewable electricity processes, respectively. Thus, the life cycle greenhouse gases (GHG) emissions amounts for about 69 and 124 kg of CO_2eq for biomass and renewable electricity processes, respectively.

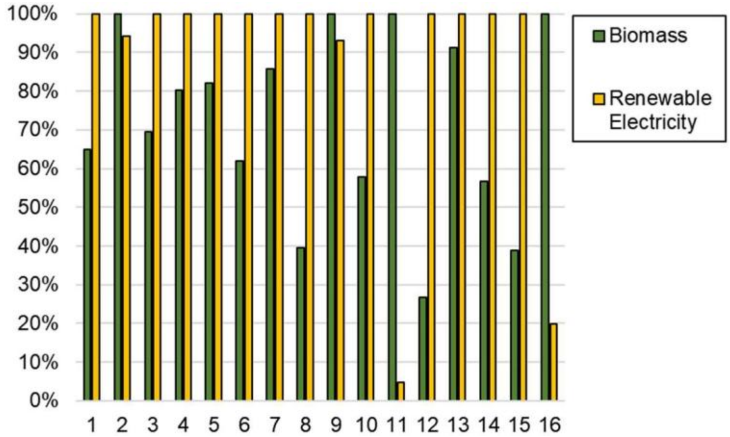


Figure 1. *Total impact comparison of both scenarios (1 – Acidification; 2 - Climate change; 3 - Ecotoxicity, freshwater; 4 - Particulate matter; 5 - Eutrophication, marine; 6 - Eutrophication, freshwater; 7 - Eutrophication, terrestrial; 8 - Human toxicity, cancer; 9 - Human toxicity, non- cancer; 10 - Ionising radiation; 11 - Land use; 12 - Ozone depletion; 13 - Photochemical ozone formation; 14 - Resource use, fossils; 15 - Resource use, minerals and metals; 16 - Water use).*

The two CDR methods are analysed from the techno-economic assessment point of view. The cost per tonne of CO_2 removed are about 127 € and 250 € per tonne of CO_2 removed biomass and renewable electricity scenario, respectively. Considering the lifecycle GHG emissions, the costs are about 137 € and 283 € per tonne of CO_2 removed net of the life cycle GHG emissions generated by the process. Further economic analysis will be done through a bottom-up engineering-economic model, together with top-down technological learning projections. The calculated trajectories represent the cost for First-Of-A-Kind and Nth-Of-A-Kind plant. Limenet[4] is industrializing the process with further research for the upscaling of this kind of processes. A pilot plant that stores CO_2 in the form of bicarbonates in the sea is under construction in southern Italy.

Acknowledgments

We thank Limenet team Giovanni Cappello, Stefano Cappello and Giovanni Perego that support supplying data necessary for the LCA and TEA analysis.

References

1. Caserini S. et al. Buffered accelerated weathering of limestone for storing CO2: Chemical background. *International Journal of Greenhouse Gas Control*, 112, 103517 (2021).
2. De Marco, S. et al. Techno-economic evaluation of buffered accelerated weathering of limestone as a CO_2 capture and storage option. Mitigation and Adaptation Strategies for Global Change, 28:17, (2023).
3. Caserini S. et al. Engineering challenges of storing CO_2 as bicarbonates in seawater for CO_2 storage and removal. 3rd International Conference on Negative CO_2 Emissions 2024 (2024)
4. www.limenet.tech

Engineering challenges of storing CO_2 as bicarbonates in seawater for CO_2 storage and removal

Conference session: Ocean Alkalinity 2

Stefano Caserini[1], Piero Macchi[2], Guido Raos[2], Selene Varliero[2], Francesco Campo[3], Valdis Bisters[3], Stefano Cappello[3], Giovanni Cappello[3], Mario Grosso[4]

[1]*Dipartimento di Ingegneria e Architettura, Università di Parma, Parma, Italy, 43100 stefano.caserini@unipr.it*

[2] *Dipartimento di Chimica, Materiali e Ingegneria Chimica "G. Natta", Politecnico di Milano, Milano, Italy, 20133. Piero.macchi@polimi.it; guido.raos@polimi.it; elene.varliero@polimi.it*

[3] *Limenet s.r.l. Benefit Corporation, Lecco, Italy, 23900. francesco.campo@limenet.tech; valdis.bisters@limenet.tech; stefano.cappello@limenet.tech; giovanni.cappello@limenet.tech*

[4] *Dipartimento di Ingegneria Civile ed Ambientale, Politecnico di Milano, Milan, Italy, 20133, mario.grosso@polimi.it*

Ocean alkalinity enhancement (OAE) is raising interest as a process for storing CO_2 and buffering the effects of ocean acidification. This increase in alkalinity can be obtained by using hydroxide ions (e.g., $Ca(OH)_2$ - a.k.a. slaked lime, SL) or carbonate/bicarbonate ions, respectively called non-equilibrated and equilibrated approaches.

The spreading of SL in seawater could be done in different ways, and the discharge in a ship's wake seems more feasible. However, this could cause high pH spikes, with two side effects.
The first is a negative impact on marine biota, which depends on the amount and duration of the spike. Secondly, the increase in pH leads to the precipitation of minerals, such as brucite and aragonite, right after the addition, with a decrease in the efficiency of the process. Those effects can be avoided with low SL dosages (e.g. ≤0.005 g/L) in cold and less salty seas,[1] together with a strong and rapid dilution of SL. Still, the direct discharge of SL requires detailed modelling of the fluid dynamics of the discharge and the kinetics of the SL dissolution. An approach that overcomes these risks is the discharge of a CO_2-equilibrated solution at the same pH of seawater, obtained by dissolving a controlled amount of CO_2 and SL in seawater inside a reactor before the discharge.[2,3] This approach produces a bicarbonate-rich solution that could store CO_2 permanently after the dilution with natural seawater. The presentation discusses the chemical background and engineering challenges of implementing this approach for CO_2 storage and removal.

As Carbon Capture and Storage, the process (Figure 1) allows the storage of CO_2 coming from an external source, such as an industrial plant (i.e. biogas upgrading, chemical, etc.) or direct capture from the atmosphere. The process uses renewable electric energy for the calcination of limestone.

As a Carbon Dioxide Removal strategy (Figure 2), the process uses the hot syngas produced from biomass gasification for the thermal calcination of limestone. Both biogenic CO_2 from syngas and “fossil” CO_2 from calcination are dissolved in seawater and react with a part of the SL produced by the calcination before discharge. This configuration implies a direct removal of atmospheric CO_2 through the permanent storage of photosynthetic carbon coming from the biomass, and allows the production of decarbonized SL that can be used for further CO_2 removal.

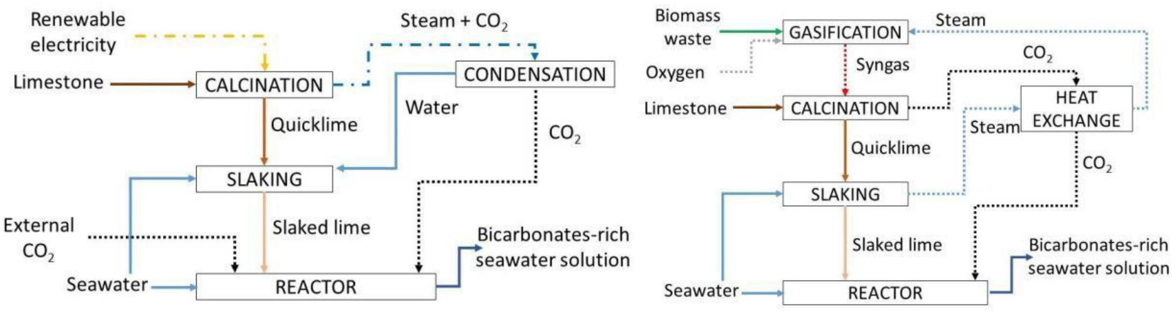


Figure 1. *Processes for the storage as bicarbonate of CO_2 from an external source (left) and of atmospheric CO_2 (right).*

Although the first configuration is simpler, it requires a large amount of cheap renewable electricity. The availability of limestone, biomass or renewable energy sources is a critical factor for the deployment of the process in different geographical contexts; thus, optimising the logistic chain is of fundamental importance.

Other engineering challenges concern the transport and the discharge of the pH-equilibrated, highly alkaline solution. The discharge through a fixed pipeline can increase alkalinity; for this reason, a mobile release is preferable, even at low speeds, i.e., from a moving barge that could also host the dissolution reactor. This approach is under development by Limenet[4] with a pilot plant in southern Italy.

References

1. Varliero, S., Buono, A., Caserini, S., Raos, G., Macchi, P. Chemical Aspect of Ocean Liming for CO_2 Removal: Dissolution Kinetics of Calcium Hydroxide in Seawater. ACS Eng. Au., in press (2024)
2. Caserini S., Capello G., Righi D., Raos G., Campo F., De Marco S., Renforth P., Varliero S., Grosso
3. M. Buffered accelerated weathering of limestone for storing CO_2: Chemical background. International Journal of Greenhouse Gas Control, 112, 103517 (2021).
4. De Marco, S. et al. Techno-economic evaluation of buffered accelerated weathering of limestone as a CO_2 capture and storage option. Mitigation and Adaptation Strategies for Global Change, 28:17, (2023).
5. www.limenet.tech

Representing the demography of the UK forest diversity using a process-based land surface model

Conference session: Forestry

Hsi-Kai Chou[1], Anna B. Harper[2], Arthur A. Argles[3], Maria Carolina Duran Rojas[1], Emma W. Littleton[1], Richard A. Betts[1,3], Peter M. Cox[1]

[1] *Global Systems Institute, University of Exeter, Exeter, United Kingdom, EX4 4QE, email: h.chou@exeter.ac.uk*

[2] *Department of Geography, University of Georgia, Georgia, USA, 30602, email: a.harper@uga.edu*

[3] *Met Office Hadley Centre, Exeter, United Kingdom, EX1 3PB, email: arthur.argles@metoffice.gov.uk*

Introduction

Global warming and climate change caused by greenhouse gas (GHG) emissions is projected to have multiple impacts on forest ecosystems. As the UK's currently planned contribution to global efforts to mitigating these impacts, the Climate Change Act has set a goal of net zero emissions of GHG by 2050. One core strategy is to use afforestation and forestry management to implement large-scale Greenhouse Gas Removal (GGR). However, the effectiveness of afforestation as a GGR strategy is difficult to fully evaluate with standard empirical models due to the complexities of environmental conditions under a changing climate. Alternatively, process-based land surface models (LSM), such as the Joint UK Land Environment Simulator (JULES), are increasingly being used to evaluate forest growth within a national GGR context as they are driven by environmental drivers. By coupling the Robust Ecosystem Demography (RED) model with JULES, we model the forest dynamic and carbon sequestration among a set of bioclimatic future projections geographically across the UK up to 2080. Our results demonstrate the capability of mapping the potential GGR across the UK while also accounting for the changing environment and risks of climate changes, which provides an estimation for national-scale afforestation evaluation towards net zero targets.

Methods

JULES was originally developed by the Met Office as a community land surface model. It is part of the UK Unified Modeling framework, where it serves as the lower boundary condition for applications ranging from weather forecasting to climate projections.[1,2] In addition, JULES simulates the fluxes between the land surface and the atmosphere, including carbon,[2] water, energy, and momentum.[1] We then couple a demography representing LSM called JULES-RED that includes a simple implementation of forestry management and a new implementation of canopy-closure.[3]

Our estimation is based on a commonly planted needleleaf tree, Sitka spruce. In which, the growth curve and demography of Sitka spruce has been calibrated in Harwood Forest site[3]. We then focus on a subset of points across Great Britain which represents different groups of climate zone (e.g. Alpine, Sub-alpine, Cool-moist, Warm-moist, Warm-dry) and most dominated soil classifications (e.g. Cambisol, Histosols, Gleysol, and Luvisol) to allow analysis of potential carbon storage in newly planted needleleaf trees.

Results

With our baseline projection, we simulated forest dynamics from 2024 until 2080, then evaluated the vegetation carbon at forest age 26, 51, 66 (Figure 1). In 2050, the vegetation carbon ranges from 8.26 kg m^{-2} to 10.16 kg m^{-2}. In 2065 (at the values increase to a range of 11.22 to 13.37 kg m^{-2}. In 2080, the average accumulated carbon is 15.79 kg m^{-2}, ranging between 14.27 kg m^{-2} and 16.63 kg m^{-2}. We map the spatial distribution of vegetation carbon stored by 2080 marked by vegetation carbon level (Figure 2) as pink: low carbon (<15.3 kgm^{-2}), yellow: mid-low carbon (15.3 – 15.8 kgm^{-2}), green: mid-high carbon (15.8 – 16.3 kgm^{-2}), deep green: high carbon (>16.3 kgm^{-2}).

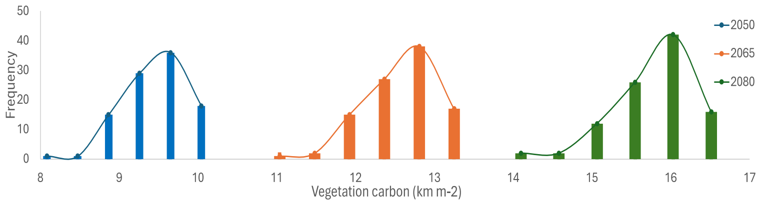


Figure 1. *The simulated vegetation carbon histogram in 2050, 65, and 80.*

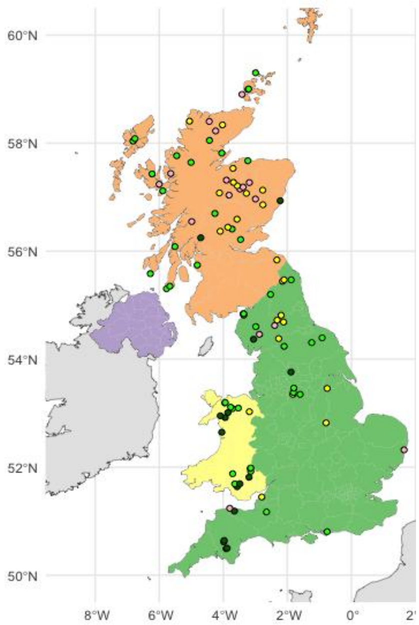


Figure 2. *The projected level of vegetation carbon (kgm-2) in 2080 on the UK map.*

Conclusion

We found that most of our sites marked as good plantation conditions were in the west part of

Great Britain, which is consistent with the rainfall condition. JULES is a useful modelling tool for predicting carbon accumulation values as both climate and atmospheric CO_2 levels change. Our results demonstrate the capability for calculating tree based GGR, and these results are a reliable reference for land use management strategy. Even with trees planted in the most effective locations, we found a maximum potential removal of 6 $MtCO_2$ by 2050, and this amount is insufficient to meet the Government's 2050 NetZero target. Our model is currently limited to the most commonly planted tree type, Sitka Spruce. We plan to extend the model for other common plantation types (e.g. Scots Pine, Larch, Oak, Beech, Sycamore, Ash, Birch). This will allow us to optimize tree species for multiple locations in the UK and determine the right tree in the right place.

References

1. Best, M. J. et al. The Joint UK Land Environment Simulator (JULES), Model description – Part 1: Energy and water fluxes. Geoscientific model development discussions 4, 595-640 (2011).
2. Clark, D. B. et al. The Joint UK Land Environment Simulator (JULES), model description–Part 2: carbon fluxes and vegetation dynamics. Geoscientific Model Development 4, 701-722 (2011).
3. Argles, A. P. et al. Modelling the impact of forest management and CO_2-fertilisation on growth and demography in a Sitka spruce plantation. Scientific Reports 13, 13487 (2023).

Direct air capture by monoethanolamine absorption with heat pump enhancements

Conference session: DACCS 1

Paul de Joannis[1,2], Christophe Castel[2], Mohamed Kanniche[1], Eric Favre[2], Olivier Authier[1]

[1] *EDF R&D, F78000, Chatou, France, email: paul.de-joannis-de-verclos@edf.fr*

[2] *Université de Lorraine, CNRS, LRGP, F-54000, Nancy CEDEX, France.*

Introduction

Carbon dioxide removal (CDR) solutions, which remove CO_2 from the atmosphere and store it permanently, have recently gained interest in the pursuit of carbon neutrality. Among these CDR technologies, Direct Air Capture (DAC) is developing rapidly and could achieve a capture capacity of 1 $GtCO_2$/yr in 2050, according to the *Net-Zero Scenario* of the International Energy Agency.

Based on the knowledge and experience of the conventional amine-based CO_2 capture process, this study investigates a DAC process using the well-known monoethanolamine (MEA) absorption process, further enhanced by integrating heat pump modifications such as Lean Vapor Compression (LVC) and Stripper Overhead Compression (SOC) in the regeneration stage to significantly reduce reboiler consumption.

Methods

The MEA-DAC process is modelled using Aspen Plus (V14), incorporating a newly validated DAC absorption model, and CAPEX are estimated with Aspen Process Economic Analyzer. The process model is based on the CCSI model, adapted for DAC environmental conditions and very low CO_2 partial pressure conditions.

A detailed mass and energy balance is provided for a base case scenario with ambient conditions (T_{air}=15°C and relative humidity=80%) of the DAC with LVC modification (Figure 1). A scrubber section is installed above the absorber to control MEA emissions. Solvent evaporation (water, MEA) and scrubber section height are investigated under various air conditions (temperature, humidity) and maximum outlet MEA emission levels in the atmosphere.

Techno-economic analysis of the MEA-DAC with various regeneration modifications is compared to the conventional stripping regeneration.

Results

The maximum MEA emissions at the air outlet have a significant impact on the dimensions of the scrubber section and therefore the overall cost of capture is reduced by 8% for the 6 ppm-mol emission limit in comparison to the 0.1 ppm-mol limit. In the base case scenario of the LVC-case, MEA and H_2O losses are high, with 1.5 kgMEA/tCO_2 and 4.9 tH_2O/tCO_2, respectively.

The implementation of heat pump enhancement results in a significant reduction in regeneration requirement by more than 25% compared to conventional MEA-based processes. However, the electrical and thermal energy requirements of the DAC process remain high, with about 2.7 MWh/tCO_2 and 8.2 GJ/tCO_2 for the LVC-case, respectively.

A high cost of capture (>1000 €$_{2022}$/tCO_2) is evaluated for all process configurations at initial development. In the reference LVC-case (1 ppm-mol MEA outlet concentration and 500 ktCO_2/yr), the cost of capture is 1139 €$_{2022}$/tCO_2. Economies of scale allow a 15% reduction in capture cost from a capture scale of 100 ktCO_2/yr to 1 MtCO_2/yr.

The MEA-DAC process is capital-intensive, with 61% of the cost attributed to the CAPEX and 39% to the OPEX for the LVC-case. The absorption/scrubber column accounts for 75% of the capital cost. Further research on cheaper packing with lower pressure drop, compatible with chemical solvent for the absorption and scrubber sections, and cheaper column architectures/structures are needed to reduce the cost of capture and fan work, thus helping the process to ensure a better efficiency.

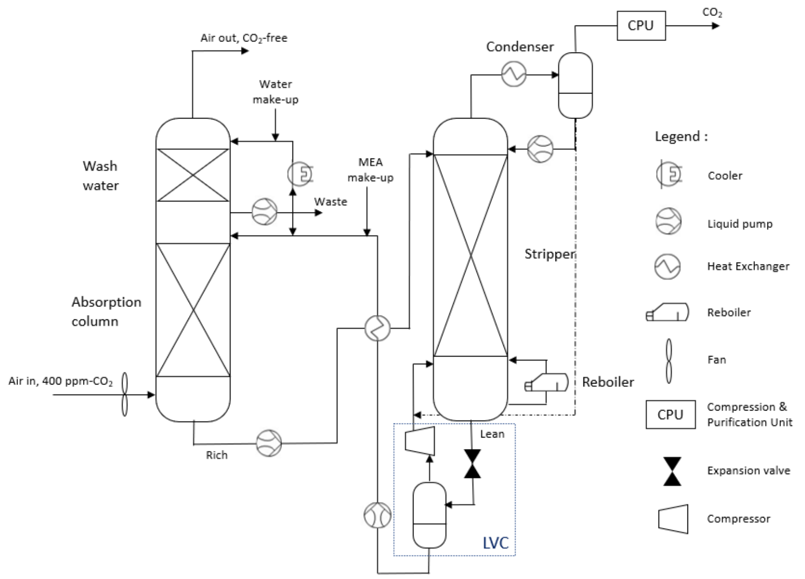


Figure 1. *Flow diagram of the MEA-DAC process with the integration of a Lean Vapor Compression (LVC-case).*

Surge in tropospheric methane concentrations: new analysis and development of new NETs

Conference session: Fundamental Sci & Tech

Renaud de Richter[1], Tingzhen Ming[2,3], Wei Li[4]

[1] *Tour-Solaire.Fr, Montpellier, France, 34090, renaud.derichter@gmail.com*

[2] *Hainan Institute, Wuhan University of Technology, Sanya, China, 572024, tzming@whut.edu.cn*

[3] *School of Civil Engineering and Architecture, Wuhan University of Technology, Hubei, China, 430070*

[4] *Institute for Materials and Processes, School of Engineering, University of Edinburgh, Edinburgh, UK EH9 3JL, wei.li@ed.ac.uk*

Abstract

Since the mid-18th century, the concentration of methane (CH_4) has risen by more than 162%. About one third of the global temperatures rise since the pre-industrial era is due to CH_4.[1] By drawing inspiration from the natural CH_4 sinks in the atmosphere, we have been able to propose several negative emissions technologies (NETs) by enhancing these sinks. Here we present a new NET capable of enhancing the hydroxyl radical sink. Preliminary cost estimates show that it is already possible to achieve a target cost close to $100/ton of CO_2-eq removed.

