ENVIRONMENTAL RESEARCH
LETTERS

PERSPECTIVE • OPEN ACCESS

Responsible carbon dioxide removals and the EU's 2040 climate target

To cite this article: Kati Koponen *et al* 2024 *Environ. Res. Lett.* **19** 091006

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
5 June 2024

REVISED
7 August 2024

ACCEPTED FOR PUBLICATION
9 August 2024

PUBLISHED
22 August 2024

PERSPECTIVE

Responsible carbon dioxide removals and the EU's 2040 climate target

Kati Koponen[1,*], Johanna Braun[2], Selene Cobo Gutiérrez[3,4], Alice Evatt[5], Lars Golmen[6], Gonzalo Guillén-Gosálbez[3], Lorie Hamelin[7], Stuart Jenkins[5], Tiina Koljonen[1], Chieh-Yu Lee[8], Fabian Levihn[9,10], Allanah J Paul[11], Goda Perlaviciute[8], Mark Preston Aragonès[11], David M Reiner[12], Lassi Similä[1], Linda Steg[8], Wijnand Stoefs[13], Nixon Sunny[14] and Constanze Werner[2]

1 VTT Technical Research Centre of Finland Ltd, Tekniikantie 21, Espoo 02044, Finland
2 Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany
3 Department of Chemistry and Applied Biosciences, ETH Zürich, Zürich, Switzerland
4 Department of Chemical and Biomolecular Engineering, University of Cantabria, Santander, Spain
5 School of Geography and the Environment, University of Oxford, Oxford, United Kingdom
6 Norwegian Institute for Water Research, Bergen, Norway
7 Toulouse Biotechnology Institute, INSA, INRAE UMR792, and CNRS UMR5504, Federal University of Toulouse, Toulouse, France
8 Environmental Psychology Expertise Group, University of Groningen, Groningen, The Netherlands
9 Stockholm Exergi AB, Stockholm, Sweden
10 Division of Sustainability, Industrial Dynamics and Entrepreneurship, Royal Institute of Technology—KTH, Stockholm, Sweden
11 Bellona Europa, Brussels, Belgium
12 Energy Policy Research Group, Judge Business School, University of Cambridge, Cambridge, United Kingdom
13 Carbon Market Watch, Brussels, Belgium
14 Centre for Environmental Policy, Imperial College London, London, United Kingdom
* Author to whom any correspondence should be addressed.

E-mail: kati.koponen@vtt.fi

Keywords: carbon dioxide removal, 2040 climate target, European Union, climate change

The European Union (EU) has recently initiated the debate on its 2040 climate targets with the EU Commission's proposal of a net 90% greenhouse gas emission reduction target relative to 1990 (EC 2024a). The EU Commission's impact assessment indicates that carbon dioxide removals (CDR) will play an important role in the EU's climate policy for 2040, on a path to EU's climate neutrality target in 2050 (EC 2024b). The science behind CDR's importance is clear: drastic and sustained emission reductions need to be supplemented with carbon dioxide (CO_2) removals to meet the Paris Agreement objectives, and to reach the EU's carbon neutrality target by 2050 (IPCC AR6 2022, ESABCC 2023). The need for CDR in 1.5 °C pathways reaching net-zero CO_2 by 2050 globally is generally projected to be higher than 10 Gt CO_2yr^{-1} removal in 2050 (Prütz *et al* 2023). Despite this, emission reductions need to be prioritized as we cannot guarantee a temperature decline after an overshoot (Schleussner *et al* 2023). One way to avoid mitigation deterrence is to create separate targets for emission reductions, permanent CDR, and the land use, land use-change, and forestry (LULUCF) sector for the EU 2040 climate framework (Reiner *et al* 2021, NEGEM 2023).

The target setting for the EU 2040 climate policy will be formulated in the coming years. The mitigation scenarios presented in the EU Commission's impact assessment do not expect a significant increase in net removals from LULUCF (land-use, land-use change and forestry) compared to the LULUCF sector target for 2030 (EU 2018, EC 2024b). However, they do set a clear role for engineered removals such as bioenergy with carbon capture and storage (BECCS) and direct air capture with CO_2 storage (DACCS) in reaching the proposed net 90% target (EC 2024b).

