NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Key findings and recommendations, including potentials and impacts of NETPs, suggestions for KPIs, R&D&I priorities, and governance structures

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Executive Summary

NEGEM - Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways - is a Research and Innovation Action funded by the EU Horizon 2020 Programme under Grant Agreement No. 869192. The aim of the project is to assess the realistic potential for different carbon dioxide removal (CDR) approaches and their contribution to climate neutrality, as a supplementary strategy to emissions mitigation. The NEGEM project was initiated back in 2018, accepted by the funder in December 2019, started in June 2020, and it will be closed in May 2024. The project has been running with a consortium of 16 excellent partners from 11 different European countries and produced almost 70 deliverables.

This summary deliverable targets at being valuable, easily accessible, and inspiring entry point into the NEGEM results for the European policymaking, and for wider research community. It brings together several key conclusions of the four years of multidisciplinary research work. The report presents the NEGEM research questions, and the multidisciplinary methods used, and discusses on responsible potentials for CDR based on the project findings. It provides suggestions for key performance indicators (KPIs) and research, development, and innovation (R&D&I) needs for various CDR approaches. Finally, it summarizes NEGEM policy recommendations. The NEGEM results show that **a multidisciplinary approach is essential to understand the wider systemic impacts of CDR approaches,** to guide in their sustainable implementation, and to guarantee their acceptability among stakeholders and citizens.

The key NEGEM conclusion is that to meet the climate goals of the Paris Agreement, drastic**, immediate, and sustained reductions in greenhouse gas emissions are needed**. To keep the warming at 1.5-2 °C, carbon dioxide removal (CDR) technologies and practices are needed but should only be relied on as a supplementary measure to emission reductions. **The smaller the residual emissions, the lower the demand for CDR.** Based on the current knowledge, it is unclear to what extent the impacts of the climate change are reversible, and thus emission avoidance is more beneficial than emission removal. Thus, in the short- to medium-term **separate targets and governance frameworks for emission reductions and CDR** are required to ensure that net-emissions are more rapidly reduced.

When evaluating various CDR options, the carbon dioxide (CO_2) storage time and vulnerability to intended and/or unintended release of CO_2 are essential. One of the NEGEM key conclusions is that **technical solutions with storage at geological time scale providing permanent CDR, are needed to reach climate neutrality**. Industrial level deployment of these technologies, such as bioenergy with carbon capture and storage (BECCS and bio-CCS) and direct air capture and storage of CO_2 (DACCS), should start latest in 2030's in order to provide CDR at gigaton scale in 2050.

On the other hand, **nature-based CDR methods, such as reforestation, can provide substantial synergies between climate change mitigation and international targets for nature restoration** (i.e. the Kunming-Montreal Global Biodiversity Framework) and broader sustainable development goals. Thus, their implementation can be justified from several perspectives. The implementation of nature-based solutions should be accelerated immediately, especially when co-benefits can be linked to targets of nature restoration and Sustainable Development Goals.

All CDR approaches have trade-offs, and **to balance the environmental and health impacts a portfolio of NETPs is needed**. A large portfolio of CDR methods would also enable the **most cost-effective** mitigation pathways. In addition, **international co-operation is a key** for the usage of biomass resources, CO_2 transportation networks, and geological storage facilities in an efficient manner. Continuous interaction

between different stakeholders and citizens, as well as a system perspective in regulation design, will enable a **social licence to operate for CDR** methods.

To be able to invest in CDR, stakeholders need clear, long-term regulation and greater certainty. Thus, there is an urgent need for clear CDR definitions, policy frameworks and accounting rules internationally, to enable the sustainable implementation of various CDR options. CDR systems can affect land usage, energy systems, the rights of local communities, and human health, which highlights the need for **comprehensive governance frameworks recognising specific features of different CDR methods**. In addition, the current market mechanisms for CDR **are severely under-resourced** and provide too little incentive to enable a CDR portfolio that could support achievement of net zero targets.