Introduction

Despite its relatively short lifetime (10 - 12 years) the atmospheric concentration of CH_4 is rising. The buildup of CH_4 during years 2020 - 2022 has been more than double the average measured over the previous 17 years, with new records set in 2020 (+15.2 ppb) and in 2021 (+17.6 ppb),[2] the previous record was set in 1991 (+14 ppb). Among the plausible cases of the 2020-2022 CH_4 surge there is: 1) a reduced atmospheric oxidative capacity[3,4,5]; 2) increased biogenic emissions mainly from tropical wetlands.[6,7] Our analysis proposes that this increase might have been caused by reduced sulfate emissions and therefore reduced deposition, which has been shown to increase methanogenesis rates in wetlands.[8,9,10]

A NET able to enhance, in suitable locations, the hydroxyl radical sink of CH_4 is proposed here,[11] with two preliminary studies based on existing ozone generation technology. One uses an industrially scaled tower model[12] allowing to reach the million tons CO_2-eq over 30 years.

Hypothesis

Commercially available ozone generators fed with dried ambient air are used, either alone and consuming electricity from the grid, or associated with a full scale hybrid air-purification tower model (Cao et al. 2015) equipped with PV panels and a humidifier (a pond).

In the troposphere one ozone generates two hydroxyl radicals trough the following reactions:

$O_3 + h\nu \rightarrow O(^1D) + O_2$ then $O(^1D) + H_2O \rightarrow 2°OH$
Then: $°OH + CH_4 \rightarrow °CH_3 + H_2O$ followed by $°CH_3 + O_2 \rightarrow CH_3O_2°$ and then $\rightarrow\rightarrow$ CO $\rightarrow\rightarrow$ CO_2

Table 1. *Cost assumptions for building the hybrid air-purification tower*

Chimney	\$80 - 90M
Canopy	\$90 - 100M
Engineering	\$5 - 15M
Ozone generators*	\$55 - 85M
PV 120-150 MW	\$130 - 160M
Pond	\$ 5 - 10M
Total cost	\$951 - 1215M

* *Seven ozone generators of 250 kg O_3/h.*

Table 2. *Cost assumptions for direct use of an ozone generator (10kg O_3/h) in suitable locations*

Electricity (grid)	\$44 / MWh
CH_4 removed	1752 tons (in 30 years)
Energy requirement	18 kWh / 1kg O_3
Ozone generator	\$400,000
Total cost	\$3.88M

For both: interest rates for a 30 years loan at 8%.

Results

Using a hybrid air-purification tower[12] for AMR, has an estimated cost ≈ \$103-132/ton CO_2-eq, while for the direct use of an ozone generator it is of ≈ \$74/ton CO_2-eq. Better social acceptability for the first is anticipated as nothing is released into the atmosphere.

Conclusion

The two cases studied show that by using existing ozone generation technology, in suitable locations, it is already possible to reach a target cost close to \$100/ton CO_2-eq removed.

References

1. IPCC, AR6 WG1, Climate Change 2021, The Physical Science Basis - Summary for Policymakers. www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf, accessed 11 August. 2021. (2021).
2. NOAA. Despite pandemic shutdowns, carbon dioxide and methane surged in 2020. https://research.noaa.gov/article/ArtMID/587/ArticleID/2742/Despite-pandemic-shutdowns-carbon-dioxide-and- methane-surged-in-2020, accessed 22 June 2021. (2021).
3. Stevenson, D.S., et al. COVID-19 lockdown emission reductions have the potential to explain over half of the coincident increase in global atmospheric methane. Atmospheric Chemistry and Physics 22, 14243-14252 (2022).
4. Peng, S., et al. Wetland emission and atmospheric sink changes explain methane growth in 2020. Nature 612, 477-482 (2022).
5. Qu, Z., et al. Attribution of the 2020 surge in atmospheric methane by inverse analysis of GOSAT observations. Environmental Research Letters 17, 094003 (2022).
6. Rosentreter, J.A., Half of global methane emissions come from highly variable aquatic ecosystem sources. Nature Geoscience 14, 225-230 (2021).
7. Yin, Y., Accelerating methane growth rate from 2010 to 2017: leading contributions from the tropics and East Asia. Atmospheric Chemistry and Physics 21, 12631-12647 (2021).
8. Dise, N. B., et al. Suppression of peatland methane emission by cumulative sulfate deposition in simulated acid rain. Biogeochemistry 53, 143-160 (2001).
9. Gauci, V., et al. Sulfate deposition and temperature controls on methane emission and sulfur forms in peat."Biogeochemistry 71, 141-162 (2005).
10. Gauci, V., et al. Halving of the northern wetland CH4 source by a large Icelandic volcanic eruption. Journal of Geophysical Research: Biogeosciences 113.G3 (2008).
11. Wang, Y., et al. "Atmospheric removal of methane by enhancing the natural hydroxyl radical sink." Greenhouse Gases: Science and Technology 12.6, 784-795 (2022).
12. Cao, Q., et al. A concept of a novel solar-assisted large-scale cleaning system (SALSCS) for urban air remediation. Aerosol and air quality research 15.1, 1-10 (2015).

Coupled uncertainty in NETs and transient climate response to cumulative CO_2 emissions

Conference session: Earth Systems Modelling 2

Carla M. Di Natale[1], Theresa Schaber[1], Giang T. Tran[2], David P. Keller[2], Jouni Susiluoto[3], Tommi Ekholm[1], Antti-Ilari Partanen[1]

[1] *Climate System Research, Finnish Meteorological Institute, Helsinki, P.O. BOX 503 FI-00101, Finland. Presenter's email: carla.di.natale@fmi.fi*

[2] *Marine Biogeochemical Modelling, GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel, Kiel, D- 24148, Germany*

[3] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, United States of America*

Introduction and Methods

To meet the Paris Agreement target, we need to complement rapid emission reductions of greenhouse gases with Negative Emission Technologies (NETs).[1] NETs remove atmospheric CO_2 and store it. However, NETs' carbon removal potential, costs, and broader impacts on the Earth system remain uncertain.[2,3] We study one unexplored aspect of NETs: whether the uncertainty in their carbon removal potential and transient climate response to cumulative CO_2 emissions (TCRE) are coupled to any degree. Some NETs could have lower carbon removal potential if TCRE is high and carbon removal is needed the most.

We simulate implementation of ocean alkalinization and reforestation from 2050 to 2300.

We estimated how TCRE and the selected NETs' carbon removal potential are dependent on climate system parameters using 300-member Perturbed Parameter Ensemble (PPE) with the University of Victoria Earth System Climate Model (UVic ESCM) and Gaussian Process (GP) emulator trained by and validated using the UVic ESCM PPE. The parameters of interest were chosen according to their expected impact on the climate and carbon uptake, and perturbed based on their prior probability distribution functions. We constrained the emulated UVic ESCM outputs with observations of key Earth system metrics, related to e.g. global warming, carbon uptake of ocean and land. To explore a larger ensemble and get posterior distributions for the parameters and relevant model outputs, we used the Markov Chain Monte Carlo (MCMC) sampling. The sampling reproduced observational uncertainty well for all used constraints. In addition to the constraints, we calculated the posterior distributions for surface air temperature, CO_2 concentration, TCRE, and carbon removal by ocean alkalinization and reforestation.

Results

The emulated TCRE ranges from 1.2 to 2.5 °C/1000 PgC, which is close to the likely range 1.0 - 2.3 °C/1000 PgC reported by the IPCC AR6.[4]Our preliminary results show that NETs are not necessarily correlated with TCRE. Ocean alkalinization (Figure 1a) shows a very narrow cumulative emission uncertainty range, because its carbon removal potential does not strongly depend on the perturbed climate system parameters. Ocean alkalinization's carbon removal potential is less sensitive to parameters that affect TCRE, since it is based on chemical, not biological processes. On the other hand, reforestation (Figure 1b) shows a larger cumulative emission uncertainty range, i.e., its carbon removal potential depends more strongly on the perturbed climate system parameters. Reforestation's cumulative emission has a positive linear correlation with TCRE: for lower TCRE values, reforestation is more efficient in removing CO_2 from the atmosphere; vice versa, in a strongly warming climate due to cumulative CO_2 emissions, low efficiency of reforestation in removing atmospheric CO_2 results in risk accumulation in climate change mitigation strategies.

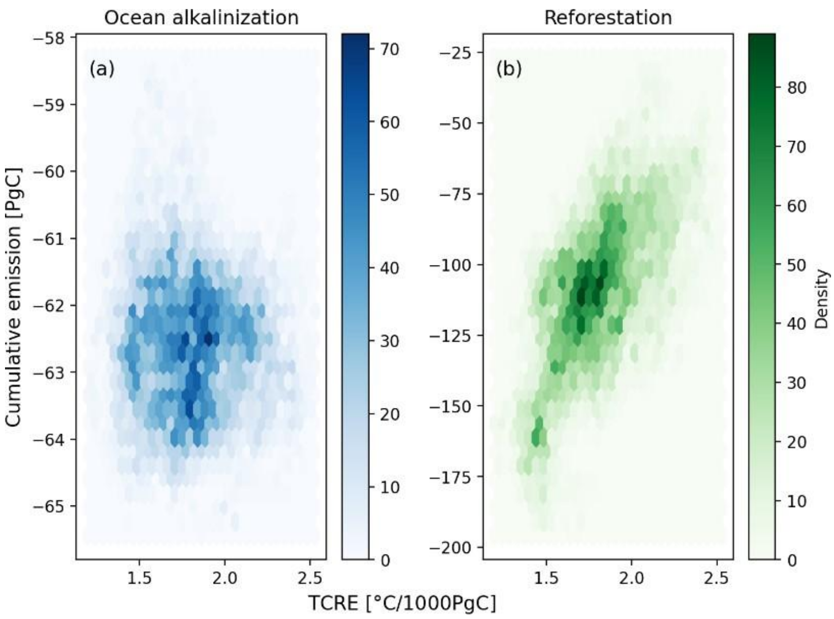


Figure 1: *NETs' carbon removal potential and TCRE correlation.*

References

1. IPCC, Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Shukla, P. R. et al.]. Cambridge University Press (2022).
2. Anderson, K. & Peters, G. The trouble with negative emissions. Science, 354, 182-183 (2016).
3. Fuss, S. et al. Negative emissions—Part 2: Costs, potentials and side effects. Environmental research letters, 13, 063002 (2018).
4. IPCC, Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V. et al.]. Cambridge University Press (2021).

Measures of efficiency to compare the carbon sequestration potential of forestation and BECCS

Conference session: Bioenergy with carbon capture and storage (BECCS) 1

Sabine Egerer [1], Stefanie Falk[1,2], Dorothea Mayer[3], Tobias Nützel[1], Wolfgang A. Obermeier[1], Julia Pongratz [1,4]

[1] *Department of Geography, Ludwig-Maximilians-Universität Munich, Munich, Germany*
[2] *Karlsruhe Institute for Technology, Karlsruhe, Germany*
[3] *Kuratorium für Waldarbeit und Forstwirtschaft e.V., Groß-Umstadt, Germany*
[4] *Max Planck Institute for Meteorology, Hamburg, Germany*

We evaluate the carbon removal potential of afforestation/reforestation (AR) as compared to herbaceous biomass plantations (HBPs) such as Miscanthus under the low-emission scenario SSP1-2.6. We define efficiency as the potential to sequester carbon in the biosphere or to store carbon in products or geological reservoirs. In addition to carbon capture and storage (CCS), we consider the effects of fossil fuel substitution (FFS) through bioenergy. We compare the cultivation of AR and HBPs on the same area using the land component JSBACH3.2 of the earth system model MPI-ESM introducing an HBP plant functional type (PFT) into the model. Our modelling results reveal that HBPs remove more carbon from the atmosphere over the long term than AR. The potential of HBPs is generally higher in South American grasslands, the Sahel, and the Eastern USA, whereas the potential of AR is higher in Southeast Asia. We find that HBP efficiency to sequester carbon depends essentially on the rate of FFS and CCS. Hence, it is important to specify their potential carefully for the future.

Introduction

Meeting the Paris Agreement's climate targets to limit global warming to well below 2°C will likely require substantial carbon dioxide removal (CDR).[1] Nearly all CDR currently deployed depends on terrestrial ecosystems (tCDR), where carbon is stored in the biosphere.[2] Among the various tCDR approaches, AR and BECCS are implemented on a large scale with the highest carbon removal. They remain most commonly applied also in future scenarios.[1] Despite the large carbon removal potential of AR and BECCS, uncertainties in carbon sequestration rates are high, and side effects on land use, water use, biodiversity, and equity exist.[3]

Methods

We use the land component JSBACH3.2[4] of the Max Planck Institute Earth System Model (MPI-ESM) extended by a new plant functional type (PFT) that represents the specific physiology and phenology of highly productive HBPs such as Miscanthus that are used for BECCS.[5] We compare the future carbon sequestration potential of AR and HBPs on the same area under the low emission scenario SSP1-2.6. The future spatial extent of AR and HBPs, respectively, is derived from the LUH2 layer that indicates the fraction of cropland used for second-generation biofuels in every grid cell and year.

Results

We find that the amount of CDR realized by HBPs and AR differs substantially depending on the levels of carbon capture and storage (CCS) and fossil fuel substitution (FFS) for BECCS (Figure 1). HBPs become more efficient in removing carbon from the atmosphere over time because they regrow quickly and are harvested every year.

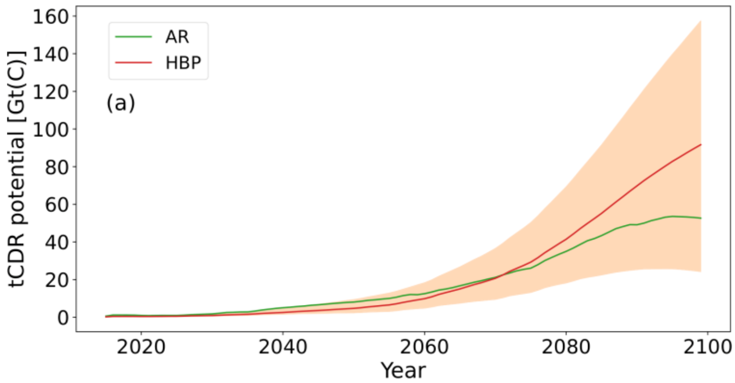


Figure 1. *tCDR potential of AR and HBPs assuming 50% FFS and SSP1-2.6 CCS rates from 2015 to 2100. The shaded areas indicate the range of tCDR potential without FFS and CCS to 100% FFS and 100% CCS.*

Conclusion

In our study, we find that BECCS has a higher carbon removal potential over a longer time period compared to AR, especially in the South American grasslands and Southeast Africa (not shown here), but will not contribute substantially to reaching short-term climate mitigation targets. Further, the efficiency of BECCS as compared to 'nature-based solutions' like AR will depend critically on the upscaling of CCS facilities, replacing fossil fuels with bioenergy in the future, and the planting of bioenergy crops in suitable locations that do not harm biodiversity, water retention, or risk food security. We show, for the first time, how these different measures can be considered simultaneously within a consistent setup as a base for a sensible balancing of interests.

References

1. IPCC Working Group III (2022). Climate Change 2022: Mitigation of Climate Change. Summary for Policymakers. Technical Report 1, Cambridge, United Kingdom and New York, NY, USA.
2. Smith, S. M., Geden, O., Minx, J. C., and Nemet, G. F. (2023). The State of Carbon Dioxide Removal. Technical report.
3. Fuss, S. et al. (2018). Negative emissions - Part 2: Costs, potentials and side effects. Environmental Research Letters, 13(6).
4. Reick, C. H., Raddatz, T., Brovkin, V., and Gayler, V. (2021). JSBACH3 The land component of the MPI Earth System Model. Technical report, Max Planck Institute for Meteorology.
5. Mayer, D. (2017). Potentials and side-effects of herbaceous biomass plantations for climate change mitigation. PhD thesis, Universität Hamburg.

Managing intermittency of renewable power in sustainable production of methanol, coupled with direct air capture

Conference session: Carbon storage, carbon usage

George J. Fulham[1*], Paula V. Mendoza-Moreno[1], Ewa J. Marek[1]

[1] *Department of Chemical Engineering and Biotechnology, University of Cambridge, Cambridge, United Kingdom, CB3 0AS*

**Presenting author, email: gf325@cam.ac.uk*

Introduction

Interfacing renewable power with chemical production, known as power-to-X (PtX), is a way to replace fossil fuels and achieve carbon capture and utilisation (CCU). However, assuming national grids can deliver renewable power with 100% availability is unrealistic, and so the time-variability of renewable sources must be addressed for PtX to become a reality. Here, we present dynamic plant operation framework developed for power-to-methanol (PtM), with CO_2 sourcing from direct air capture (DAC). Coupling process modelling and life cycle analysis, we search for the most cost-effective solutions with which to achieve net drawdown of CO_2 through DAC-PtM.

Methods

We consider a wind-powered DAC-PtM plant with capacity for 50,000 tonnes of methanol per annum. All CO_2 is from low-temperature direct air capture (LT-DAC) with solid sorbents, with H2 derived from electrolysis of water. The facility is powered entirely by either an onshore or offshore wind farm, for which we utilise real-world wind data for 60 candidate locations worldwide. To allow uninterrupted production during periods of low wind, we consider reserve storage of compressed CO_2 and H2 in tanks, and of electricity in batteries. We then introduce four parallel reactors for methanol synthesis; by taking the reactors on- and off-line dynamically, the production of methanol and electricity demand are adjustable to match the available wind power, alleviating the need for reserve storage. The process (Figure 1) is described fully in previous work.[1]

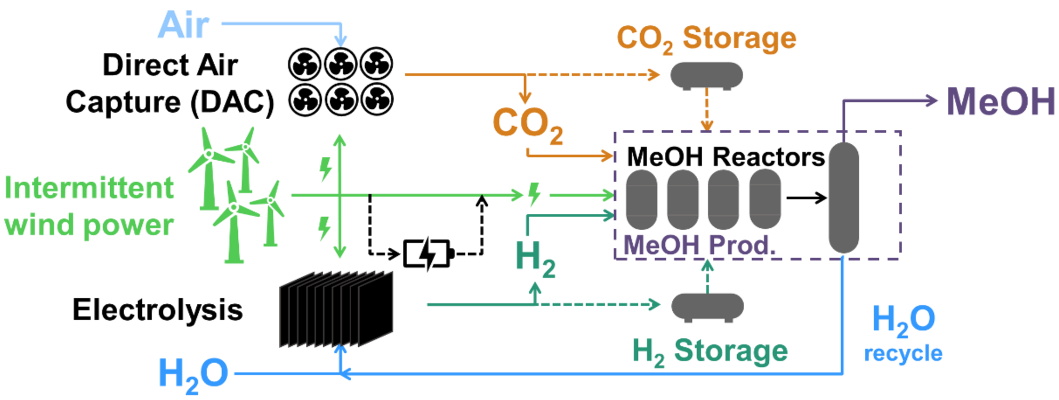


Figure 1. *A schematic of the wind-powered DAC-PtM process considered for dynamic operation.*

Results

A full process model [1] shows DAC-PtM is 38% efficient in converting electricity to methanol, rising to 57% under optimistic assumptions for anticipated improvements to electrolysis, DAC, and catalysts for methanol synthesis. Using real-world wind data, we evaluate the spread of wind-powered DAC-PtM (Figure 2a), defining a plant capacity factor, CF_{plant}, to compare plant capacity (50,000 tonnes p.a.) against the actual yield of methanol (which varies according to available wind power). In general, the offshore sites lead to higher CF_{plant} (Figure 2a) – i.e. more methanol production. However, the costly installation of offshore farms results in higher overall costs vs onshore wind (Figure 2b). Under the pessimistic cases, sub-optimal plant performance is compounded by below-average wind power to cause drastic price rises; whereas, the optimistic model price competitive with methanol from fossil fuels (Figure 2b).