Even though the science clearly communicates the need for CDR, the realistic potentials for CDR deployment are not well understood. Traditionally, the need for CDR in reaching climate targets has been defined by the Integrated Assessment Model (IAM) mitigation scenarios, such as those used in the IPCC reports (IPCC AR6 2022). These scenarios represent a '*target-based*' back-casting approach of cost optimization, where CDR deployment is dependent on the interplay with mitigation technologies and measures over time defining the demand for CDR to meet a certain mitigation target (e.g. 1.5 °C). However, the findings do not necessarily illustrate the responsible potential for CDR, when considering implications for planetary boundaries, land or biomass use, energy systems, environmental pollutants, human health, or public perceptions. All CDR options come with varying environmental externalities, costs, and social implications, thus requiring a multidisciplinary approach for the analysis.

The NEGEM project[15] has taken many of these necessary steps to study the deployment of responsible negative emissions and their contribution to achieving climate neutrality. The aim of the project was to filter the realistic potentials of CDR, when considering various constraints for responsible potentials, and to derive the associated frameworks for realistic deployment (figure 1). To support the responsible deployment of CDR in the EU we discuss some key findings and policy recommendations from the project.

In NEGEM, various modelling approaches were used to study responsible CDR potentials, and the strengths and limitations of these approaches are summarized below (table 1). First, to understand the environmental externalities of various CDR approaches, NEGEM applied a *life cycle assessment* (LCA) analysis, which enabled the co-studying of cradle-to-grave greenhouse gas emissions, environmental, resource, and health impacts (Cobo *et al* 2022, 2023). Impact categories such as global warming impacts, and damage to human health, ecosystems and resources depletion connected to emissions to soil, air and water, and input requirements (including land, water and fossil resources) were studied. A key conclusion was that none of the CDR methods performed better than the others in all impact categories, and thus a portfolio of CDR options is needed to balance the trade-offs of different CDR methods.

Second, NEGEM evaluated the potential for BECCS from bioenergy crops without further transgressing the planetary boundaries (Rockström *et al* 2009), while reserving current agricultural areas for food, fodder, and fibre provision. The *biosphere model* LPJmL was applied to provide spatially explicit and process-based analysis of terrestrial planetary boundary transgressions. This analysis indicated that planetary boundary constraints for freshwater use, nitrogen flows, land-system change, and biosphere integrity, combined with forest protection, effectively restricted plantation-based BECCS potentials to nearly zero. This implies that the supply for BECCS from bioenergy crops outside agricultural land is significantly limited in comparison to the overall BECCS demand illustrated by IAM-scenarios in IPCC AR6 (2022) to stay below 2 °C warming (Braun *et al* 2022). It was concluded that increasing BECCS potentials will hinge upon concurrent transformations in the food system to provide land for other uses within the established planetary boundaries. For example, ambitious scenarios for dietary changes such as the EAT-Lancet Planetary Health Diet could release pastureland for BECCS and reforestation (Braun *et al* 2023). Similar supply-based approaches are recommended for the EU impact assessments, to ensure that CDR deployment in Europe looks beyond climate change to other planetary boundaries. Acknowledging the role of large-scale transformation of the food sector (e.g. dietary changes) to enable sustainable BECCS-based CDR in Europe is essential.

Third, the results on the limited BECCS potential from the LPJmL modelling suggest a more diverse pool of CDR approaches will be needed, compared to the IPCC's AR6 scenario database, to deliver CDR at scale. A large portfolio of CDR methods based on the LCA study were applied in an *energy system modelling exercise* with the Pan-European TIMES-VTT model (Lehtilä *et al* 2023). This showed that a large portfolio of CDR methods can provide cost-efficient approaches for reaching the European carbon neutrality targets by 2050. The limited potential for BECCS resulted in an increased use of DACCS, despite its higher costs. This led to a significantly increased need for renewable electricity, on top of electricity needs for a hydrogen economy, electrification of transport, and industrial decarbonization. Even with the limited biomass feedstock potential, BECCS was still available at limited scales from the improved use of current bioenergy feedstock, residual biomass from forestry and agriculture, and by capturing existing biogenic CO_2 point-source emissions. BECCS investments could be cost-efficient when integrated not only in power production, but especially in combined power and heat production, biorefineries producing liquid and gaseous biofuels, as well as in existing large scale point sources of biogenic CO_2 e.g. in the pulp and paper industries. Thus, when planning for BECCS application in the EU, NEGEM's results suggest it is valuable to consider a diverse set of BECCS applications[16], in addition to the sustainability of the biomass feedstock.