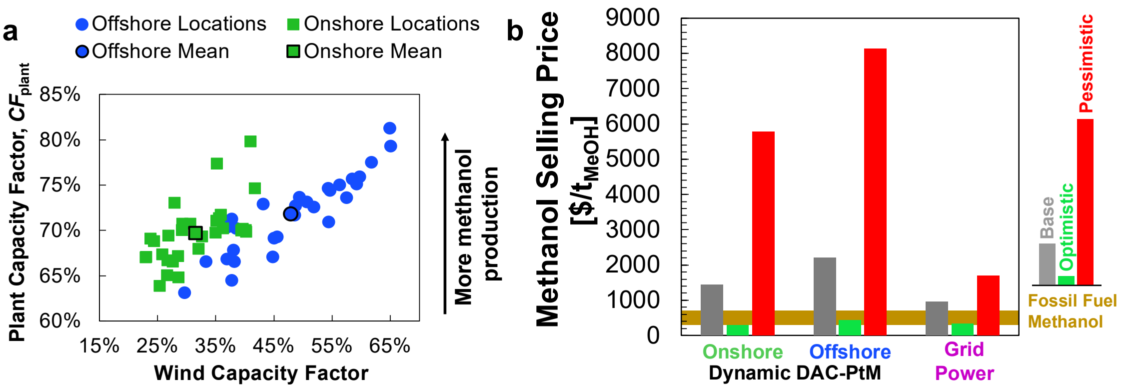


__Figure 2.__ a) the plant capacity factor across the considered wind farm locations; b) the selling price of methanol determined for wind-powered and grid-powered DAC-PtM.

Grid power is cheaper than wind power (Figure 2b). However, a life cycle assessment conf1irms grid-powered DAC-PtM (taking the Brazilian, European, and Chinese grids) is environmentally worse than using fossil fuels, whilst wind-powered DAC-PtM achieves a substantial net drawdown of ~1100 kg CO_2eq per tonne of MeOH produced (Figure 3), demonstrating successful CCU[1].

References

1. Fulham, G.J., et al. Managing Intermittency of Renewable Power in Sustainable Production of Methanol, coupled with Direct Air Capture. Energy and Environmental Science [Advance Article] (2024).

The importance of distinguishing between natural and managed tree cover gains in the moist tropics

Conference session: Forestry

Xueyuan Gao,[1*] Peter B. Reich[2,3,4], Jeffrey R. Vincent[5], Matthew E. Fagan[6], Robin L. Chazdon[7], Steffen Fritz[8], Dmitry Schepaschenko[8,11], Matthew D. Potts[9,10], Matthew C. Hansen[1], Martin Jung[11], Pedro H. S. Brancalion[12,13], María Uriarte[14], Trevor F. Keenan[9,15,16], Thomas W. Crowther[17], Ralph O. Dubayah[1], Myroslava Lesiv[8], Shunlin Liang[18], Dongdong Wang[1]

2. *Department of Geographical Sciences, University of Maryland, College Park, MD, USA*
3. *Institute for Global Change Biology, University of Michigan, Ann Arbor, MI, USA*
4. *Department of Forest Resources, University of Minnesota, St. Paul, MN, USA*
5. *Hawkesbury Institute for the Environment, Western Sydney University, Penrith, New South Wales, Australia*
6. *Nicholas School of the Environment, Duke University, Durham, North Carolina, USA*
7. *Department of Geography and Environmental Systems, University of Maryland Baltimore County, Baltimore, MD, USA.*
8. *Forest Research Institute, University of the Sunshine Coast, Sippy Downs, Queensland, Australia*
9. *Advancing Systems Analysis Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria*
10. *Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA, USA*
11. *Carbon Direct, Inc., New York, NY, USA*
12. *Biodiversity and Natural Resources Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria*
13. *Department of Forest Sciences, University of São Paulo, Piracicaba, Brazil*
14. *Re.green, Rio de Janeiro, Brazil*
15. *Department of Ecology, Evolution and Environmental Biology, Columbia University, New York, New York, USA*
16. *Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA*
17. *Earthshot Labs, Mill Valley, CA USA*
18. *Institute of Integrative Biology, ETH Zurich (Swiss Federal Institute of Technology), Zurich, Switzerland*
19. *Jockey Club Laboratory of Quantitative Remote Sensing, Department of Geography, University of Hong Kong, Hong Kong, China*

**Correspondence to: Xueyuan Gao, xygao@termail.umd.edu*

Abstract

Nature-based climate solutions, such as forest restoration, offer a promising approach to mitigate the effects of global climate change, conserve biodiversity, and enhance rural livelihoods. As monocultures of exotic trees comprise nearly half of the restoration area pledged by over 60 nations to the Bonn Challenge and these plantations have contrasting environmental outcomes compared to natural forest restoration, it is critical to distinguish between these tree cover restoration types when monitoring forest restoration. We used a 30-meter tropical moist forest cover change dataset developed by the European Commission's Joint Research Centre and a new 100-meter global forest management type dataset to identify tree cover gains on former agricultural lands and to assess ongoing tropical landscape

restoration efforts. Secondary natural forests account for only 67% of tree cover gains post-agriculture across the Amazon, Borneo and Central Africa over the period 1982 to 2015. Timber plantations, oil palm plantations and other agroforestry types account for 0.2%, 1%, and 18% of forest cover gains, respectively, suggesting that trees planted for commercial purposes are a substantial part of remotely sensed tropical tree cover gains. Looking at tree cover gains on former agricultural lands across the entire tropical forest region, we estimate around 61% and 27% to be natural secondary forests and managed tree systems, respectively. We call on a rigorous monitoring, reporting and verification system to account for carbon, biodiversity, and production trade-offs of forest restoration approaches, which will help improve the integrity of forest-based credits in voluntary carbon markets and the assessment of forest-featured Nationally Determined Contributions in the UNFCC Global Stocktake.

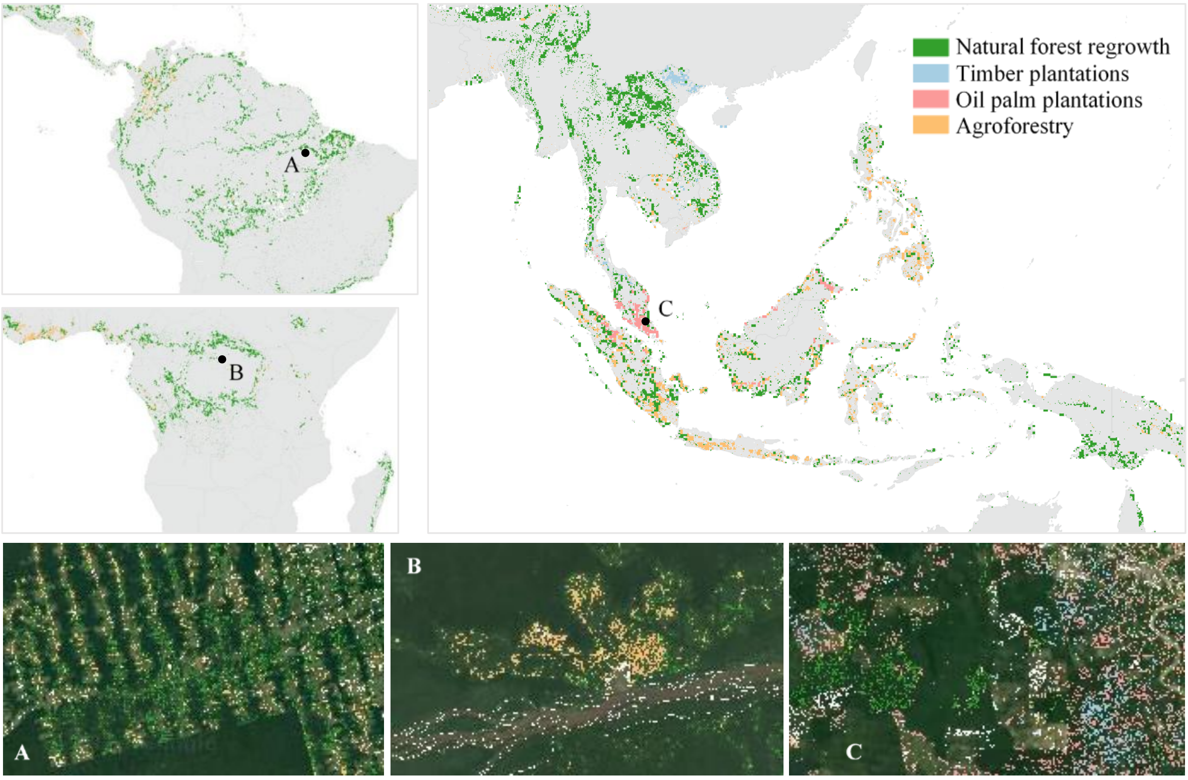


Figure 1. *Moist tropical tree cover restoration areas and types on former agricultural land in 2015. The continental maps were aggregated from 100 meter to 10,000 meter resolution for visualization. Three sites (A, B, and C) were selected to show the heterogeneity of the landscape in the original 100-meter resolution where white colour areas represent other land cover types.*

Assessing current and future CDR potentials for Germany using a multistep assessment framework

Conference session: National Pathways

Felix Gulde[1], Maximilian Witting[1], Karina Winkler[2], Frederike Neuber[3], Christian Baatz[3], Matthias Garschagen[1]

[1] Department of Geographie, Ludwig Maximilians University, Munich, Germany, 80539, email (corresponding author): felix.gulde@lmu.de

[2] IMK-IFU, Karlsruhe Institute for Technology, Garmisch-Partenkirchen, Germany, 82467

[3] Faculty of Arts and Humanities, Christian Albrechts University, Kiel, Germany, 24118

Introduction

The political formulation of net-zero and later net-negative GHG emission targets underscores the need for carbon dioxide removal (CDR) options, since hard-to-abate residual emissions are very likely to remain until the end of the century.[1] Although CDR options are urgently needed, their implementation depends on various time and context specific factors and can result in significant impacts on humans and the environment.[2] While knowledge about biogeophysical CDR potentials and their impacts on the earth system is increasing, the understanding of their feasibility and desirability in different socio-economic contexts is still.[3] Furthermore, existing multidimensional assessment frameworks[4] focus on evaluating the current feasibility of individual CDR options rather than considering a portfolio of options at different time scales.

The research project STEPSEC investigates the potentials of the land-based CDR options BECCS, forest management and afforestation/reforestation under socio-ecological constraints in Germany. Therefore, a multistep assessment framework has been developed to evaluate the feasibility and desirability of current and future CDR portfolios.

Methods

The developed assessment framework, called “Sandwich-Model” (Figure 1), is based on an extensive literature review and a co-creation approach together with selected stakeholders. To ensure comprehensiveness and accessibility, a heterogeneous range of expertise was considered when selecting the stakeholders, with participants from politics, civil society, business, and research. Furthermore, the identification and selection of criteria and evaluative standards were conducted and discussed through literature research, expert judgment by scientists, and participatory stakeholder engagement.

Additionally, a set of Shared Socioeconomic Pathway (SSP) narratives for Germany has been developed and modelled to inform the future assessment of CDR portfolios. This consecutive and iterative process involved multiple stakeholder workshops and expert interviews.

Results

Preliminary results from applying the STEPSEC assessment framework in the German context reveal different feasibility and desirability challenges and opportunities for land-based CDR (e.g. impacts of CDR on biodiversity or food production) according to time and socioeconomic context in which they are deployed. Based on the assessment results, exemplary context specific enabling conditions highlight the enhancement opportunities for both feasibility and desirability.

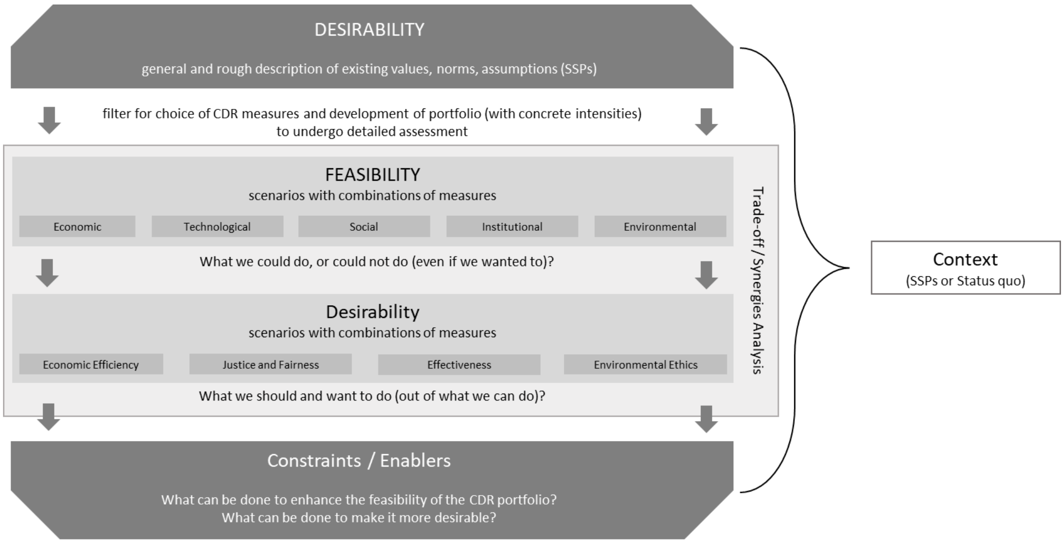


Figure 1. *The STEPSEC Assessment Framework "Sandwich-Model".*

Conclusion

The developed Sandwich-Model enhances existing frameworks by explicitly differentiating between feasibility and desirability. By guiding the assessment through these two key realms ("What can be done?" and "What should be done?"), it helps to highlight and distinguish descriptive aspects from those based on existing ethical and normative considerations as well as value judgements. In addition, the developed SSP narratives not only offer important contextual information for the assessment but also provide general and rough implications on existing values and norms, e.g. regarding the selection of CDR methods for the portfolio or the weighting of individual assessment aspects. Furthermore, taking the respective context into account also facilitates the identification of clearly targeted enabling conditions. Finally, the development and assessment of CDR portfolios extends the assessment of single CDR methods, as different intensities and combinations of measures are considered.

References

1. IPCC Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. et al. (eds.)]. Cambridge University Press, Cambridge, UK (2022).
2. Smith, S. M., et al. (eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition. University of Oxford (2024).
3. Nielsen, K.S., et al. Improving Climate Change Mitigation Analysis: A Framework for Examining Feasibility. One Earth 3.3, 325–336 (2020).
4. Förster J., et al. Framework for Assessing the Feasibility of Carbon Dioxide Removal Options Within the National Context of Germany. Front. Clim. 4, 758628 (2022).

Impacts of CO_2 loading on the stability of aminopolymer sorbents for direct air capture

Conference session: Direct Air Carbon Capture and Storage (DACCS) 1

Yoseph Guta[1], Sichi Li[2], Marcos F. Calegari Andrade[2], Elwin Hunter-Sellars[2], Amitesh Maiti[2], Simon Pang[2], Carsten Sievers[1], Christopher W. Jones[1]

[1] *School of Chemical and Biomolecular Engineering, Georgia Institute of Technology, Atlanta, GA 30332, United States, email: carsten.sievers@chbe.gatech.edu; cj103@gatech.edu*

[2] *Materials Science Division, Lawerance Livermore National Laboratory, Livermore, CA 94550, United States, email: pang6@llnl.gov*

This work investigates the impact of CO_2 loading on the oxidative degradation of a model aminopolymer sorbent (poly(ethylenimine)-alumina (PEI/Al_2O_3)) at various temperatures and CO_2-air gas mixtures using experimental techniques such as TGA, in situ ATR-FTIR, and 1H relaxation and advanced simulations. For each CO_2-air mixture studied (0.04%, 1%, and 5% CO_2-air), there is a region of temperature (55 – 80 °C for 0.04% CO_2-air, 75 – 85 °C for 1% CO_2-air, and 80 – 100 °C for 5% CO_2-air) in which sorbent deactivation accelerates (more than 50% of the initial CO_2 adsorption capacity is lost). The region of temperature sorbent deactivation accelerates varies with the CO_2 loading. Under high CO_2 loadings, chemisorbed CO_2 species (alkylammonium carbamate and carbamic acid) can enhance sorbent stability. From deep potential molecular dynamics simulations and experimental results, increasing the CO_2 loading minimizes PEI branch mobility and increases the energy barrier for radical propagation, minimizing sorbent degradation. However, below a certain CO_2 loading these species can accelerate sorbent deactivation by promoting C-N bond cleavage reactions and oxidative degradation due to increased mobility. Sorbed CO_2's tendency to accelerate oxidative degradation also depends on several factors, including the presence of radicals on the chain and temperature. This work demonstrates the role CO_2 plays in sorbent stability and the importance of considering various atmospheric components in DAC sorbent design and development.

Results

Figure 1a shows the sorbent mass change over time for different temperatures (30 – 100 °C) under the dry 0.04% CO_2-air mixture. In the temperature range between 30 °C and 55 °C, a continuous increase in the sorbent mass is observed throughout the exposure period (18 hours). As the temperature increases from 55 °C to 60 °C, the sorbent mass profile shows an initial mass increase followed by a decrease. This trend continues above 60°C, with the transition from mass increase to decrease occurring faster as the temperature rises. Interestingly, the CO_2 adsorption capacity measurement of the sorbent after exposure to 0.04% CO_2-air for 18 hours at 60 °C, illustrated in Figure 1b, shows 13% increase in sorbent deactivation compared to 55 °C. These results imply that the sorbent mass trend shown in Figure 1a is due to the transition from CO_2 adsorption to sorbent deactivation.

Figure 1b also shows higher onset temperatures for sorbent deactivation under 1% and 5%

CO_2- air compared to 0.04% CO_2-air. This is mostly due to the increased CO_2 concentration. Under high CO_2 concentration (1% and 5% CO_2) the amine sites are rapidly occupied, forming chemisorbed CO_2 species resulting in the interlinking of amine chains and reducing PEI chain mobility. The reduction in PEI chain mobility limits interactions leading to C-N bond cleavage reactions and subsequent accelerated sorbent deactivation. Conversely, under 0.04% CO_2-air, the C-N bond cleavage reactions occur frequently, presumably due to fewer CO_2 sorption induced crosslinks, thus sorbent deactivation is accelerated. The extent of sorbent deactivation generally increases with temperature except when under 0.04% CO_2-air decelerates at 90 and 100 °C. This unique behaviour associated with 0.04% CO_2-air presumably occurs due to the lack of sufficient chemisorbed CO_2 to accelerate sorbent deactivation beyond the deactivation achieved at 80 °C (55%).