Fourth, a crucial part of NEGEM was to understand the *socio-economic implications* of CDR methods. MONET-JEDI modelling was applied to study the impacts of CDR methods on jobs creation in the EU (Bui *et al* 2024). The study demonstrated that inter-regional supply chains provide critical opportunities for the creation of jobs across different regions in Europe, highlighting the economic value of intra-European collaboration in delivering EU-level CDR targets.

In addition to studying the CDR potentials and costs, expert elicitations were conducted in NEGEM

[15] A four years' research project 'Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways' (2020–2024) funded by European Union Horizon 2020 Research and Innovation program (under Grant Agreement 869192).

[16] Currently the Commission impact assessment seems to include BECCS for power and for biogas production.

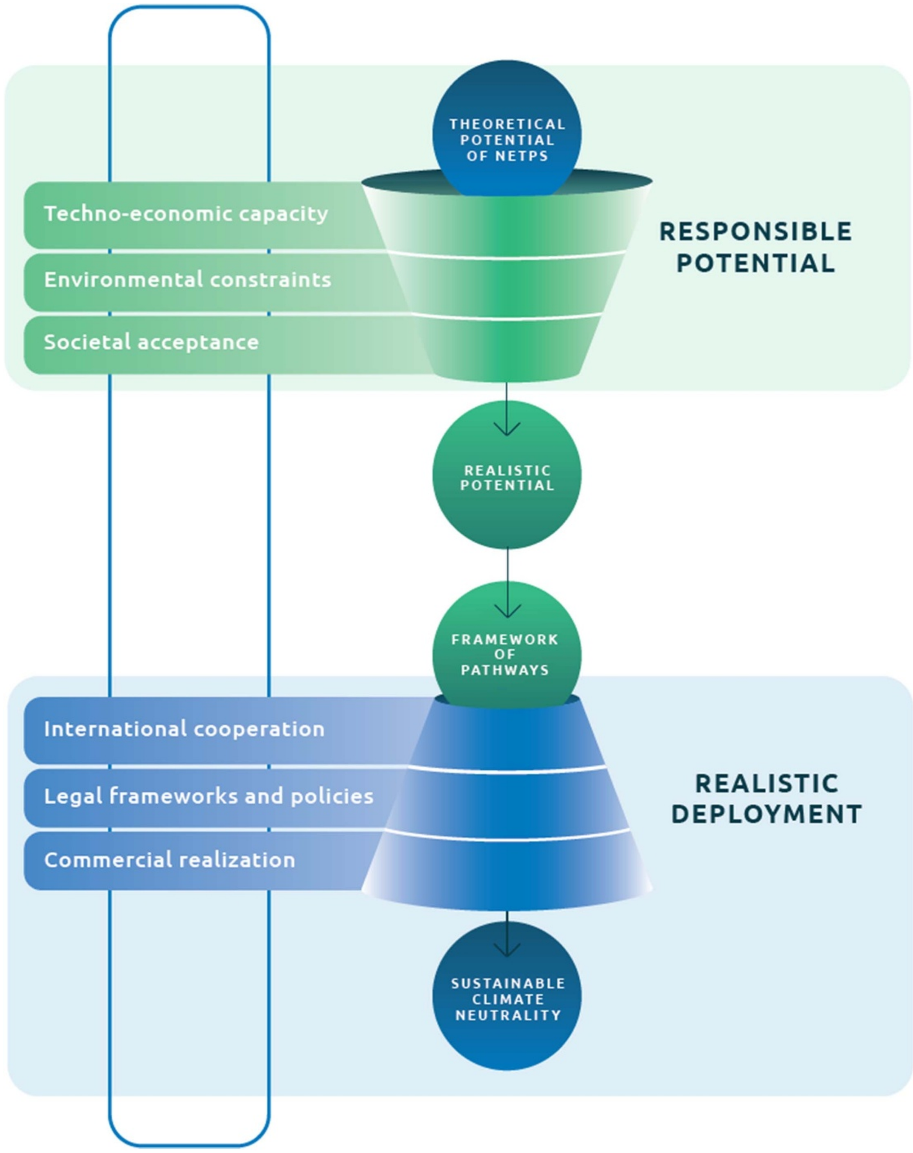

Figure 1. Multidisciplinary NEGEM framework for assessing realistic potential and responsible deployment of CDR.