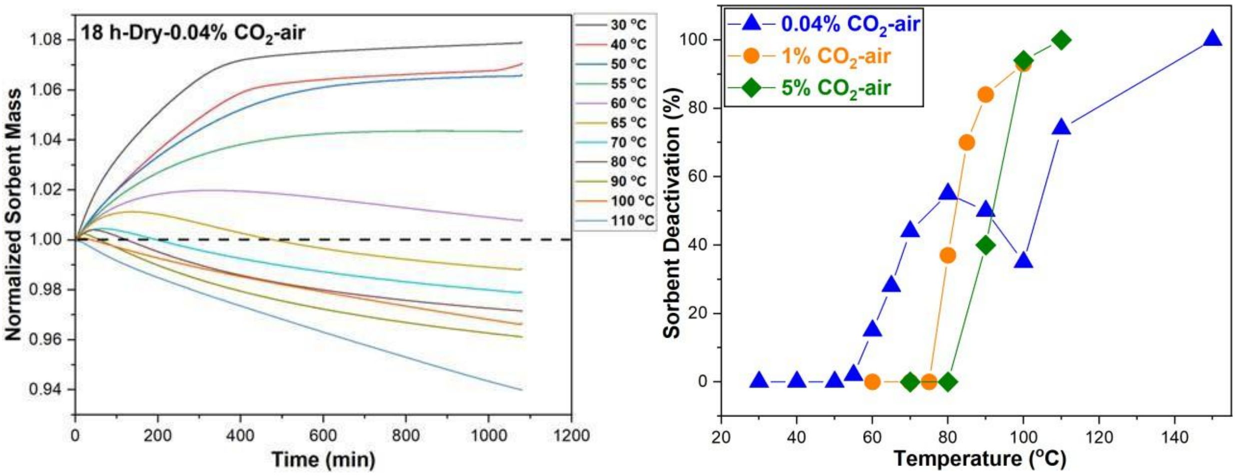


Figure 1: (a) Sorbent mass changes under 0.04% CO2-air from 30–110 °C as a function of time. (b) Sorbent deactivation under dry 0.04%, 1%, and 5% CO2-air for 18 hours as a function of temperature

Conclusion

In summary, our results reveal the complex impact of CO_2 on the oxidative degradation of aminopolymer sorbents (PEI/Al2O3). We find that chemisorbed CO_2 acts as a catalyst, expediting PEI oxidation through the acceleration of acid-induced C−N bond cleavage. Conversely, elevated CO_2 concentrations induce extensive acid-base interactions, effectively immobilizing polymer side chains and impeding radical propagation, thereby retarding the overall oxidation kinetics. These divergent mechanisms give rise to intricate oxidation profiles, highlighting the intricate nature of CO_2's influence on aminopolymer stability. Our findings reconcile seemingly conflicting data in the literature on the impact of CO_2 on amine oxidation while explaining the subtle effect of CO_2 concentration on amine stability. Beyond enhancing our fundamental understanding of sorbent behaviour, our findings hold practical significance for the optimization of CO_2 capture and sorbent regeneration processes, offering pathways to mitigate the environmental impact of sorbent degradation. Furthermore, our identification of high side chain mobility and acidic chemical environments as key factors in accelerating aminopolymer oxidation suggests promising avenues for materials design to reduce the oxidation rate of amine sorbents.

Quantifying persistent aromatic carbon (PAC) in biochar

Conference session: Biochar

Nikolas Hagemann[1,2], Jens Leifeld[1], Rebecca Wolf[1,2], Vinayak Kamra[1,2], Volker Herdegen[3], Silvio Vosswinkel[3], Hans-Peter Schmidt[2], William Meredith[4], Clement Uguna[4], Colin E. Snape[4]

[1] Agroscope, Zurich, Switzerland, 8046, nikolas.hagemann@agroscope.admin.ch

[2] Ithaka Institute, Goldbach, Germany, 63773 and Arbaz, Switzerland, 1974, info@ithaka-institut.org

[3] Technische Universität Bergakademie Freiberg, Freiberg, Germany, Volker.Herdegen@tun.tu-freiberg.de

[4] University of Nottingham, Faculty of Engineering, Nottingham, NG7 2TU, United Kingdom, Colin.Snape@nottingham.ac.uk

Introduction

Biochar is a pyrogenic carbonaceous material that is deliberately produced by the pyrolysis of biomass and that is used, e.g., as a soil amendment. Carbon storage by soil-applied biochar is a key aspect of Pyrogenic Carbon Capture and Storage (PyCCS[1]) and has been third-party certified since 2020.[2] For certification, it is crucial to determine the quantity of biochar-carbon that is sequestered at any point in time after its soil application, i.e., it is necessary to predict the persistence of biochar in the environment. Biochar contains a variety of carbon compounds representing a range of different stabilities to microbial and chemical degradation, including easily degradable aliphatic compounds to hardy accessible carbon in large polycondensed aromatic clusters. Currently, the determination of the stable carbon fraction is based on an approximate estimation using the molar H to C_{org} ratio ($H/C_{org} < 0.4$ equals 75% of total organic carbon (TOC) in biochar is stable > 1000 years[2]). However, this current stability assessment is predominantly based on short-term degradation data obtained in the lab or field and archaeological data, which are both easily overinterpreted. Observations of the natural pyrogenic carbon cycle, however, imply that biochar is partly easily degradable (50 to 100 years) and partly highly stable (millennia).[3] To quantify persistent aromatic carbon (PAC, also referred to as stable polycyclic aromatic carbon – SPAC) in environmental samples, the analytical method of hydropyrolysis (HyPy) was developed. HyPy is analytical pyrolysis at 550 °C occurring under a high pressurized hydrogen atmosphere (150 bar) to selectively remove labile carbon compounds (≤7 condensed aromatic rings). The remaining carbon is highly condensed (>7 aromatic rings) and can be quantified.[4] Microbial degradation of individual compounds with <7 condensed aromatic rings is well described in the literature for controlled laboratory conditions, showing strongly decreasing decomposition rate constants with an increasing number of condensed rings.[5] For conditions in terrestrial and aquatic environments, it is assumed that the components consisting of more than 7 condensed rings are stable in the long term (centuries to millennia). The stability is further enhanced by their physical protection in the biochar matrix preventing access for microorganisms.[3] Here, we apply HyPy analysis using 22 experimental biochars that cover systematically the entire range of industrial biochars. We suggest HyPy and proxy parameters to quantify the part of biochar that can be considered a geological carbon sink when applied to soil.

Methods

Biochars were produced from straw and wood at defined temperatures (400-800 °C, in 50 °C or 20 °C steps) using a continuously operating pyrolysis unit ("PYREKA"[6]). The resulting biochars were characterized according to standard practice.[7] Milled biochars (< 2mm) were mixed with sand, a microbial inoculum extracted from compost and a mineral nutrient solution. The samples were then incubated for 12 months at 20 °C in a high-resolution respirometer.[8] We performed HyPy[4] and conductivity measurements.[9]

Results

Biochars showed PAC contents of 47-97% of their TOC, which correlates with decreasing H/Corg ratio until values of 0.25 (almost 100% PAC for H/Corg ≤ 0.25). During incubation, 0.1 to 1.1% of TOC were released. When biochars presented a conductivity of at least 10 mS cm^{-1} (total range: 0 – 1230 mS cm^{-1}), PAC content was at least 90%. PAC content did not predict the degree of degradation during incubation, showing that the speciation and stability of non-PAC are not correlated with PAC content. We suggest that HyPy analysis is a simple and quantitative method to predict the persistent carbon fraction in biochar.

References

1 Schmidt, H.-P. et al. Pyrogenic carbon capture and storage. GCB Bioenergy 11, 573-591 (2019). https://doi.org:http://doi.org/10.1111/gcbb.12553

2 EBC. Certification of the carbon sink potential of biochar, Ithaka Institute, Arbaz, Switzerland. (http://european-biochar.org). Version 2.1E of 1st February 2021. (2020).

3 Bird, M. I., Wynn, J. G., Saiz, G., Wurster, C. M. & McBeath, A. The Pyrogenic Carbon Cycle. Annual Review of Earth and Planetary Sciences 43, 273-298 (2015). https://doi.org:https://doi.org/10.1146/annurev-earth-060614-105038

4 Meredith, W. et al. Assessment of hydropyrolysis as a method for the quantification of black carbon using standard reference materials. Geochim Cosmochim Ac 97, 131-147 (2012). https://doi.org:https://doi.org/10.1016/j.gca.2012.08.037

5 Cerniglia, C. E. Biodegradation of polycyclic aromatic hydrocarbons. Biodegradation 3, 351-368 (1992). https://doi.org:10.1007/BF00129093

6 Hagemann, N. et al. Wood-based activated biochar to eliminate organic micropollutants from biologically treated wastewater. Sci Total Environ 730, 138417 (2020). https://doi.org:10.1016/j.scitotenv.2020.138417

7 EBC. European Biochar Certificate - Guidelines for a sustainable production of biochar. European Biochar Foundation (EBC), Arbaz, Switzerland. www.european-biochar.org. Version 10.3E of 5th Apr 2023. (2012).

8 Nordgren, A. Apparatus for the continuous, long-term monitoring of soil respiration rate in large numbers of samples. Soil Biology and Biochemistry 20, 955-957 (1988). https://doi.org:https://doi.org/10.1016/0038-0717(88)90110-1

9 Eurofins-Umwelt-Ost-GmbH. Conductivity meter Black Gauss I - technical documentation. Zenodo (2023). https://doi.org:https://doi.org/10.5281/zenodo.8197758

Public perceptions and socially responsible direct air capture in Teesside

Conference session: Social and Ethical 1

Molly James[1], Natalie Carter[2], and Rory Brown[3]

School of Geography and the Environment, University of Oxford, UK, mollyeijames@gmail.com
Department of Geography, University of Cambridge, UK, nlc42@cam.ac.uk
Airhive, London, UK, W12 7RZ, rory.brown@airhive.earth

Introduction

The Tees Valley is a region in Northeast England and one of the six large industrial clusters in the UK. The existing infrastructure and decarbonisation plans, including the proximity to ports for offshore renewable energy and geological storage sites, make the Tees Valley a prospective location for commercial direct air capture (DAC). Understanding the localised public perceptions and how civil society conceptualise socially responsible DAC can generate principles for socially desirable DAC deployment and inform public engagement strategies going forward.

Methods

The empirical data was collected during three trips to the Tees Valley between October 2023 and March 2024. Semi-structured interviews were carried out with civil society organisations (N = 16) and members of the public (N = 22) across the five boroughs of the Tees Valley.

Results

We find even the very construct of the 'Tees Valley' is disputed and the grouping of the five boroughs is seen as a fairly new political concept. Public identity is built on a long-standing connection to the region and its historic industry, in particular the paternal role of British Steel and ICI. The area is now considered to be 'postindustrial' in comparison to the heyday of these paternal companies, with significant socio-economic decline and unemployment. There is a scepticism over who benefits in the area and a distrust over the ability of the council and the government responding to people's needs.

There is significant recognition and support of the climate benefits that DAC can generate. DAC is perceived as an industrial technology appropriate for the area, while being perceived amongst parts of a wider system, with ripple effects from net zero and the fate of carbon. Net zero holds political connotations of taxes and unrealised benefits. Physicality, including the specific location within Teesside, land use, and safety concerns, is significant and contingent on proximity and impact of the facility. There is support for climatic, social, and economic opportunities, however, ethical concerns mean this is often contingent on adequate governance, such as DAC being delivered with concurrent mitigation solutions and remaining accountable through facilitation by the public sector. DAC is perceived as a means of reducing particulate pollution in the local area, demonstrating some confusion over the technology and the characteristics of CO_2.

The public prioritises open, accurate, and accessible information for reclaiming democracy and agency in any significant development. There is support for formal avenues for public consultation, which have legitimacy and take place at a time where project characteristics can still be changed. Agency in the processes of public involvement was seen as crucial, set up against a backdrop of countless meaningless engagement processes by new industry in the region. The public envision socialised industry in the area going beyond spurious engagement sessions, towards industry having a civic responsibility to open up their facilities and educate, support local initiatives, and invest in community provisions. Transparency and accountability are found to be assured through proximity to the public sector, such as partnering with a university or receiving public funding.

Public perceptions of DAC in the Tees Valley

- Climate benefits
- Energy requirements: financial and ethical
- Industrial technology: appropriateness for area
- Location and land use
- Geological storage: safety and ethics
- Moral hazard and ethical concerns
- Net zero ripple effects: financial and political
- Physical risks and safety
- Distrust of governance
- Local opportunities: social and economic
- Conflation of CO_2 with particulate pollution

Tenets of socially responsible DAC

- Democracy of information
- Genuine recognition of the role of the public
- Formal avenues for legitimate consultation
- Socialised benefits
- Public sector arm

Conclusion

More research is needed into the local environmental impacts. As DAC moves from being located in inaccessible areas towards industrial areas, there needs to be a widespread understanding of the localised environmental impacts. We find the public often conflate CO_2 with particulate pollution, expecting health and life expectancy benefits. Understanding the true impact on particulate pollution is necessary for environmentally just and socially desirable DAC. Early consideration of local populations will aid in understanding local place, social context, and place history. It will quell fears and misunderstandings and inform project development going forward. Local communities should be valued for their knowledge of the area and their input for developing DAC deployment. The provision of accessible accurate information was seen as a way to reclaim democracy, agency, and power.

There is an onus on recognising the land, nature, and people, also present in an area often treated as industrial brownfield. The paternal role of historical industrial players has forged a unique identity and the public see new industry as a continuation of this, through which companies become a part of the social fabric. This was envisioned through a civic responsibility to open up their facilities for viewing, provide educational and social initiatives, and invest in community projects and facilities. The development of community benefit plans can provide a formal structure through which benefits can flow to local communities.

Feasible deployment of carbon capture and storage and the requirements of climate targets

Conference session: Carbon storage, carbon usage

Tsimafei Kazlou[1,2], Aleh Cherp[3,4], Jessica Jewell[1,2,5,6]

[1] Centre for Climate and Energy Transformation (CET), University of Bergen, Bergen, Norway, 5007, email: tsimafei.kazlou@uib.no
[2] Department of Geography, Faculty of Social Sciences, University of Bergen, Bergen, Norway, 5007
[3] Department of Environmental Sciences and Policy, Central European University, Vienna, Austria, 1100
[4] International Institute for Industrial Environmental Economics, Lund University, Lund, Sweden, 223 50
[5] Division of Physical Resource Theory, Department of Space, Earth and Environment, Chalmers University of Technology, Gothenburg, Sweden, 412 58
[6] Advancing Systems Analysis Program, International Institute for Applied Systems Analysis, Laxeburg, Austria, 2361

Introduction

Carbon Capture and Storage (CCS) plays a key role in climate mitigation pathways, yet its feasibility is vigorously debated.[1] The recent interest in CCS[2] including negative emission technologies – direct air capture (DACCS) and bioenergy with CCS (BECCS) – is reflected in plans to increase CCS capacity eight-fold from 2023 to 2030.[3] However, ten years ago, a similar wave of CCS plans failed spectacularly. Can the new push bring CCS "on-track"[4] for the Paris climate targets?

Answering this question requires overcoming three challenges. The first is anticipating how many CCS plans are likely to succeed. The second is projecting medium-term growth of CCS given the uncertainty about the drivers of and barriers to its uptake.[5] The third is estimating feasible long-term growth rates that depend on the size of the future CCS market.[6]

We address these challenges by building on the tradition of using empirical evidence from historical technology analogies or `reference cases'.[7] Using advanced policy-driven technologies as reference cases, we contribute with three methodological innovations. First, we analyse historical failure rates of planned projects to estimate feasible near-term (5-10 years) CCS capacity. Second, we use this estimate to project a range of medium-term (10-20 years) CCS capacity assuming quasi-exponential growth as in historical analogies. Finally, we estimate the feasible range of long-term (20-80 years) CCS growth rates[8] based on peak growth rates of historical analogies. Finally, we compare our findings to CCS growth in the IPCC AR6 ensemble[4] and estimate the feasible range of CO_2 captured and stored with CCS over the 21st century.

Results

We find that only a handful of climate mitigation pathways (10%, IPCC Categories 1-4) depict CCS capacity growth compatible with even the most optimistic assumptions when (1) CCS plans double by 2025 and their failure rate drops in half, (2) CCS expansion in 2030-2040 is as fast as solar power in 2010s or nuclear power in the 1960s-1970s, and (3) its subsequent multi-decadal growth is as fast as the growth of nuclear in the 1970s-1980s. Only 33% of pathways meet the first two constraints and only 26% – the last one. Virtually all pathways that meet all three constraints depict <600 $GtCO_2$ captured and stored by 2100 (at 95th percentile). Under the less realistic assumptions of the doubling of CCS plans by 2025, zero failure rate, and growth similar to that of Flue Gas Desulphurisation (FGD), this amount can increase to 1100 $GtCO_2$, which still stands in contrast to a large number of 1.5°C- and 2°C-compatible pathways, envisioning up to 1400 $GtCO_2$ captured and stored by 2100.

Conclusion

Our findings contribute to the debate about the potential role of CCS (incl. BECCS and DACCS) in climate mitigation.[1] Today, BECCS and DACCS only account for 10% of CCS plans and while their development is important, it is the success of the remaining 90% of CCS projects that will be pivotal in enabling negative emission technologies that would rely on capture, transportation, and long-term storage developed for other CCS applications. Our results illustrate the challenges for this wider and diverse technological ecosystem, that is key to BECCS and DACCS success – reaching take-off by 2030, achieving rapid acceleration in the 2030s, and ensuring sustained long-term growth. We show that overcoming these challenges under the most optimistic assumptions would be compatible with only 10% of IPCC AR6 pathways which capture and store <600 $GtCO_2$ by 2100.

References

1. Stoddard, I. et al. Three Decades of Climate Mitigation: Why Haven't We Bent the Global Emissions Curve? Annual Review of Environment and Resources 46, 1–37 (2021).
2. Martin-Roberts, E. et al. Carbon capture and storage at the end of a lost decade. One Earth (2021).
3. IEA. CCUS Projects Explorer (2023). URL https://www.iea.org/data-and-statistics/data-tools/ccus-projects-explorer
4. Byers, E. et al. AR6 Scenarios Database (2022). URL https://doi.org/10.5281/zenodo.5886912
5. Wilson, C. & Grubler, A. Lessons from the history of technological change for clean energy scenarios and policies. Natural Resources Forum 35, 165–184 (2011).
6. Rogers, E. M. Diffusion of Innovations. The 5th edition. (The Free Press, 2003).
7. Jewell, J. & Cherp, A. The feasibility of climate action: Bridging the inside and the outside view through feasibility spaces. WIREs Climate Change (2023).
8. Cherp, A., Vinichenko, V., Tosun, J., Gordon, J. A. & Jewell, J. National growth dynamics of wind and solar power compared to the growth required for global climate targets. Nature Energy 6, 742–754 (2021).

Does Europe need carbon dioxide removals? A large portfolio of negative emissions technologies and practices in scenario modelling for carbon neutrality

Conference session: National Pathways

Kati Koponen[1], Johanna Markkanen[1], Antti Lehtilä[1], Lassi Similä[1], Göran Koreneff[1], Tiina Koljonen[1]

[1] *VTT Technical Research Centre of Finland, Ltd. Espoo, Finland, 02044, email: kati.koponen@vtt.fi*

Introduction

European Union (EU) has committed to reach net zero greenhouse gas (GHG) emissions by 2050 as set in the European Climate Law (Regulation (EU) 2021/1119). In February 2024, European Commission (EC) proposed an interim target for 2040 aiming for 90% reduction in net GHG emissions.[1] Achieving these targets requires rapid, drastic, and sustained GHG emission reductions in all sectors, as well as increasing the carbon sinks in the land use sector (LULUCF). In addition, negative emission technologies and practices (NETPs) will likely be needed as a supplementary measure. With the Pan-European TIMES model, we studied alternative carbon neutrality scenarios for 31 European countries by including a large portfolio of NETPs. Both nature-based solutions, such as af-/reforestation (A/R) and soil carbon sequestration (SCS), as well as technology-based options, such as bioenergy with carbon capture and storage (BECCS), direct air capture and storage (DACCS), biochar, and enhanced weathering (EW), were considered.

Methods

The study was made as a part of the NEGEM project focusing on "Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways".[2,3] The project studied the realistic potential for NETPs, while taking into consideration technological, environmental, social, and political constraints. The project results on the various constraints were taken into account when creating three different storylines to describe the role of NETPs in varying future developments. Three scenario storylines illustrating potential opportunities and constraints for a large scale NETP implementation were created, focusing on 1) optimistic technology development (Technology-scenario), 2) strict protection of planetary boundaries (Environment-scenario), and 3) increased self-sufficiency due to geopolitical risks with policy fragmentation (Security-scenario). In addition, two cases with a full and a limited portfolio of NETPs were studied, the limited one excluding EW and SCS.

A bottom-up technology-rich partial equilibrium model PAN-European TIMES-VTT model (based on open access JRC-EU-TIMES) was used, and scenarios were modelled for "EU-31" region. The model included only CO_2 emissions, and the trajectories were considered up to 2060. No other GHGs nor LULUCF sector were included in the modelling.

Results

European and country specific NETP portfolios are presented for each scenario (example in Figure 1). The results show that the demand for NETPs could be in a gigaton scale to reach carbon neutrality in Europe by 2050.

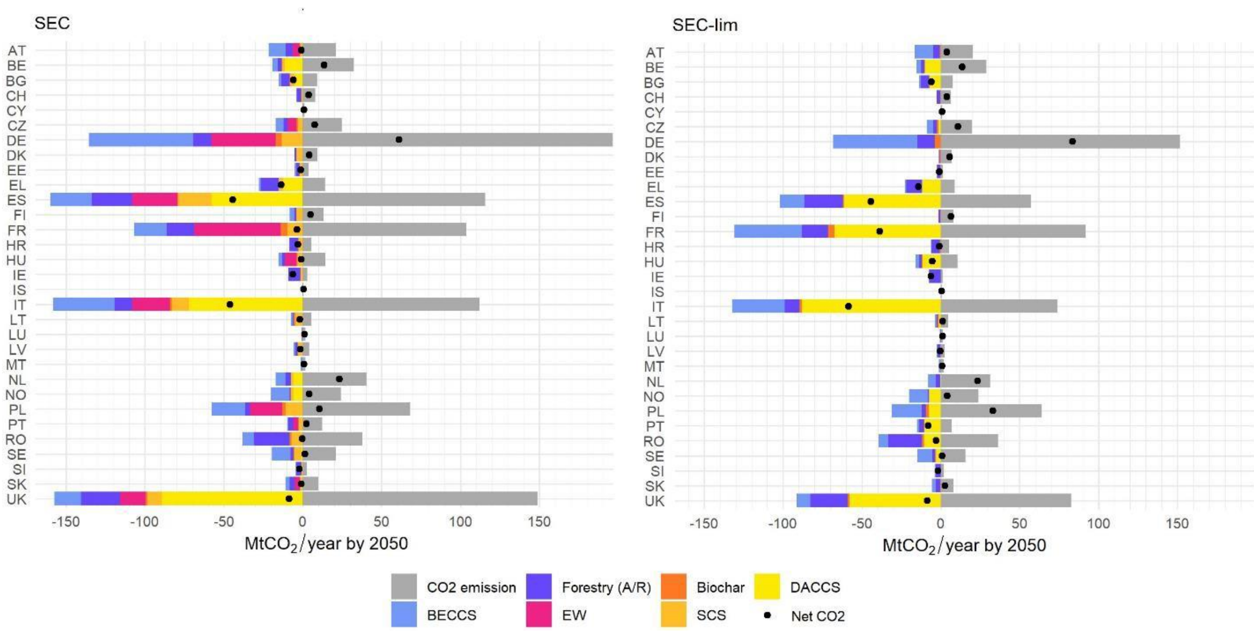


Figure 1: An example of the country specific scenario results for Security scenario.

Conclusion

The results indicate that responsibly deployed NETPs could provide cost-effective solutions to supplement emission reductions. As different countries have different opportunities to implement NETPs, none of the NETP options should be excluded from mitigation portfolios at this stage. On the other hand, the results show the need for stricter GHG emission reduction polices to avoid over-reliance on NETPs.

Authors acknowledge funding from the EU H2020 NEGEM project (ref 869192).

References

1. European Commission (EC). 2024. Impact assessment report. Securing our future: Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society. (https://ec.europa.eu/commission/presscorner/detail/en/qanda_24_589)
2. Lehtilä et al. 2023. Quantitative assessments of NEGEM scenarios with TIMES-VTT. https://www.negemproject.eu/wp-content/uploads/2023/11/NEGEM_D8.2_NEGEM-scenarios.pdf
3. Markkanen, J., Koponen, K., Lehtilä, A. 2024. Sustainable negative emissions in Europe: Evaluating scenarios to meet carbon neutrality by 2050. Manuscript submitted 5/2024.

Policies to incentivise the efficient use of CDR in agriculture: Economic assessment and stakeholder perception of policy instrument strategies

Conference session: National Policy

Klaas Korte[1], Veronika Strauss[2], Erik Gawel[1], Till Markus[3], Carsten Paul[2], Romina Schaller[3]

[1] *Department of Economics, Helmholtz Centre for Environmental Research, Leipzig, Germany, 04318, email: klaas.korte@ufz.de, erik.gawel@ufz.de*

[2] *Leibniz Centre for Agricultural Landscape Research, Müncheberg, Germany, 15374, email: Veronika.Strauss@zalf.de, Carsten.Paul@zalf.de*

[3] *Department of Environmental and Planning Law, Helmholtz Centre for Environmental Research, Leipzig, Germany, 04318, email: till.markus@ufz.de, romina.schaller@ufz.de*

Introduction

Measures for carbon dioxide removal (CDR) in agriculture (e.g. cover cropping, agroforestry or the integration of perennial and leguminous crops into crop rotations) frequently provide addition-al environmental benefits, such as improvements in biodiversity, soil and water quality. As cli-mate protection as well as the environmental co-benefits often are of public good character, market incentives for the implementation of the CDR measures can be inefficiently low. Hence, policy interventions may be considered to correct for insufficient market signals and to increase incentives for the application of CDR measures in agriculture. In doing so, different instrumental strategies can be applied in policy making. Thus, the question arises which strategy or strategies should be applied when aiming at an efficient application of CDR measures in agriculture.

Methods

The assessment of the policy instrument strategies is based on two pillars: economic theory (effectiveness, efficiency, political feasibility) and a stakeholder evaluation gathered in an impact assessment workshop with stakeholders from Germany.

Results

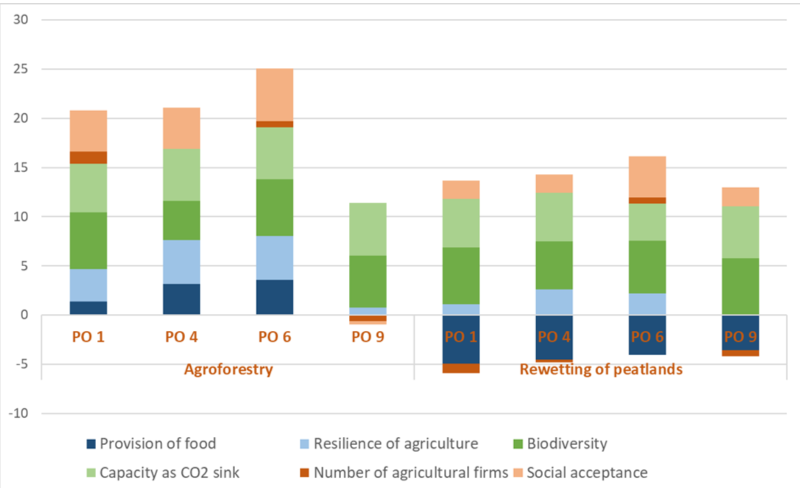
When striving for appropriate policy designs to incentivise the efficient application of CDR measures in agriculture, policy makers can choose between different leverage points (promotion of CDR measures vs. limitation of alternatives) as well as different allocation rationales (price-based vs. command and control vs. informational/suasive instrumental strategy vs. direct governmental supply). Accordingly, a number of different instrument strategies, being the result of a combination of leverage point and allocation rationale, is at choice as depicted in Table 1.

Table 1. *Leverage points and allocation rationales for policy instrument strategies*

Leverage point / Allocation rationale	Promotion of CDR measures	Limitation of conventional alternatives
Price-based	e.g. subsidisation of CDR, carbon market integration	e.g. taxation of conventional land use or inputs
Command and control	e.g. removal of regulatory hurdles, prescription of CDR application	e.g. prohibition of conventional land uses
Informational – suasive	e.g. information campaigns	e.g. removal of conventional uses from agricultural curricula
Direct governmental supply	e.g. implementation of CDR measures on state-owned land (incl. rental/purchase of additional areas for this purpose)	e.g. exclusion of conventional practices on state-owned land (incl. rental / purchase of additional areas for this purpose)

Applying economic theory shows that different strategies have various strengths and weaknesses regarding their effectiveness, efficiency and political feasibility. For instance, a strategy that relies on promotional, price-based instruments could, in principle, achieve a high degree of effectiveness in the application of CDR measures. From a neo-classical economics point of view such strategy would also promise a high degree of efficiency, but market distortions and transaction costs challenge this outcome. Moreover, a strategy that (solely) relies on subsidisation would very likely overburden public households and, hence, seems not to be politically feasible.

As a complementation to the economic assessment, we asked stakeholders (farmers, environmental lobbies, public administration, certification companies) to assess impacts of 4 of the poli-cy instrument strategies on relevant economic, environmental and socio-cultural aspects for the CDR measures (a) agroforestry and (b) rewetting of peatlands, and to weight the impacts based on perceived relative importance. Adding up the weighted impacts, the informational / suasive instrument was ranked highest for both measures (Figure 1).



PO1: Direct governmental subsidisation of CDR measures

PO4: Removal of regulatory hurdles for CDR measure implementation

PO6: Enhanced provision of information and promotion activities on potentials and benefits of CDR measures

PO9: Exclusion of conventional practices on publicly owned land

Figure 1. *Results of the weighted impact assessment from the stakeholder workshop*

The results of these two assessments suggest that a mix of instrument strategies is necessary for a policy design to be effective, efficient and politically feasible.

Atmospheric CO_2 removal deposits (ACORDs) – a policy tool designed to fulfil the 1.5-degree target

Conference session: Economics

Anders Lyngfelt[1], Mathias Fridahl[2], Oscar Stenström[1]

[1]Chalmers University of Technology, Göteborg, Sweden, email: anders.Lyngfelt@chalmers.se
[2]Linköping university, Linköping, Sweden, email: Mathias.Fridahl@liu.se

Introduction

In a recent paper we propose that CO_2 emitters are obliged to remove their emissions from the atmosphere. [1] This obligation is enforced through a deposit fee levied on emitters, equivalent to the cost of negative emissions. The fee is placed into a fund and its value is represented by a deposit deed issued to the emitter. The deposit, including revenues, can only be redeemed upon the verification of negative emissions (Fig. 1). Moreover, the deposits deeds are tradable.

The rationale behind this proposal stems from the daunting task our future generations will face in deciding how to distribute the substantial costs associated with the required negative emissions, both internationally and domestically. Which finance ministers will prioritize negative emissions over healthcare, education, social security, justice, and defence? Given that the emissions in the upcoming years will necessitate future negative emissions, we argue that it is reasonable for those responsible for these emissions to also finance their future removal (Fig. 2). The system of deposit deeds, with designated owners, should help safeguard against diversion of the funds, in contrast to e.g. funds controlled by governments.

To further tighten the noose on emitters, we propose the use of progressively increasing overcompensations, i.e., emitters are required to remove more CO_2 than they emit. This means that future emissions would not only be compensated but would also contribute to lowering atmospheric concentrations of CO_2. Wealthier countries, that have the major responsibility for the present climate crisis, will thus have a tool to address historical emissions.

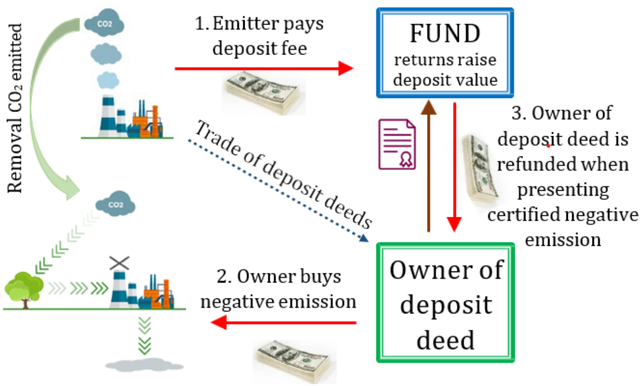


Fig. 1. Use ACORDs to finance negative emission

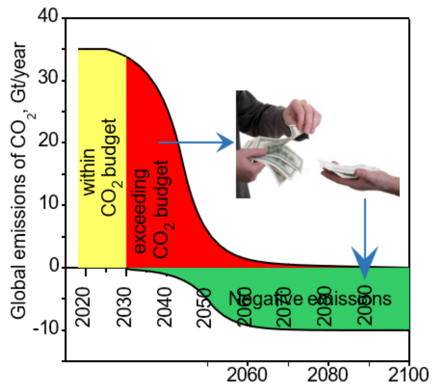


Fig. 2. Intertemporal aspect of ACORDs

Is the execution of such a system feasible, or could it potentially become feasible? What is the influence of a compelling example, i.e., would it be enough with one or a few countries implementing the system to put the pressure on other governments to act accordingly? In an upcoming paper, we will delve into various aspects of this proposal. Further, we will present a survey of experts opinions, assessing their views in favour of and against ACORDs.

Methods

A survey was distributed among experts on negative emissions. Of the 69 respondents 53 identified themselves as researchers, while 9 were in the private sector and 4 were with NGOs. 48 indicated negative emissions were a large part of their professional occupation, 20 a medium part and 1 a small part. The survey included 19 statements.

Results

Statements supporting the proposal but not directly related to the ACORDs showed the highest level of agreement, 1a to 4a (Fig. 3). Thus, there was strong agreement that the carbon budget for 1.5-degree target is soon exhausted (1a), that substantial negative emissions will be needed (1b) and that our descendants will have difficulty in agreeing on the financing of these (2a/b). For statements clearly related to the ACORDs (4b to 9c), the agreement level was lower and within the range Neither to Agree. As an example, "*Overcompensations should eventually be introduced and be gradually increased to address historical emissions in rich countries*", (9a), was in the middle between Neither and Agree.

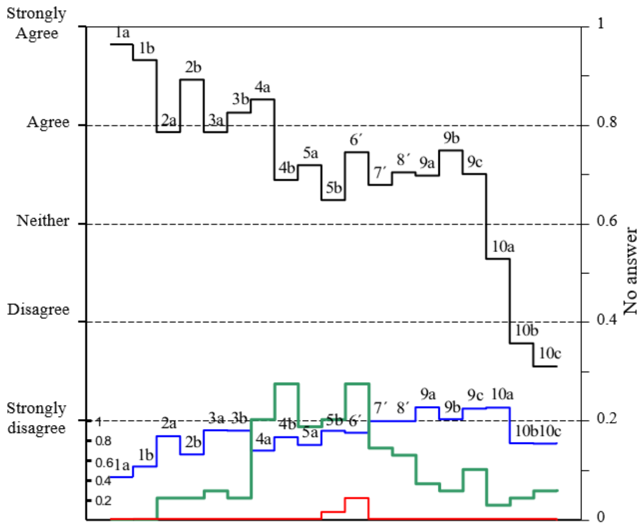


Fig. 3. *Level of agreement (black), σ (blue), no answer (green), objection to question (red).*

The final statements (10a-10c) were contradictory to the proposal. The disagreement was clear on the statements that negative emissions are not urgent and are better postponed until fossil emissions are faced out (10c and 10b). Interestingly, there was a wide variation between Strongly Agree and Strongly Disagree for statement 10a: "Introducing a system for financing negative emissions would mean great risks of delaying the phasing out of fossil emissions". This concern was also raised in comments, while others argued "We need to do all of it right now". In the coming paper, the results of the survey and the many interesting comments by the respondents will be further discussed.

References

1. Lyngfelt, A., Fridahl, M., and Haszeldine, S., FinanceForFuture: Enforcing a CO_2 emitter liability using Atmospheric CO_2 Removal Deposits (ACORDs) to finance future negative emissions, Energy Research & Social Science 107, 103356 (2024).

The state of innovation in carbon dioxide removal

Finn Müller-Hansen[1], Jan C. Minx[1,2], Ben Probst[3], Gregory Nemet[4,5], Morgan Edwards[4,5], Malte Toetzke[3], Sarah Lück[1], Tim Repke[1], Jenna Greene[5], Zachary Thomas[5], Kavita Surana[6,7], Kathleen Kennedy[7], Andrew Zaiser[4], Volker Hoffmann[3], Laura Diaz Anadon[8], Tim Engelmann[3]

[1] *Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany.*
[2] *Priestley International Centre for Climate Futures, University of Leeds, UK.*
[3] *Group for Sustainability and Technology, ETH Zurich, Switzerland*
[4] *La Follette School of Public Affairs, University of Wisconsin—Madison, U.S.*
[5] *Nelson Institute Center for Sustainability and the Global Environment, University of Wisconsin— Madison, U.S.*
[6] *Vienna University of Economics and Business, Vienna, Austria*
[7] *Center for Global Sustainability, School of Public Policy, University of Maryland College Park, USA.*
[8] *Department of Land Economy, University of Cambridge, UK*

Carbon dioxide removal (CDR) is critical to achieving the Paris climate goals, but there is a considerable gap between how much CDR is required in Paris-consistent mitigation scenarios and countries' proposals to scale CDR in the short and long term. The next two decades will be decisive for scaling novel CDR such as direct air carbon capture and storage (DACCS), enhanced weathering and bioenergy with carbon capture and storage (BECCS). Decisions related to this scale up would benefit from data on research, development and deployment of CDR, but those data have not been available until recently, hindering our understanding of the state of innovation in CDR.

In this presentation, we show a comprehensive assessment of the state of innovation in CDR, based on our work for the second edition of the State of Carbon Dioxide Removal report.[1] Our assessment is global and covers ten different CDR methods. We apply a broad definition of innovation as a sequence of stages moving from invention to commercialization and diffusion (see Figure 1). We cover technology supply push (R&D, demonstrations, scale-up) to demand pull factors. We construct indicators to characterize some of these main stages by collecting and classifying large amounts of data from different sources including bibliographic, research project and patent databases, using machine-learning methods.

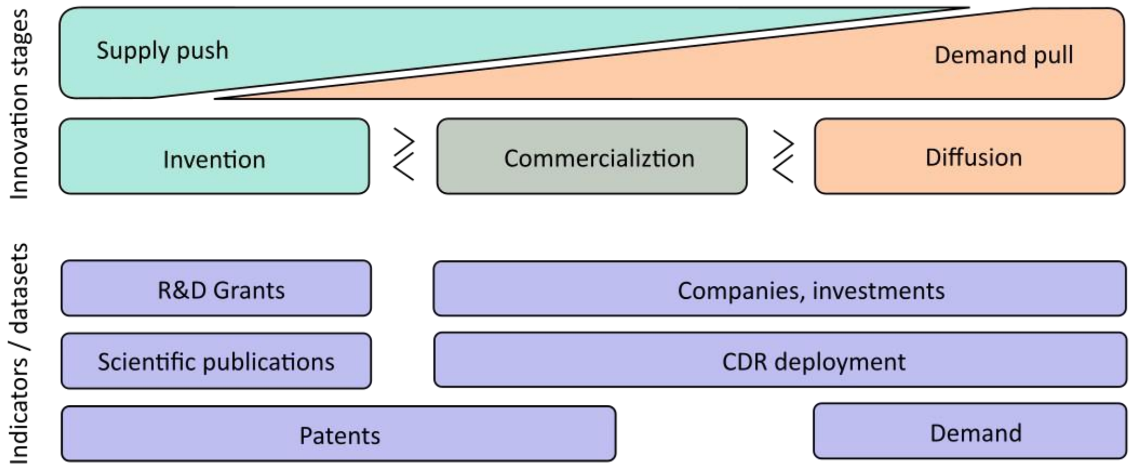


Figure 1. *The process of innovation in carbon dioxide removal consists of a sequence of interlinked stages that feedback and build on one another. For the first time, we quantify several of these stages using data-driven and AI-enhanced approaches*.

Throughout the last two decades, we find large increases in activities on early stages of the innovation chain such as research projects, academic publications and patenting. Research projects, as measured by the number and funding volume of R&D grants, have experienced two periods of fast increase around the turn of the century as well as the early 2010s, but growth rates have decreased in recent years. Nevertheless, the increase is higher than for all mitigation technologies, amounting to 3-4% of the funding volume. We also observe a diversification of CDR methods over time, with the strongest increase in biochar and DACCS over the last decade.

A similar trend can be observed in the published scientific literature: While afforestation and soil carbon have dominated the CDR literature in the early 2000s, the share of biochar articles strongly increased thereafter. With 21% growth per year, the total number of scientific publications grew even faster than R&D grants. While the number of all CDR patents also shows a continually increasing trend, patents, which have been filed in at least two countries and therefore constitute a high-value innovation, have decreased since 2010. This is partly driven by a decrease in the number of BECCS patents, which was the most patented CDR method at the peak. Other highly patented CDR methods include biochar, afforestation and blue carbon.

Regarding later stages of innovation, we find strongly increasing investments in CDR startups since around 2015, especially in firms working on DACCS and forestry and to a lesser extent on biochar, soil carbon and enhanced weathering. These investments only make up around 1% of total investments in clean-tech startups and declined in 2023 from 2022. Several US and EU programs support the implementation of CDR demonstration plants with removal activities at the megaton scale anticipated for the next few years. The announced ambitions of companies to scale up their technologies matches the CDR needs that Paris-consistent mitigation scenarios project until 2050. However, these plans will only materialize if there is sufficient demand for CDR. To generate this demand, policy makers need to establish large-scale funding schemes to finance these activities or regulate companies to balance their residual emissions with removals in order to reach net-zero goals.