with input from BECCS and DACCS experts. The results showed that the experts' estimations on the cost development of both technologies varied significantly (Abegg *et al* 2024). Most DACCS experts believed that economies of scale and better materials will reduce costs over time. On the contrary for BECCS, the experts believed that it might struggle to scale up given the distinctive and unique characteristics of each plant. In addition, the cost of biomass was expected to increase, e.g. owing to increasing demand. Thus, it is important to consider the inherent uncertainty in the evolution of costs for CDR applications. Further research and demonstration, and improvements in the energy efficiency of DACCS facilities are needed for large-scale deployment, as proposed in the EU Commission's 2040 impact assessment (EC 2024b).

A definitive role for CDR in the EU's 2040 climate policy is contingent on securing the social license to operate. Several NEGEM studies on stakeholder perceptions offered varying views on CDR methods, and the key learning that enabling discussion between stakeholders is essential. All stakeholders, regardless of sector (NGO or private sector), considered the storage permanence of the CDR options as a key dimension (Reiner *et al* 2024). On the other hand, a wide survey showcased that the public preferred af-/reforestation (with less permanent storage) over DACCS as a CDR solution. The public also thought that CO_2 emissions reductions through renewable energy and behaviour change should be prioritized above CDR (Lee *et al* 2023).

When deciding and communicating on the objectives of CDR, it is crucial to understand the

Table 1. Various modelling approaches applied for studying CDR in NEGEM.

Modelling approach	Life cycle assessment (LCA)	Process-based biosphere model	Bottom-up, technology rich partial equilibrium modelling	Mixed integer linear optimisation with extension to analyse socio-economic impacts
Model used in NEGEM	ReCiPe 2016/Environmental footprint impact assessment methods	LPJmL	VTT-TIMES, Pan-European TIMES-VTT	MONET-JEDI
Scope	Product/system: Per unit tCO_2 removal	Global	Global, European	European
Method	Comparison of environmental sustainability performance of NETPs on different human health, ecosystems quality, and resources depletion impact categories	Quantify biophysical potential of vegetation-based NETPs constrained by planetary boundary limits	Determining the optimal (least cost) co-deployment of CDR pathways to meet regional or national removal targets in different scenarios, energy system impacts captured	Evaluating the socio-economic impact of the deployment of CDR by estimating the value added to the economy and the employment opportunities created
Perspective	Case specific	Supply-based	Target- driven	Target- driven
Strength	**Enables comparison of various CDR methods over several impact categories**	**Provides understanding on the sustainable supply and scale of CDR respecting planetary boundaries**	**Provides information on the scale of CDR solutions needed to reach a certain climate target, on cost-optimal CDR portfolios, and on energy supply/demand created by CDR**	**Provides information on jobs and economic value created by varying CDR portfolios**
Limitation	Case specific, does not fully capture systemic impacts of e.g. scaling the CDR solutions	Limited to certain biomass types, does not include e.g. residual biomass sources	Perfect foresight, results depend on the constraints given/not given by the modeller.	Perfect foresight, results depend on the constraints given/not given by the modeller and independent of the other models.
Reference	Cobo *et al* (2022, 2023)	Braun *et al* (2022, 2023)	Lehtilä *et al* (2023)	Bui *et al* (2024)

role of different methods. The permanence of the CO_2 storage is a key factor:

- Nature-based approaches such as reforestation are needed due to their co-benefits and can significantly contribute to reaching the international targets for nature restoration, e.g. Kunming-Montreal biodiversity targets. The LPJmL analysis further quantified substantial co-benefits for shifting towards the safe operating space within planetary boundaries (Braun *et al* 2022, Braun *et al* 2023). These methods could be deployed immediately for their co-benefits and are likely publicly accepted. However, nature-based approaches include significant risks of carbon storage reversal (Mitchell-Larson and Allen 2021).
- Engineered CDR with geological timescale storage (BECCS and DACCS) is needed to permanently store CO_2 for a durable net zero policy in the mid-century (Allen *et al* 2022). Sourcing sustainable biomass for BECCS, along with clean energy for DACCS, remain key limiting factors to the wide-scale use of such CDR methods. It is important to prepare for engineered CDR now, to enable gigaton-scale application in the 2040s and 2050s. From early on in technology development, it is important to take into account public perceptions, as engineered CDR is likely to trigger public opposition.