In summary, we find evidence of increasing activities especially for early stages of innovation. While the activities are regionally concentrated in the US, EU and China, we observe a diversification across CDR methods. However, later stages will need continuous support and funding to further scale activities to the required levels of removal. Future work will investigate the linkages between indicators to better understand critical innovation dynamics in CDR and inform CDR policies geared towards reaching the Paris climate goals.

References:

1. Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., & Vaughan, N. E. (2024). The State of Carbon Dioxide Removal—2nd Edition. The State of Carbon Dioxide Removal. https://osf.io/f85qj/

Tightening the 'net': Fair and legitimate mechanisms for matching removals and residuals

Conference session: Removals and residual emissions

Duncan P. McLaren[1]

[1] *Emmett Institute, UCLA School of Law, Los Angeles CA, USA. email: mclaren@law.ucla.edu*

Introduction

Net zero goals imply a balance between residual emissions and removals. It is typically presumed that the process of matching residuals and removals will be market-based, and effectively some form of offsetting. Evidence of the widespread shortcomings of offsetting in carbon markets to date has focused attention on the quality of removals, with, for example, proposals for limiting trading to 'permanent' removals.[1] Concerns about offsetting also exacerbate civil society opposition to carbon removal as a 'false solution' [2].

In this debate the quantity and nature of residuals is often treated as a given.[3] But in practice vested interests are already acting to assert legitimacy for particular existing or anticipated residual emissions through their interventions in climate policy generally, and removals techniques in particular. As a result while removals are increasingly subject to challenge and demands for standards, the residuals component of net zero remains an opaque category determined primarily by economic actors claims of what is 'hard to abate'. In turn this means that demand for removals might exceed what can be sustainably and fairly supplied, while socially beneficial residuals are suppressed for lack of purchasing power, and luxury emissions remain unabated.

Methods

Proposals for alternatives to market-based matching of residuals and removals have been debated and deliberated on in stakeholder workshops in the EU and USA with collectively more than 50 participants drawn from climate policy and carbon removal scholars, businesses, non-governmental organisations and policy makers.

Results

The deliberations revealed a strong and widely shared appetite for alternative, non-market mechanisms for matching or balancing removals and residuals, and in particular for a mechanism which imposes equivalent and proportionate standards on both removals and residuals.

They also suggest merit in further exploring the potential for a balancing mechanism based on a double-pool model in which regulatory licensing authorities certify sustainable removals, and legitimate residuals respectively; and operate aggregation mechanisms (e.g. auctions) to on the one hand build a sustainable portfolio of removals, and on the other, limit certified residuals to an equivalent aggregate quantity.

The discussions further suggest value in considering a role for a third, separate agency which mediates the balancing role independently of the agencies certifying removals quality (as fair and sustainable) and endorsing legitimate residuals, respectively.

Conclusion

There is a risk that presumptions about net zero will lock in suboptimal market based mechanisms for matching residuals and removals. An alternative double-pool balancing mechanism shows potential to 'tighten the net' of net-zero, minimising residuals to those genuinely hard to abate and socially necessary; and maximising the availability of sustainable removals so as to contribute to subsequent drawdown of atmospheric carbon dioxide.

References

Include any references as a list in this section, following the Nature style-guide.

1. Integrity Council for the Voluntary Carbon Market, The Core Carbon Principles. Website: https://icvcm.org/core-carbon-principles/ (undated)
2. Chemnick, 'False promise': DOE's carbon removal plans rankle community advocates. https://www.eenews.net/articles/false-promise-does-carbon-removal-plans-rankle-community-adv ocates/ 25 September 2023.
3. Buck, H.J., et al. Why Residual Emissions Matter Now. Nature Climate Change 13(4), 351-8 (2023).

Earth system trade-offs and responses to large-scale carbon dioxide removal portfolio deployment

Conference session: Earth Systems Modelling 1

Yiannis Moustakis[1], Hao-wei Wey[2], Tobias Nuetzel[1], Andreas Oschlies[2], Julia Pongratz[1,3]*

*[1]Department of Geography, Ludwig-Maximilians-Universität München, Germany *corresponding author: julia.pongratz@lmu.de*
[2] GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
[3] Max Planck Institute for Meteorology, Hamburg, Germany

Reaching net-zero or -negative emissions necessitates the deployment of Carbon Dioxide Removal (CDR) methods. Even though research has focused on the desirability, feasibility, and potentials of individual land- and ocean-based CDR options, the responses of the Earth System to large-scale deployment of diverse CDR portfolios and the climate and carbon cycle feedbacks and trade-offs between the different carbon sinks remain understudied. Here we employ two Earth System Models (MPI-ESM and FOCI) that capture the complex land-atmosphere-ocean feedbacks within the Earth system to study the interactions and joint impacts of large-scale (i) Afforestation/Reforestation (AR) and (ii) Ocean Alkalinity Enhancement (OAE) application, under a high-emissions scenario (SSP3-7.0).

As target CDR level, we develop an ambitious yet spatiotemporally plausible AR scenario. To this end, we leverage 1,259 Integrated Assessment Model-generated scenarios available within the AR6 Scenarios Database, while also considering biodiversity constraints and restoration potential maps. In our scenario, AR reaches ~935 Mha globally, sequestering ~138 PgC. We use this level of CDR also as the total sequestration in the OAE scenario. For OAE, we apply alkalinity continuously over the coastlines globally. We also perform factorial simulations to capture the isolated and synergistic effects between the two methods and identify the emerging carbon trade-offs when a diverse CDR portfolio is employed.

We find that land- and ocean-based CDR work nearly additively. Ocean feedbacks are more strongly compensating AR sequestration than land feedbacks are compensating OAE sequestration. Thus, AR is less efficient than OAE in terms of $GtCO_2$ removed from the atmosphere, for every $GtCO_2$ sequestered through the CDR method. We also tested the sensitivity of the carbon cycle response to the scale of CDR, comparing the previous land and ocean CDR simulation with one where the CDR deployment is halved. Again we find that carbon sequestration scales nearly linearly. For the two methods tested here, our findings suggest that a portfolio of CDR methods, which seems beneficial in view of diversifying risks and remaining below ecologically and socially acceptable levels, does not compromise the efficiency of individual applications.

The economics of carbon dioxide removal technologies using equilibrium modelling

Conference session: Economics

Romain Presty[1,2], Olivier Massol[3], Pascal da Costa[4]

[1]CentraleSupélec, Université Paris-Saclay, Laboratoire Genie Industriel, 3 rue Joliot-Curie, 91192 Gif- sur-Yvette, France, email: romain.presty@centralesupelec.fr

[2] Center for Energy Economics and Management, IFP School, 228 av. Napoléon Bonaparte, 92852 Rueil-Malmaison, France, email: romain.presty@ifpen.fr

[3] CentraleSupélec, Université Paris-Saclay, Laboratoire Genie Industriel, 3 rue Joliot-Curie, 91192 Gif- sur-Yvette, France, email: olivier.massol@centralesupelec.fr

[4] CentraleSupélec, Université Paris-Saclay, Laboratoire Genie Industriel, 3 rue Joliot-Curie, 91192 Gif- sur-Yvette, France, email: pascal.dacosta@centralesupelec.fr

Introduction

The recent IPCC report presented that carbon dioxide removal (CDR) will have a critical role to play in meeting the 1.5°C objective. This objective can hardly be attained without a large-scale deployment of CDR methods. This study examines the economics of a large-scale and market-driven deployment of CDR technologies, namely bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS), using a spatial and dynamic equilibrium model. That model allows us to investigate the CDR technologies that will be deployed, their localization, and quantity. However, our results will be impacted by the negative emission price determined at the supply and demand equilibrium. This approach allows us to investigate this CDR deployment effect on negative emission price and the impact of the future demand for negative emissions on all previously named components.

Methods

Our approach is a year-by-year model from 2025 to 2050 that focuses on the Northern Sea adjacent countries. Our methodology mobilizes non-cooperative game theory concepts as we model the economic interaction between agents subject to an endogenous CO_2 price using a Generalized Nash Equilibrium problem. We calibrate the model using recent data and projections for 2050 from various sources. In our situation, we have 7 regions (France, Benelux, Germany, Denmark, Sweden, Norway, and the UK) that compete in investing in BECCS and DACCS each year. It is important to note that BECCS can only be achieved on already existing facilities with biogenic CDR potential. Their goal is to maximize the net present value of the profits made during the whole period. On the other side, we have the demand for negative emissions. We created two types of demand scenarios. First, we have an exogenous demand (model A) corresponding to a situation in which companies or governments must buy negative emissions, being price-takers. In the second scenario, we have an endogenous demand (model B) which here represents a situation where companies or governments must reduce their emissions with two levers, abating emissions or buying negative emissions. This demand is modelled with 2 main components:

Government pledges to negative emissions, and the marginal abatement cost curve of hard-to-abate sectors. We created three levels of demand: high, moderate, and low. The following section investigates the moderate demand scenario.

Results

Our results provide detailed projections of the technologies that will be deployed, including their scale, geographic distribution, and projected timelines (Figures 3 and 4). In addition, our findings assess the supply-demand effect on net negative emission price (Figure 1) and the amount of net negative emission (Figure 2). The "net" means that we considered the whole supply chain's emissions and removed it from the output. The results express investments in a market-based situation, any form of subsidies can modify the curves. For instance, subsidizing the difference between the red and the blue lines in Figure 1 would increase the amount of net negative emission by the gap between the two lines in Figure 2. BECCS investments are mostly influenced by transport and storage infrastructures, and biogenic CDR potential. For DACCS, investments are mostly depending on energy cost and its CO_2 efficiency. To stay competitive, investing in transport and storage infrastructures or energy decarbonization would incentivize BECCS and DACCS investments without direct subsidies. If not, direct help is needed for regions investing later.

Figure 1

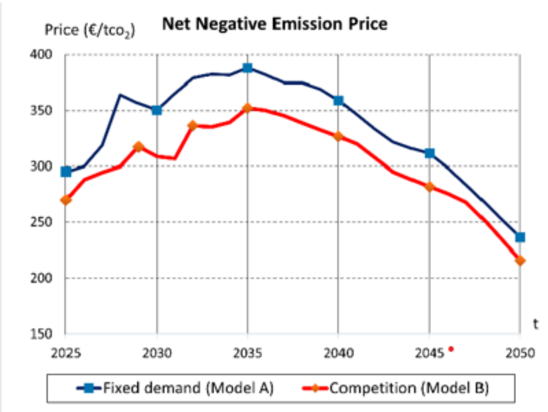


Figure 2

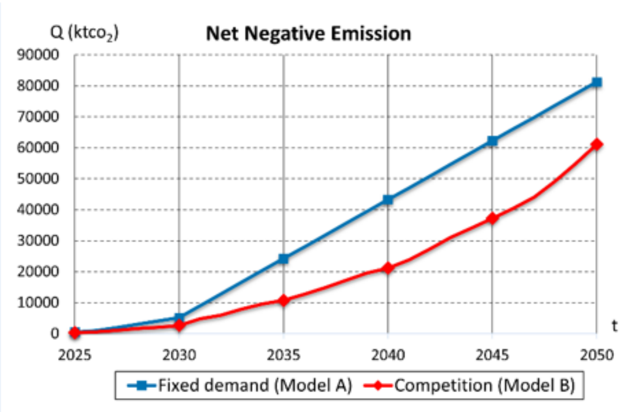


Figure 3

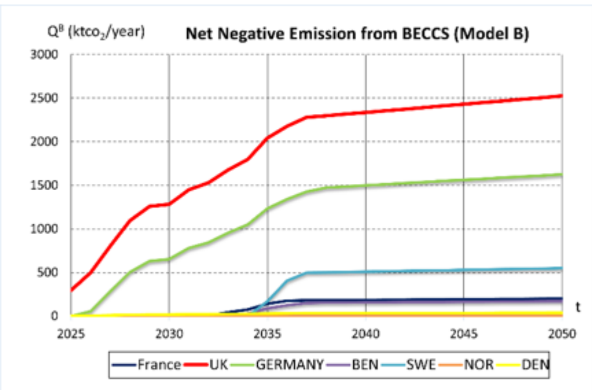
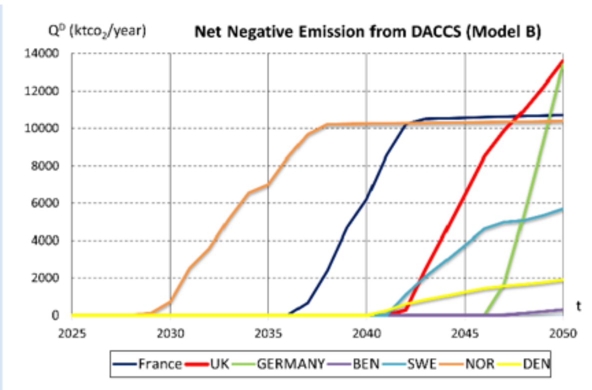


Figure 4



Spatial analysis of CDR implications for global biodiversity refugia

Conference session: Earth Systems Modelling 1

Ruben Prütz[1,2,3], Joeri Rogelj[3,4,5], Sabine Fuss[1,2], Jeff Price[6], Nicole Forstenhäusler[6], Rachel Warren[6], Andrey Lessa Derci Augustynczik[5], Petr Havlík[5], Florian Kraxner[5]

[1] Geography Department, Humboldt University of Berlin, Berlin, Germany
[2] Mercator Research Institute on Global Commons and Climate Change (MCC), Berlin, Germany
[3] Grantham Institute for Climate Change and the Environment, Imperial College London, London, UK
[4] Centre for Environmental Policy, Imperial College London, London, UK
[5] International Institute for Applied Systems Analysis (IIASA), Vienna, Austria
[6] Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK

Background

Due to ongoing delays in emission reductions, and as more and more countries set net-zero CO_2 targets, carbon dioxide removal (CDR) is continuously gaining attention. Virtually all Paris-aligned AR6 mitigation pathways imply gigatonne-scale CO_2 removal even before mid-century, with further upscaling thereafter. Integrated assessment models, used to explore the solution space, currently primarily rely on removals via bioenergy with carbon capture and storage (BECCS) and afforestation, which require massive amounts of land to meet scenario-implied removals. This substantial land demand is expected to have consequences for biodiversity, which could limit the sustainable scaling potential. Depending on the mode of implementation, afforestation could also benefit habitat conservation, easing the immense pressure on biodiversity due to global warming and deforestation.

Objective

By combining spatial data on biodiversity refugia with spatial time series data from three different models (GLOBIOM, AIM and GCAM) on bioenergy crop plantations and afforestation for different scenarios, we compare land use and warming-related pressure on remaining global biodiversity refugia. We evaluate different biodiversity recovery assumptions after peak warming, consider the land pressure of deforestation, and explore additional warming-related refugia loss when excluding CDR from scenarios. We also analyze warming-related and land-related impacts on today's biodiversity refugia in isolation to be able to compare these two drivers side-by-side.

Preliminary results

We show how scenarios with more ambitious temperature outcomes result in higher land pressure on remaining biodiversity refugia areas as more land-intensive CDR is implied. Meanwhile, more decisive climate action, including more CDR, substantially reduces the warming-related loss of remaining biodiversity refugia areas. The underlying biodiversity recovery assumptions strongly impact the degree of warming-related refugia loss with considerably less influence on land use-related implications. The perceived trends are stronger towards 2100 compared to mid-century. Generally, the warming-related impact on biodiversity refugia appears to be larger than the land-related impact of mitigation measures in most of the analysed cases. However, there are notable differences in these two drivers across regions, models and underlying biodiversity recovery assumptions.

Monitoring, reporting and verification of greenhouse gas removals: Untangling the web

Conference session: Poster Session

Sue Rodway-Dyer[1], Jo House[2], Natasha Martirosian[3], Evangelos Mouchos[4], Murali Thoppil[5], Ben Newport[6]

[1]School of Geographical Sciences, University of Bristol, Bristol, UK, BS8 1SS, email: sue.rodway-dyer@bristol.ac.uk; [2]Jo.House@bristol.ac.uk; [3]natasha.martirosian@bristol.ac.uk; [4]evangelos.mouchos@bristol.ac.uk; [5]murali.thoppil@bristol.ac.uk; [6]murali.thoppil@bristol.ac.uk

Introduction

The principles of Monitoring, Reporting and Verification (MRV) of Greenhouse Gas Removals (GGR) are Accuracy, Transparency, Consistency, Comparability, and Completeness but the reality is the use of variable definitions, methods, uncertainties, system boundaries and baselines, and few include all GGR approaches or externalities or the full life-cycle. There are no current internationally agreed standards and there are equity issues.

Methods

A grey literature review and comparative analysis of methods and approaches to GGR MRV produced a roadmap of current MRV regulations, protocols, frameworks, standards, certification schemes etc. with the aim of identifying gaps, barriers, opportunities, (un)certainties, best practice, and user priorities. The research investigated accuracy vs pragmatism, research priorities, ways forward for rapid action, and longer-term goals. Methods also included workshops with stakeholders e.g. CO_2RE GGR-Demonstrator projects, Department for Energy Security and Net Zero Innovation funded projects etc.

Results

The roadmap collated data to form a comparative analysis of methods and approaches to GGR MRV for 145 projects/organisations. The poster shows common findings across CDR technologies (Table 1) and provides more specific examples for biochar and Enhanced Rock Weathering to highlight the differences in GGR methods.

Conclusion

Common findings confirmed the variability of baselines and life-cycle impacts, the uncertainty over permanence, along with the lack of commonality on agreements within Voluntary Carbon Markets. A credible regulatory framework is needed to ensure investor, producer and public confidence. A regulatory body needs clear powers that can work across multiple GGR technologies and services from carbon to sustainability. Protocols and standards need to be harmonised internationally with flexibility to respond to improved data, methods, technology, best practices (within and outside carbon markets) and changing targets. Therefore, MRV needs to be beyond carbon, and across the full life-cycle, to meet multiple goals and opportunities. It requires coordination across regulatory systems and incentive frameworks.

***Table 1**. Common findings across CDR technologies*

Common findings across CDR technologies	
Baselines, boundaries and additionality	• Often undefined: *"Baselines"* against which to calculate *"additional"* change to what would occur without targeted CDR activity e.g.: compared to when (date), what (historical management), how life-cycle and co-products are included, national boundaries e.g. importing/exporting resources/co-products • Net-negativity across full Life-Cycle impacts are difficult to assess.[1]
Permanence / durability of carbon stores	• Varying/uncertain levels of permanence across CDR methods • Fungibility/comparability/commonality is a challenge, limited agreement on how to address.[2]
Methodological approaches to quantifying removals - accuracy versus pragmatism	• Key for investor and public confidence, credibility and integrity • High variability compromises integrity and makes investor and regulatory decision-making challenging e.g. quantification principles, definitions and methods, transparency (e.g. commercial interests)[3] • Some methods too high-tech for capacity and capability of practitioners, or too inaccurate for investor confidence.
MRV beyond carbon - externalities, co-benefits and trade-offs	• Comparable evaluation needed across different CDR approaches for informed decision making • Few include direct MRV of non-Greenhouse Gas impacts • Reliance on separate environmental regulation or add-on sustainability certification criteria e.g. peatland carbon code, woodland carbon code.
Policy / governance	• Currently private-sector MRV standards “fairly onerous”, with a ‘laundry list’ of requirements • Plethora of private standards • Emerging complex landscape of EU and US frameworks, regulatory values and approaches[2].

References

1. Butnar, I., et al. Assessing Life Cycle Methods for scalable Carbon Dioxide Removal. IREs Energy and Environment – (in press).
2. Smith, S. M., et al. (eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition.
3. Arcusa, S. & Sprenkle-Hyppolite, S. Snapshot of the Carbon Dioxide Removal certification and standards ecosystem (2021–2022). Climate Policy 22, 1319–1332 (2022).

Carbon dioxide removal: A source of ambition or of delays?