The commercialization methods for engineered CDR are currently under-resourced, and often concentrate on non-permanent removals (Hickey *et al* 2023). In addition to increasing their financing, international collaboration is needed to scale up CO_2 transport and storage facilities. Recent EU policies in the NET Zero Industry Act, such as the injection capacity obligation (ICO) requiring oil and gas producers within the EU to contribute to the Union-wide target of 50 Mt of CO_2 injection capacity by 2030, are intended to provide a useful driver for this in the short term (Evatt *et al* 2024). Beyond these, supply-side and producer mandates which secure stable and long-sighted investments in permanent CO_2 disposal provide valuable policy levers, particularly in sectors where demand-led investment signals are lagging (Jenkins *et al* 2023). International collaboration beyond the EU level is also needed to deploy the most cost-optimal CDR pathways (Chiquier *et al* 2022). However, international collaboration should not result in irresponsible outsourcing of CDR into non-EU states creating conflicts with sustainable development goals, but aim for encouraging optimal and sustainable use of regional biogeophysical resources with respect to environmental and socio-economic factors. In addition, international collaboration is needed to rapidly establish science-based monitoring practices and regulations.

It is vital to emphasize that CDR is not a silver bullet for solving the climate crisis. Rather, sustainable CDR solutions, which remove CO_2 permanently from the atmosphere, should be considered as unavoidable, scarce, and expensive, and must be implemented alongside substantial emission reductions. The lower the residual emissions, the less Europe will rely on CDR.

Key NEGEM policy messages for the EU's 2040 climate target:

- Set realistic, separate, and legally binding targets and policies for emission reductions, permanent CO_2 removals with geological storage, and LULUCF sector.
- Recognize the different roles and co-benefits of various CDR methods. The CO_2 storage time and vulnerability to intended/unintended release of CO_2 is essential.
- Adopt Member State-specific CDR portfolios, which consider the individual country's characteristics. Apply a multidisciplinary approach driven by sustainable supply of CDR, opposed to one following (unrealistic) CDR targets.
- Invest in research and development of CDR approaches and design policy and financial mechanisms which allow for learning and securing support from the society at large.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://cordis.europa.eu/project/id/869192/results.

Acknowledgments

The authors want to acknowledge the funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869192 (NEGEM). The authors also acknowledge the work and support of all the NEGEM-project partners.

ORCID iDs

Kati Koponen https://orcid.org/0000-0003-1472-4184
Selene Cobo Gutiérrez https://orcid.org/0000-0002-2879-6261
Alice Evatt https://orcid.org/0009-0002-4660-9260
Lars Golmen https://orcid.org/0009-0001-1711-1183
Gonzalo Guillén-Gosálbez https://orcid.org/0000-0001-6074-8473
Lorie Hamelin https://orcid.org/0000-0001-9092-1900
Stuart Jenkins https://orcid.org/0000-0003-2284-0302
Tiina Koljonen https://orcid.org/0000-0002-7503-6417
Chieh-Yu Lee https://orcid.org/0000-0002-1545-3569
Fabian Levihn https://orcid.org/0000-0001-7028-0624
Allanah J Paul https://orcid.org/0000-0003-1037-5239
Goda Perlaviciute https://orcid.org/0000-0003-1380-7340
Mark Preston Aragonès https://orcid.org/0009-0004-3491-8917
David M Reiner https://orcid.org/0000-0003-2004-8696
Lassi Similä https://orcid.org/0009-0009-2619-2462
Linda Steg https://orcid.org/0000-0002-8375-9607
Wijnand Stoefs https://orcid.org/0009-0006-7263-2420
Nixon Sunny https://orcid.org/0000-0002-2353-8263
Constanze Werner https://orcid.org/0000-0003-1511-3086

References

Abegg M, Clulow Z, Nava L and Reiner D 2024 Expert insights into future trajectories: assessing cost reductions and scalability of carbon dioxide removal technologies *Front. Clim.* **6** 1331901

Allen M, Friedlingstein P, Girardin C A J, Jenkins S, Mitchell-Larson E, Peter G P and Rajamani L 2022 Net zero:

science, origins, and implications *Annu. Rev. Environ. Resour.* **47** 849–87

Braun J, Werner C, Lucht W and Gerten D 2022 Global NETP biogeochemical potential and impact analysis constrained by interacting planetary boundaries (available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5ecd9ec33&appId=PPGMS)

Braun J, Werner C, Lucht W and Gerten D 2023 Global impacts of NETP potentials on food security and freshwater availability, scenario analysis of options and management choices (available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5fc739b54&appId=PPGMS)

Bui M, Sunny N, Chiquier S, Patrizio P and Mac Dowell N 2024 Quantify the socio-economic value of intra-European collaboration (available at: www.negemproject.eu/wp-content/uploads/2024/04/D-7.4-Quantify-the-socio-economic-value-of-intra-European-collaboration.pdf)

Chiquier S, Fajardy M and Mac Dowell N 2022 CO2 removal and 1.5 °C: what, when, where, and how? *Energy Adv.* **1** 524–61

Cobo S, Galán-Martín Á, Tulus V, Huijbregts M A J and Guillén-Gosálbez G 2022 Human and planetary health implications of negative emissions technologies *Nat. Commun.* **13** 2535

Cobo S, Negri V, Valente A, Reiner D, Hamelin L, Mac Dowell N and Guillén-Gosálbez G 2023 Sustainable scale-up of negative emissions technologies and practices: where to focus *Environ. Res. Lett.* **18** 023001

EC 2024a Communication from The Commission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of The Regions Securing our future Europ"s 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society COM/2024/63 final (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2024%3A63%3AFIN)

EC 2024b Commission Staff Working Document Impact Assessment Report Part 1 Accompanying the Document Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Securing our future Europ"s 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52024SC0063)

ESABCC 2023 Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050 (available at: https://climate-advisory-board.europa.eu/reports-and-publications/scientific-advice-for-the-determination-of-an-eu-wide-2040)

EU 2018 Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU (available at: https://eur-lex.europa.eu/eli/reg/2018/841/oj)

Evatt A E A, Jenkins S and Allen M 2024 Assessment of the potential for an NETP "capacity market" (available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e50ac73269&appId=PPGMS)

Hickey C, Fankhauser S, Smith S M and Allen M 2023 A review of ccommercialization mechanisms for carbon dioxide removal *Front. Clim.* **4** 1101525

IPCC AR6 WG III. IPCC 2022 *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press) (https://doi.org/10.1017/9781009157926)

Jenkins S, Kuijper M, Helferty H, Girardin C and Allen M 2023 Extended producer responsibility for fossil fuels *Environ. Res. Lett.* **18** 011005

Lee C Y, Perlaviciute G and Steg L 2023 Public awareness and assessments of NETPs: results of a series of cross-national public surveys (available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e50525fd51&appId=PPGMS)

Lehtilä A, Koponen K, Similä L, Markkanen J, Koreneff G and Koljonen T 2023 Quantitative assessments of NEGEM scenarios with TIMES-VTT (available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e503ac22c9&appId=PPGMS)

Mitchell-Larson E and Allen M 2021 Interactions and trade-offs between nature-based and engineered climate solutions (available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5e3f47de2&appId=PPGMS)

NEGEM 2023 NEGEM science-policy brief (available at: https://www.negemproject.eu/wp-content/uploads/2023/08/NEGEM-Policy-Brief-2040-Target.pdf)

Prütz R, Strefler J, Rogelj J and Fuss S 2023 Understanding the carbon dioxide removal range in 1.5 °C compatible and high overshoot pathways *Environ. Res. Commun.* **5** 041005

Reiner D, Hannula I, Koljonen T, Allen M, Lucht W, Guillén-Gosálbez G and Mac Dowell N 2021 Europe's 'green deal' and carbon dioxide removal *Nature* **589** 19

Reiner D, Nava L and Clulow Z 2024 *Final Report of Stakeholder Survey* (available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e50aad8dfb&appId=PPGMS)

Rockström J *et al* 2009 Planetary boundaries: exploring the safe operating space for humanity *Ecol. Soc.* **14** 32

Schleussner C F *et al* 2023 *Overconfidence in Climate Overshoot* (ESS Open Archive) (https://doi.org/10.22541/essoar.170158343.39134302/v1)