Conference session: Removals and residual emissions

Juanita von Rothkirch[1], Olivier Ejderyan[2], Michael Stauffacher[3]

[1]Department of Environmental Systems Science, ETH Zürich, Switzerland, email: juanita.rothkirch@usys.ethz.ch
[2] Research Institute of Organic Agriculture, Switzerland
[3] Department of Environmental Systems Science, ETH Zürich, Switzerland

Introduction

The tension implicit in CDR - its necessity but the danger of causing delays in mitigation- has attracted much interest among researchers, decision-makers, and citizens. Researchers and organisations have warned that large-scale implementation of CDR methods, as modelled in most IPCC scenarios, is unlikely to be feasible, as many methods are expensive and may negatively affect biodiversity, water resources, food production, and energy availability.[1,2] Thus, placing unrealistic expectations on such methods risks is dangerous. If they fail to materialize, they will delay our climate mitigation targets, thereby subjecting future generations to the severe consequences of climate change.[3,4] However, few studies have explored how CDR could be leading to a delay in emissions mitigation in given contexts, or what is being done to prevent this.[5]

In this study,[6] we explored the mechanisms how Swiss actors' expectations over CDR can lead to increasing or preventing delays. Switzerland is home to growing businesses in CDR and has pioneered the implementation of international offsetting projects under Article 6.2 of the Paris Agreement. We followed an approach called "sociology of expectations", which assumes that positive expectations about a technology - also called promises - are important for guiding activities, attracting the interest of other actors, and driving investment.[7,8] However, promises often lead to diverting attention away from other solutions. Promises can also lead to disappointment when risks are overlooked, actions are not well coordinated, and technologies do not perform as expected.[7] In the case of CDR, this would result in delays in climate change mitigation, as residual emissions would not be sufficiently addressed. Ideally, then, promises around a technology should be realistic and risks and concerns should be addressed from the start.

Methods

We used a qualitative research approach employing stakeholder interviews, Swiss parliamentary motion documents, and participant observations for primary data collection. In our interviews, we asked participants about their perceptions on (1) the need for and role of CDR in targeting Swiss emissions, (2) CDR methods to be employed, and (3) regions where CDR methods should be implemented. The interviews were fully transcribed and, together with the documents, systematically coded using a qualitative data analysis software. We looked for promises about and concerns over CDR as well as how interviewees used these to promote or delegitimize CDR.

We analysed how much agreement there is on promises and concerns, and which are expressed in private or public spheres. We discussed what this might mean for mitigation deterrence risks.

Results and Discussion

We found that numerous promises help legitimize and attract interest in CDR, elevating expectations of its role in the battle against climate change. These include arguments on the need for CDR, its feasibility, the economic benefits it can bring, as well as the responsibility of Switzerland to deploy CDR methods. Actors use discursive strategies and rules to limit CDR and avoid disappointment in its contribution to climate mitigation. For instance, by carefully approaching issues such as methods' carbon cycles and cost-efficiency logics that contribute to the substitution of reductions by CDR in integrated assessment models. The idea that emissions reduction should prevail over carbon removal is promoted accordingly, by using sentences such as "reductions first" in events and texts. We highlight that this, ironically, seems to help legitimize the idea of CDR while dodging the question of how much removal is possible and for balancing which emissions. Superficial engagement with the issue is reinforced by the sentiment that the mitigation deterrence rhetoric erodes trust in CDR. We argue that this can contribute to mitigation delays by evading the debate on how much removal will be possible, which emissions should be balanced with it, as well as by taking resources from alternative measures.

Recommendations

We recommend the following measures to limit the potential for CDR to cause delays in emissions mitigation:

- Actors should be vocal about the challenges and risks of CDR methods, with the vision of promoting CDR in a realistic way. In this context, it is essential to find formats and create a culture in which actors feel open to share criticisms, concerns, and risks, including when talking about CDR to audiences outside of the CDR community.

- Actors should become explicit about the meaning of residual emissions and 'reductions first'. This means clarifying stakeholder expectations about what is expected to be eliminated, deciding what CDR will and will not be available for, and considering alternatives to CDR to address residual emissions. In some cases, sufficiency measures will be less constrained by natural, social, and financial resources and should therefore also be included as possible measures.

- We need to reflect in the CDR community on the ways in which we write and discuss the issue, so that mitigation deterrence is no longer seen by some as an unnecessary or damaging discussion, but as the question of how to make CDR live up to its promises, and the promises up to the realities of CDR.

References

1. Creutzig, F. Economic and ecological views on climate change mitigation with bioenergy and negative emissions. GCB Bioenergy 8, 4–10 (2016).
2. Heck, V., Gerten, D., Lucht, W. & Popp, A. Biomass-based negative emissions difficult

to reconcile with planetary boundaries. Nature Climate Change 2018 8:2 8, 151–155 (2018).
3. Anderson, K. & Peters, G. The trouble with negative emissions. Science (1979) 354, 182–183 (2016).
4. European Academies Science Advisory Council (EASAC). Forest Bioenergy Update: Bioenergy and Its Role in Integrated Assessment Models. https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_BECCS_Commentary_2022_WEB_final.pdf (2022).
5. Carton, W., Hougaard, I. M., Markusson, N. & Lund, J. F. Is carbon removal delaying emission reductions? Wiley Interdiscip Rev Clim Change 14, (2023).
6. von Rothkirch, J., Ejderyan, O. & Stauffacher, M. Carbon dioxide removal: A source of ambition or of delays? Examining expectations for CDR in Swiss climate policy. Environ Sci Policy 153, 103659 (2024).
7. Borup, M., Brown, N., Konrad, K. & Van Lente, H. The sociology of expectations in science and technology. Technol Anal Strateg Manag 18, 285–298 (2006).
8. Van Lente, H. Navigating foresight in a sea of expectations: lessons from the sociology of expectations. https://doi.org/10.1080/09537325.2012.715478 24, 769–782 (2012).

Current rates of carbon dioxide removal through afforestation and reforestation

Conference session: Global Policy 2

Clemens Schwingshackl[1], Thomas Gasser[2], Richard A. Houghton[3], Julia Pongratz[1,4]

[1] Department of Geography, Ludwig-Maximilians-Universität München, Munich, Germany, email: c.schwingshackl@lmu.de
+ International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
[3] Woodwell Climate Research Center, Falmouth, MA, USA
[4] Max Planck Institute for Meteorology, Hamburg, Germany

Introduction

Current amounts of carbon dioxide removal (CDR) stem almost exclusively from afforestation and reforestation and durable storage in harvested wood products. However, the amount of CO_2 currently taken up by these forest-based CDR measures remains uncertain, as does their distribution across the world. This makes it hard to track mitigation efforts, to assess potentials to increase forest-based CDR, and to assess the vulnerability of the stored carbon to the impacts of climate change. On the one hand, the high uncertainty arises from challenges in precisely defining re/afforestation in the context of CDR, where the permanence of the forest cover changes needs to be considered. On the other hand, only very few estimates of the carbon uptake through re/afforestation exist at present, mostly based on national greenhouse gas inventories, which, however, do not directly quantify carbon fluxes from afforestation and reforestation. Here we present new estimates of the carbon removals by re/afforestation based on multiple bookkeeping models, a methodology consistent with the assessments of the annual Global Carbon Budget.

Methods

We use estimates from three bookkeeping models (BLUE[1], H&C2023[2], OSCAR[3]) that are used to provide land-use CO_2 emissions for the Global Carbon Budgets.[4] We split the net land-use fluxes into different components to isolate CDR. We define CDR through afforestation and reforestation as all CO_2 fluxes that are due to afforestation and reforestation, forest (re-)growth after abandonment of agricultural areas, and the establishment of forest plantations.

Results

Globally, afforestation and reforestation removed -1800 $MtCO_2$/year (-1200 to -2200 $MtCO_2$/year; full range across models) on average in 2000-2022 (Figure 1a). Throughout this period, the amount of carbon removed by afforestation and reforestation was persistently larger than -1500 $MtCO_2$/year. The amount of removed carbon increased until the early 2010s, followed by a slight decrease in recent years. China, the EU27, the USA, and Brazil are responsible for more than 50% of CDR due to afforestation and reforestation (Figure 1b), yet with partly large uncertainties, especially in China, the EU27, and Brazil.

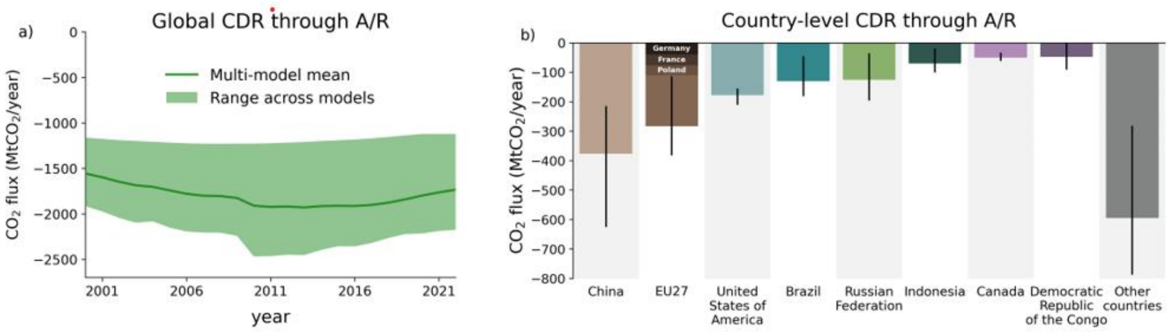


Figure 1. *Current rates of carbon dioxide removal (CDR) through afforestation and reforestation (A/R). (a) Global estimates and (b) estimates for regions and countries with largest CDR through A/R (averaged over 2013-2022). The negative values indicate carbon removal from the atmosphere. Bars in (b) represent the multi-model mean and whiskers the range across the three bookkeeping models. Country names in the EU27 bar indicate the three EU27 countries with the largest afforestation/reforestation fluxes (Germany, France, Poland).*

Conclusion

Currently, CO_2 removal by afforestation and reforestation is dominating global CDR rates: More than 99.9% of all current CDR is due to afforestation and reforestation.[5] Precise and reliable estimates of the CO_2 removals through afforestation and reforestation are thus paramount to monitor global CDR efforts. Our estimates contribute to a better understanding of the uncertainties of current CDR deployment rates. Yet, additional improvements are necessary, for instance regarding the inclusion of reforestation projects and the consideration of how natural disturbances and forest degradation impact carbon fluxes in re/afforestation projects.

References

1. Hansis, E., et al. Relevance of methodological choices for accounting of land use change carbon fluxes. Global Biogeochem. Cycles 29, 1230–1246 (2015).
2. Houghton, R. A. and Castanho, A. Annual emissions of carbon from land use, land-use change, and forestry from 1850 to 2020. Earth System Science Data 15, 2025–2054 (2023).
3. Gasser, T., et al. Historical CO_2 emissions from land use and land cover change and their uncertainty. Biogeosciences 17, 4075–4101 (2020).
4. Friedlingstein, P., et al. Global Carbon Budget 2023. Earth System Science Data 15, 5301–5369 (2023).
5. Smith, S.M., et al. (eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition (2024).

Achieving BECCS with chemical looping combustion

Conference session: BECCS 1

Ivana Staničić[1*], Tobias Mattisson[1], Joakim Brorsson[2], Anders Hellman[2], Magnus Rydén[1], Judit Fortret Casabella[1], Gajanan Dattarao Surywanshi[3], Jonatan Gastaldi[1], Anders Lyngfelt[1]

[1] *Department of Space, Earth and Environment, Division of Energy Technology, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden*
[2] *Department of Physics, Division of Chemical Physics, Chalmers University of Technology*
[3] *Department of Chemistry and Chemical Engineering, Chalmers University of Technology*
**e-mail: stanicic@chalmers.se*

Introduction

There are currently no multi-national incentives to promote negative emissions and BECCS. At the same time negative emissions are needed on a significant scale and need to be implemented rapidly. The question is if there are ways to accelerate deployment of BECCS rapidly without short-term policy instruments. Chemical looping combustion (CLC) has some pervasive characteristics, which could mean that the technology can be implemented for heat and power production at low economic risk, even in current market conditions. Chemical looping combustion, as displayed in Fig. 1, can burn biomass and biobased waste, with the generated CO_2 obtained inherently in pure form.[1] The technology has been demonstrated in >50 pilot units and most recently up to 5 MW.[2] There are some compelling reasons why we believe the technology can be viable today, and we provide our thoughts below.

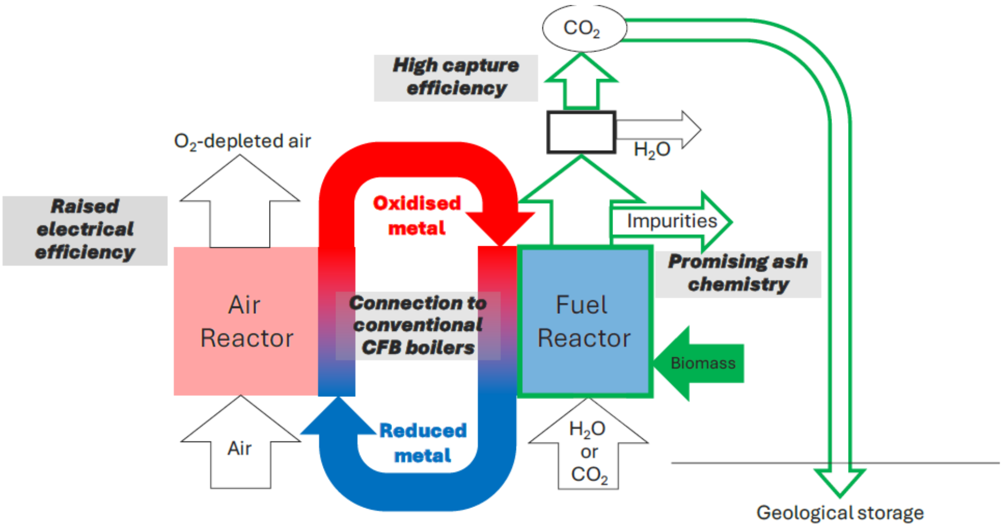


***Figure 1**. Schematic overview of BECCS with chemical looping combustion.*

1. Low energy penalty for carbon capture

The first advantage with CLC comes from splitting the combustion into two steps using solid metal oxides, called oxygen carriers. The particles are oxidised in the air reactor (AR) before being transported to the fuel reactor. In the fuel reactor (FR), fuel is converted to CO_2 and H2O using oxygen delivered by the oxygen carriers. After condensing the steam from the flue gas, a highly concentrated CO_2-stream is obtained suitable for carbon capture and storage as illustrated in Fig.1. Thus, CO_2 can be captured without the large energy penalty of competing technologies. Additionally, a high fraction of volatiles in biomass fuels is an advantage when utilised in CLC, as oxygen carriers can react directly with these gases providing a high CO_2 gas yield. Lastly, the effluent from the AR should be free from impurities as long as no char leaks from the FR with the solids circulation.[3]

2. Raised electrical efficiency

An additional benefit of decoupling reduction and oxidation is that impurities are primarily concentrated in the FR, and impurities are thus avoided in the AR. This implies that CLC could result in a significant reduction in the maintenance costs, as well as higher electrical efficiency, as steam is produced in the ash-free AR. The feasibility of such improvements was investigated by a techno-economic analysis of CLC in an existing CHP plant in Skövde, Sweden.[4] The study concluded that it is possible to raise the steam temperature and electricity output, and that CLC is associated with a lower capture cost and energy penalty compared to an MEA process.

3. Connection to conventional CFB boilers

Almost all CLC pilot units are designed based on interconnected fluidised beds, and in fact, most of the designs for upscaling are based on circulating fluidised beds, but with an added fuel reactor. For instance, Lyngfelt et al. proposed a 200 MW_{th} CLC design composed of two CFB boilers that enables flexible operation, thus the unit can be used both as a conventional CFB without CO_2-capture, but also in “CLC-mode” when conditions for CO_2 capture and BECCS are viable.[3] For an end-user, the added cost for the fuel reactor should be low, but would enable a multi-purpose and flexible operation reducing both technical and economic risks.

4. Promising ash chemistry

Agglomeration and high-temperature corrosion are common problems in conventional CFB boilers, and especially for biomass and biobased waste. CLC differs from conventional combustion as the oxygen carrier can capture impurities that are responsible for high-temperature corrosion, without forming sticky compounds. Both iron- and manganese-based oxygen carriers have been examined extensively and shown to capture problematic impurities.[5] Due to this, less metal chlorides are expected to form compared to conventional combustion, which has positive implications for corrosion.[6]

Conclusion

CLC has many advantages, besides low carbon capture costs, low energy penalty and promising chemistry of impurities there are also important features such as increasing the steam temperatures and electrical efficiencies in combination with the similarities to conventional CFB boilers that can drive BECCS deployment and play an important role in the energy transition in reaching net zero targets by 2050.

References

1. Lyngfelt, A. Chemical-looping combustion of solid fuels – Status of development.

Applied Energy 113, 1869-1873 (2014).
2. The Chinese research group has made significant progress in the field of chemical looping combustion. Tsinghua University (2024). [Press release] Available at: https://www.te.tsinghua.edu.cn/info/1095/3291.htm (Accessed: 10th June 2024)
3. Lyngfelt, A. et al. Achieving Adequate Circulation in Chemical Looping Combustion–Design Proposal for a 200 MWth Chemical Looping Combustion Circulating Fluidized Bed Boiler. Energy & Fuels 36, 9588-9615 (2022).
4. Fortret Casabella, J. & Chehade, Y. Feasibility study of implementing Chemical Looping Combustion with BECCS - Process modeling and techno-economic analysis of a CHP plant at Skövde Energi. [Master's thesis, http://hdl.handle.net/20.500.12380/306381] (2023)
5. Staničić, I. et al. Investigating the Interaction between Ilmenite and Zinc for Chemical Looping. Energy & Fuels 37, 7856-7870 (2023).
6. Staničić, I. et al. Thermodynamic Analysis on the Fate of Ash Elements in Chemical Looping Combustion of Solid Fuels–Iron-Based Oxygen Carriers. Energy & Fuels 36, 9648-9659 (2022).

Preconcentration of methane by vacuum-temperature swing adsorption for removal from air

Conference session: Methane Removal

Sai Gokul Subraveti[1], Giorgia Mondino[2], Richard Blom[2], Rahul Anantharaman[1]

[1]*SINTEF Energy Research, Trondheim, Norway, email: sai.gokul.subraveti@sintef.no*
[2]*SINTEF Industry, Oslo, Norway*

Introduction

The rise in greenhouse gas (GHG) concentrations in the atmosphere is a key driver of global warming. While GHG mitigation efforts have predominantly centred on carbon dioxide (CO_2), the recent sixth assessment report from the Intergovernmental Panel on Climate Change (IPCC) emphasized the impact of non-CO_2 greenhouse gases such as methane (CH_4) on global warming and its role in meeting climate neutrality by 2050. Despite CH_4's lower atmospheric concentrations (~2 ppm) compared to CO_2 (417 ppm), it has more than doubled since preindustrial times, with agricultural activities, such as cattle, manure, etc., as the dominant source of anthropogenic CH_4 emissions. The CH_4 concentrations at these emission sources are higher than in the ambient air, typically around 10 – 1000 ppm. With over 25 times more global warming potency compared to CO_2 over a 100-year horizon, removing CH_4 from the atmosphere or other dilute sources presents an opportunity to slow down climate change. In contrast to CO_2, which needs to be separated, CH_4 is reactive and can be removed by converting it to CO_2 or other products. However, the extremely diluted concentrations of CH_4 make the conversion very challenging.

This study examines the feasibility of preconcentrating CH_4 from highly dilute sources, such as 2 ppm, 20 ppm, and 200 ppm CH_4 feed concentrations, to around 1% using the vacuum-temperature swing adsorption (VTSA) process before the conversion. The process performance limits are identified through integrated adsorbent-process optimizations that minimize the exergy consumption and maximize the productivity of the process.

Results

The results indicated that, depending on the methane concentrations in the air, the minimum exergy consumption falls within the range of 3.4-22 MJ per kg equivalent CO_2, while the maximum productivity ranges from 0.6-4.9 kg equivalent CO_2/h per m^3 adsorbent. Moreover, high-purity CO_2 (i.e., 70-96%) was obtained in the CH_4-enriched product, demonstrating the potential of co-removing both CH_4 and CO_2. Optimized CH_4 isotherms for the hypothetical adsorbents exhibited moderate loadings of 0.1 to 0.3 mmol/g and heats of adsorption of around 32 kJ/mol.

Next, several adsorbents are experimentally screened for their ability to adsorb CH_4 at the desired feed compositions. In the experiments, CH_4 isotherms of standard adsorbents such as activated carbons and zeolites, along with novel metal-organic frameworks such as CALF-20, UTSA-16, KAUST-7, and PCN-250 are measured at the ppm levels and different temperatures.

The CH_4 isotherm measurements on these materials did not show any considerable loadings, suggesting that adsorbing CH_4 at the ppm levels can be challenging.

Conclusion

The performance limits of the VTSA process for methane preconcentration suggest that it has the potential to remove CH_4 from agricultural sources. However, directly removing methane from the air may not be technically feasible. Particularly, the key process performance indicators, namely, exergy consumption and productivity, when expressed in kg equivalent CO_2, are comparable to direct air CO_2 capture. However, the real isotherms measured for various adsorbents showed extremely low CH_4 capacities at the desired partial pressures. Therefore, future research needs to focus on finding the right adsorbents for this separation.

Acknowledgments

This work has received support from the project "The Norwegian Continental Shelf: A Driver for Climate-Positive Norway" (NCS C+) funded by the Research Council of Norway (328715) under the green platform program.

Sequencing carbon dioxide removals into the EU ETS

Conference session: Global Pathways

Darius Sultani[1], Sebastian Osorio[1], Claudia Günther[1], Michael Pahle[1], Katrin Sievert[2], Tobias S. Schmidt[3], Bjarne Steffen[2], Ottmar Edenhofer[1,4,5]

[1] Potsdam Institute for Climate Impact Research, Germany, corresponding author: sultani@pik-potsdam.de
[2] Climate Finance and Policy Group, ETH Zurich, Switzerland
[3] Energy and Technology Policy Group, ETH Zurich, Switzerland
[4] Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany
[5] Technische Universität Berlin, Germany

Introduction and approach

While there is consensus on the high-level vision of removals,[1] conceptual details still need further substantiation. Previous work has shaped a good understanding of the challenges decision-makers will face on the way.[2] However, what the path from today's policies to this vision should look like is still unclear. We address this gap in three parts. We (1) characterise a first-best vision for removals in the form of an economically desirable, long-term regulatory framework to work towards to.[3] We (2) then analyse the implications of a first-best integration of permanent removals into the EU's carbon compliance market using the numerical model LIMES-EU. Results underpin the general cost-effectiveness of integration. However, high uncertainty on CDR cost and fragmented regulation give rise to the risks of abatement deterrence and excessive biomass use, which need to be accounted for through a second-best sequencing approach. We consequently (3) derive a three-stage path for removal integration into the EU ETS, based on risk reduction contingencies that serve as preconditions for entering subsequent stages.

A first-best vision for removals

To ramp-up removal capacities efficiently, in the long run, an economically desirable regulatory framework would fulfil three key requirements:

1) <u>Pigouvian efficiency</u>: To ensure an optimal balance between abatement and removals, marginal abatement cost should be able to meet marginal (permanent) removal cost. Pigouvian efficiency also entails comprehensive Pigouvian pricing, especially to account for externalities from removals in the land-use sector.
2) <u>Enhanced supply-side efficiency</u>: To ensure cost-effective supply of removals at scale, the long-term regulatory framework should entail removal certificates from international and temporary removals.
3) <u>Readiness for overshoot management</u>: Targets and institutions need to be in place to reduce overshoot once the carbon budget has been depleted.

We model a first-best – i.e. direct and unconstrained – integration of permanent removals (BECCS and DACCS) into the European carbon compliance market. A first-best integration can incentivise removals and cut allowance prices considerably (Figure 1a), but results rely on progress in technological learning of DACCS (Figure 1b).

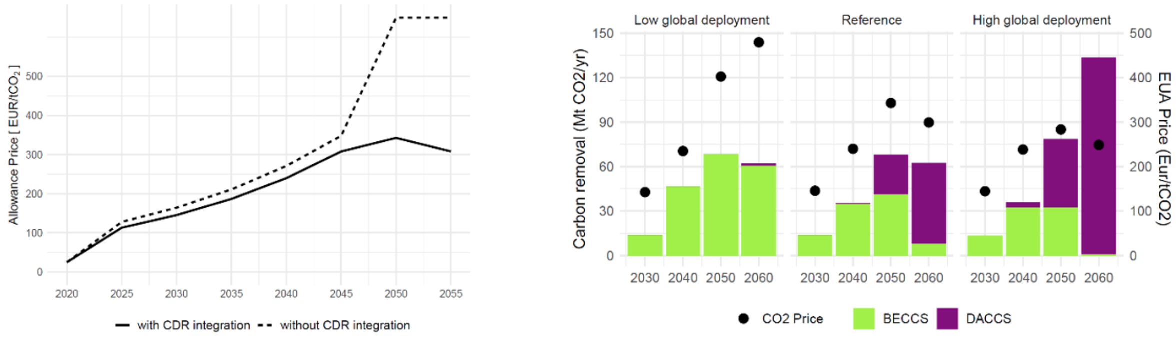


Figure 1. *Panel (a) to the left shows EUA prices with and without a first-best integration of permanent removals into the EU ETS. Panel (b) gives removal deployment and EUA prices under three scenarios for global DACCS deployment, and hence DACCS prices due to technology learning.*

Based on these results, we identify abatement deterrence and excessive biomass use as main risks of such a first-best integration. To provide a policy path that both accounts for these risks but also leads towards the first-best vision, we propose a sequencing approach for removals into the EU ETS.

Sequencing removals into the EU ETS: Three stages for an integration in a second-best setting

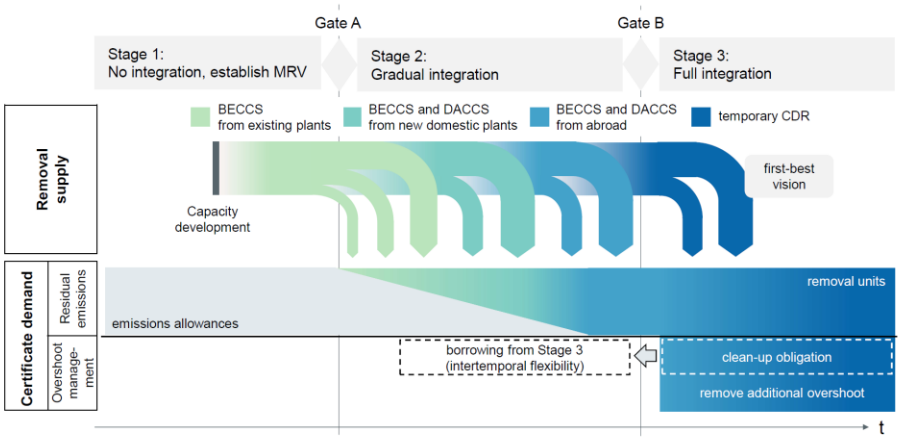


Figure 2. *Stage-gate approach with three governance stages of integrating removals into the EU ETS, building on Burke and Schenuit.*[4]

The proposed approach (Figure 2) starts with separated systems, but ends in full integration. Before a subsequent stage is entered, certain conditions - serving as safeguarding gates - have to be fulfilled. From Stage 2 onwards, removal certificates are admitted to the system, albeit in a restricted way at first (indicated by the initially more narrow inflows of removal supply). Integration starts with existing BECCS plants, but opens up gradually until the first-best vision materialises upon integration of international and temporary removals. Borrowing from future removals provides intertemporal flexibility. This could be realised through clean-up certificates, which come with a clean-up obligation for the overshoot emitted.[5]

The success of such a sequencing approach hinges on the credibility to follow through with all three stages, yet leaving sufficient flexibility to account for technology and policy learning. This governance challenge strengthens the case for a European Carbon Central Bank. Further discussions are needed, however, to define the exact functions such a new institution should take on, and by which rules these functions would be performed.

References

1. Babiker, M. et al. Cross-sectoral perspectives. in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Shukla, P. et al.) (Cambridge University Press, 2023). doi:10.1017/9781009157926.005.
2. Anderson, K. et al. Controversies of carbon dioxide removal. Nat. Rev. Earth Environ. 4, 808–814 (2023).
3. Dolphin, G., Pahle, M., Burtraw, D. & Kosch, M. A net-zero target compels a backward induction approach to climate policy. Nat. Clim. Change 13, 1033–1041 (2023).
4. Burke, J. & Schenuit, F. Governing Permanence of Carbon Dioxide Removal: A Typology of Policy Measures. (2023).
5. Lessmann, K., Kalkuhl, M., Gruner, F. & Edenhofer, O. Emissions Trading with Clean-up Certificates: Deterring Mitigation or Increasing Ambition Levels? (forthcoming). Preprint at (2024).

Assessing a complex biochar system with circular economy principles

Conference session: Biochar

Cecilia Sundberg[1], Harry Tibbetts[1], Lisa Zakrisson[1], Mary Njenga[2,3], Catherine Ndinda[2,3], Ivan Kozyatnyk[4]

[1] Department of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala, Sweden, 750 07, email: cecilia.sundberg@slu.se

[2] Wangari Maathai Institute for Peace and Environmental Studies, University of Nairobi, Nairobi, Kenya, e-mail: m.njenga@cifor-icraf.org

[3] Centre for International Forestry Research-World Agroforestry (CIFOR-ICRAF), Nairobi, Kenya, e-mail: m.njenga@cifor-icraf.org

[4] Department of Health, Medicine and Caring Sciences, Unit of Clinical Medicine, Occupational and Environmental Medicine, Linköping University, Linköping, Sweden, 581 83, e-mail: ivan.kozyatnyk@liu.se

Introduction

Life cycle analysis (LCA) is well established for measuring greenhouse gas (GHG) balances of carbon dioxide removal (CDR) systems. For CDR that uses biomass, issues related to land use and biomass co-product use have climate impact but are difficult to determine with LCA. Also, early in a research process it is difficult to quantify climate impacts due to lack of data. Circular bioeconomy is considered a promising strategy for resource-efficient biomass use with low environmental impacts, but lacks operational assessment methods. The aim was to develop a method to assess the sustainability of complex biochar systems, applied to a case study in a research project in Kenya using biochar in greywater treatment.

Methods

A method for assessing complex biochar systems using circular bioeconomy principles was developed and applied, alongside an existing life cycle framework, which was also used for a qualitative climate impact assessment.

Circular bioeconomy principles identified were to:

- safeguard ecosystems by minimizing emissions, limiting land degradation and protecting biodiversity
- avoid waste by using biomass efficiently, making use of residues and by retaining resource quality over time
- prioritize basic human needs, and sectors without sustainable alternatives
- recycle nutrients and carbon back to land
- minimize use of non-renewable energy and materials

In the system studied, biochar, produced as a byproduct of gasifier cookstoves, was mixed with a coagulant protein from Moringa oleifera seeds to treat greywater in a residential, rural setting. Previous research demonstrated promising results from this process, inspiring the novel system design to be compared with a baseline of moringa-based agroforestry with seed oil extraction and residual use for animal feed.

Results

Life cycle thinking identified 5 functions where the system and the baseline differed: cooking energy, animal feed, greywater treatment, water recycling and soil amendment with biochar carbon storage.

In the circular bioeconomy assessment, opportunities for improvement compared to the baseline were identified for all principles and their sub criteria. Some risks for poor outcome were identified, which would need to be considered in further research and in future implementation of the system. These risks include traditional charcoal production methods, reduction in animal feed production and spreading of contaminants from wastewater to soil.

In the climate impact assessment, traditional charcoal methods and animal feed baseline were also identified as risks. Methane and nitrous oxide formation in greywater filter and end use of filter material were identified as uncertainties to investigate in further research. Climate benefits identified were long-term carbon storage in biochar, reduced emissions from cooking and reduced demand of forest fuelwood. In conclusion, the method was successful in identifying opportunities, risks and knowledge gaps for climate impact and for circular bioeconomy.

Spatially analysis identifies the potential for biochar production in Great Britain

Conference session: Biochar

Yuzhou Tang[1], Disni Gamaralalage[2], Jon McKechnie[3], Tim T. Cockerill[4]

[1]*School of Mechanical Engineering, University of Leeds, Leeds, LS2 9JT, UK, email: Y.Tang@leeds.ac.uk*
[2]*University of Nottingham, University Park, Nottingham, NG8 1BB, UK, email: disni.gamaralalage@nottingham.ac.uk*
[3]*University of Nottingham, University Park, Nottingham, NG8 1BB, UK, email: jon.mckechnie@nottingham.ac.uk*
[4]*School of Mechanical Engineering, University of Leeds, Leeds, LS2 9JT, UK, email: t.cockerill@leeds.ac.uk*

Introduction

Biochar has been extensively studied due to its potential to substantially contribute to greenhouse gas removal targets, facilitate the adoption of agricultural greenhouse gas (GHG) reduction measures, and enhance soil quality. Biochar is derived from the pyrolysis of biomass, which includes distributed agricultural and forestry residues, along with discrete feedstock like digestate. Yet, there are currently no large-scale biochar production facilities in Great Britain (GB), and its feasibility is debated with respect to negative impacts on broader sustainability issues. Here, we propose spatially explicit methods tailored to two distinct feedstock distribution types. Using these methods, we evaluate the marginal cost curves for biochar decarbonisation in the context of scaling up production to achieve net-zero targets. Furthermore, we analyse the challenges and opportunities associated with large-scale production for each feedstock type, providing valuable insights for policymakers and industry stakeholders.

Methods

In this study, the life cycle assessment (LCA) and techno economic analysis (TEA) are used to the biochar decarbonisation potential and corresponding marginal cost. LCA is a decision support tool used to understand the environmental impacts of the commercial products, which considers the entire life cycle of a product, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment and final disposal. TEA is a systematic method for evaluating the economic performance of a design process. We develop two parallel spatial models to analyse the feedstock supply situation and determine the factory strategies for the estimate for the potential biochar production in GB.

A distributed spatial modelling is employed to devise factory strategies for the distributed feedstock source of straw. Given the widespread distribution of farmland, we consider each potential location within the study area as a possible feedstock supply point and aim to identify suitable processing site locations across the region. We assume that the utilisation of the proportion of all straw sold for non-agricultural purposes (22%) and the market prices as feedstock for biochar production. Initially, we use QGIS software to analyse the distribution and estimate the potential supply quantity of feedstocks. Following this, based on PyQGIS functions, we calculate the mass-distance from each potential processing site to every feedstock supply point. Using a mass-distance-minimisation approach, we then apply a particle swarm optimisation model to determine the optimal number and locations of processing sites. Finally, by integrating the results of the spatial model with LCA and TEA, we conduct a detailed analysis of the marginal costs associated with biochar decarbonisation.

For the feedstocks available in discrete locations, the co-location of biochar production plant with the feedstock facility is considered. Thus, for discrete feedstocks like digestates, the anaerobic digestion plant locations are considered as the prospective biochar plant locations. Then the optimal plant locations for the selected discrete feedstock in the region to achieve minimum cost identified in the model. The evaluation is based on the approximate heuristic algorithm considering the theory of Maranzana (1964). Total availability of currently produced digestate for the biochar production is considered in this work. The cost estimation calculations and models are developed using Python and the actual road transportation distances are estimated using the Openroute service module. The optimisation model delivers the optimum number and scale of biochar production plants and their optimum groups of feedstock suppliers and the GHG removal.

Results

We estimate that 2.4 Mt of straw can be sourced from the market to produce biochar, along with 13.3 Mt of dry digestate material available in GB. These feedstocks can yield a total carbon sequestration of 1.7 Mt CO_2 eq from straw and 2.8 Mt CO_2 eq from digestate. Additionally, they can produce 3.6 million GJ of energy from straw and 4.4 million GJ of energy from digestate. We estimate the marginal costs of biochar production in each region for distributed and discrete feedstocks by solving a cost-minimisation problem with costs and life-cycle emission sources. The sensitivity analysis is applied to analyse the impact of parameters on the marginal costs.

This study elucidates the critical role of biochar in achieving net-zero targets and provides the government with essential insights for biochar investment. It emphasises the distinct challenges and opportunities associated with two different feedstock types. Our research helps to understand the primary issues in scaling up these feedstocks, highlighting their respective contributions to carbon sequestration and energy production. Straw and digestate differ in terms of availability, transportation logistics, and processing efficiency, making it crucial to address their unique environmental, economic, and technological challenges for large-scale biochar application.

But when? Temporal compression in life cycle accounting for carbon dioxide removal

Conference session: Life Cycle Assessment

Samantha Eleanor Tanzer[1]

[1]*Department of Engineering Systems and Services, Faculty of Technology, Policy and Management, Delft University of Technology, Delft, Netherlands, 2628 BX, s.e.tanzer@tudelft.nl.*

If the fundamental purpose of carbon dioxide removal (CDR) is to mitigate global warming via the decrease of atmospheric greenhouse gas concentrations, then the key metric of CDR is the amount by which atmospheric GHGs decreased, the so-called "net removal".[1] Thus, life cycle greenhouse gas accounting[2] (LCA), a modelling methodology used to estimate all GHG emissions associated with a system regardless of when or where they occur,[3] arises as a necessary assessment tool to determine whether it is possible for a given CDR activity to result in net removal.

Conventional (or so-called "static") LCA does not distinguish between emissions/impacts that happen at different points in time. This is a feature, not a bug: all impacts are weighted equally and characterized to the same time-horizon, thus giving an even treatment of impacts across a system's lifecycle and compressing them into a single-point "global warming potential" (GWP) metric. However, CDR systems display a diversity of intertemporal dynamics[4] that define many of the relative advantages and disadvantages of each system. This nuance is lost or distorted in the temporal compressions that occur in static LCA, even beyond those occurring due to the limitations of the conventional GWP-100 characterization factors.[5] In particular, as each emission or extraction—regardless of when they occur—uses a characterisation factor with the same time-horizon, static LCA has an inherently inconsistent impact time-horizon, thus distorting when a system exhibits net removals.

Critical questions about CDR that are not answerable via static LCA include:

- When does a system [begin to] result in net removals? (the so-called "carbon payback period")

---

[1] Net removal = atmospheric CO_2 extracted and stored – all GHG emissions directly and indirectly associated with extraction and storage.

[2] Formally, a life cycle assessment should encompass encompassing multiple impact categories to provide a comprehensive picture of a system's environmental impacts and trade-offs. However, I am presently only referring to the estimation of life cycle impacts from greenhouse gases.

[3] Including emissions of the activities themselves, as well as upstream emissions from supply chains and downstream emissions of use, waste disposal, and end-of life.

[4] Including the rate of CO_2 uptake, the expected duration of CO_2 storage, the risk of reversal, and the timing of associated emissions relative to the timing of uptake and storage.

[5] Such as the averaging of disparate impact profiles within the time-horizon, cut-off of impacts beyond the time-horizon, the zero-rating of biogenic CO_2 emissions, the inability to account for the impacts of temporary storage, and their dependency on the concentration of atmospheric greenhouse gases.

- When does a system stop resulting in net removals? (e.g., due to reversal or accumulated associated emissions, such as from ongoing monitoring and maintenance. This is of particular importance for systems where storage is fundamentally temporary or has a high risk of reversal.)
- When does a system exhibit peak impact or benefit?

Furthermore, as most forms of CDR are not yet implementable at the desired scale, CDR LCAs are predominantly ex-ante, assuming efficiencies and economies of scale which are not currently realized. Yet, LCAs on CDR rarely make explicit reference to the temporal boundaries or time-frame of the system and its impacts or consider the future developments of the background economic or climate systems. This often results in an unacknowledged "tomorrow's technology today" situation with a future foreground system but present-day background system.

Many LCA researchers are working on improving the handling of system temporality in LCA, such as via dynamic LCA,[6] prospective LCA,[7] and improved characterisation factors for temporary or delayed impacts,[8] but static LCA with conventional characterization still dominates CDR literature. The relatively simple methodology of static LCA and its ability to answer the foundational question of a CDR system means that this is likely to continue. Therefore, I provide the following recommendations for improving the treatment of temporality in static LCAs on CDR systems:

1. Be explicit with temporal boundaries and assumptions, including the time frame of the system, duration of activities, the [projected] maturity of the CDR technology, the modelled duration of storage and impact time-horizons.
2. Storage monitoring and maintenance should be included, either for the entire storage for CDR requiring active maintenance or for as long as needed to ensure storage security.
3. Functional units should specify the storage medium and considered storage duration.
4. For systems with long rotation biomass, delayed uptake, or temporary storage, consider corrective characterization factors alongside standard factors
5. Characterize GWP over multiple time horizons.
6. Discuss temporality in the contribution analysis and perform sensitivity and uncertainty analyses on temporal characteristics-and variations in background systems.
7. Indicate the carbon payback period of a system.

[6] Where impacts are considered over a fixed time-horizon, using dynamic characterization factors that account for when in the time-horizon the emissions occur.

[7] Which alters background system databases to allow an LCA to explicitly consider technological developments under different scenario futures, such as the shared socioeconomic pathways.

[8] Such as for the rate of biomass [re]growth, short-lived climate forces, temporary storage of CO_2, or for changing atmospheric GHG concentrations.