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Introduction

This deliverable aims at drawing conclusions on realistic and sustainable potentials of Carbon Dioxide Removal (CDR) based on the results produced in the NEGEM project during its four-year duration. CDR (also called as negative emissions) can be created with so called Negative Emission Technologies and Practices (NETPs)[1]. As written in the project plan, recommendations presented aim at summarising the following findings and key measures:

- The potential role of CDR in the EU's efforts in sustainable transformation to a climate neutral society.
- Impacts of implementation of CDR on technical, societal and environmental systems, including suggestions for Key Performance Indicators (KPIs) for ex-post and ex-ante monitoring.
- Research, Development & Innovation (R&D&I) priorities for alternative CDR approaches.
- Governance structures to support the sustainable implementation and deployment of CDR.

The NEGEM project was initiated back in 2018, accepted by the funder in December 2019, started in June 2020, and it will be closed in May 2024. During the years of its planning and execution, major shocks hit nations, societies, and individuals globally and in Europe. It is safe to say that foreseeing all the crises ahead during the time the project was planned would have been challenging. Inevitably, the project was not able to make it through these crises without being impacted – including both the practical research work and the results.

First, the COVID-19 pandemic with direct consequences most severe around Q1/2020– Q1/2022, forced the NEGEM consortium to major adjustments in research plans. For example, the consortium needed to turn the events of the project partially or completely in virtual mode, implying sudden needs for improvised and innovative solutions. Only in October 2022, nearly two and a half years after the project kick-off, was the consortium able to safely arrange its first physical General Assembly. Furthermore, hard border restrictions during the pandemic made international recruitment complicated, which had an impact on execution of the project.

During the toughest times of the pandemic, there was discussion in media and academia if remote working, decreased demand for transportation and industrial products, etc., could make permanent changes in behavior. There were hopes that such changes could make enduring contributions to climate change mitigation, the effort needed and thereby also to the volumes of CDR needed. Indeed, slowdown of economy caused by the pandemic exceptionally decreased the global greenhouse gas emissions in 2020. However, global emissions seem to have reverted to a growing trend. As a positive aspect for the NEGEM project, the forced virtual mode of co-operation has clearly increased global presence in the events, to an extent that hardly would have been possible in pre-COVID world.

Second, the full-scale military invasion of Ukraine started by Russia in February 2022 has severely reshaped the geopolitical landscape. Following the aggression, energy prices skyrocketed and the

[1] In this report, both terms CDR and NETPs are used. NETPs was the original term used in the project, but during the project CDR was the term adopted e.g. by the European Commission.

turbulence in energy markets forced the regions and governments to critically and urgently review the validity of their energy policies, particularly in Europe. Also, energy infrastructure and pipelines directly hit during the war has severely challenged the former cornerstones of the European energy policy. The energy security questions raised as a consequence have also been reflected in the NEGEM research on the role of CDR. Particularly, the “Security” scenario used for the assessments, has been largely inspired by role of CDR in the conflict circumstances in line with the reality of 2020’s.

During the duration of the NEGEM project, scientific knowledge on climate change, as well as global climate negotiations have proceeded with IPCC AR6 released in 2021–2023 and the annual COP meetings as major milestones. In this respect, the Nationally Determined Contributions (NDCs) including countries’ efforts to reduce national emissions outlined in the Paris Agreement, have been updated during the project and included in the assessments to reflect the evolvement of climate policies globally. However, not all the most recent advancements, such as the pledge to move away from fossil fuels decided in the UN Climate Change Conference (COP28) in December 2023, could be included in NEGEM analyses but are left for further studies.

The EU policies on energy and CDR have evolved during the project years faster than initially anticipated. In addition to the long-term challenges of climate change and other environmental impacts, energy supply and competitiveness, the policies have been and are significantly developing as a response of the EU to the recent crisis. The Fit for 55 package on EU target of a net domestic reduction of greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels, part of the European Green Deal presented in 2019, has framed the EU climate policy during the last few years (Timeline - European Green Deal and Fit for 55 - Consilium (europa.eu)). As a response to the attack of Russia to Ukraine, the EU launched the RePowerEU plan in May 2022, targeting at diversifying energy supply and diminishing reliance on fossil fuels, especially on Russian energy. Up-to-date information on policy developments has been taken into account in the NEGEM scenario modelling as much as possible.

Regarding the policy developments on CDR, the EU Commission published the draft of EU wide voluntary Carbon removals certification framework (CRCF) in November 2022. In addition, an expert group on carbon removals was established, with a strong participation from NEGEM (three partners directly involved as members, and several partners invited to some of the meetings as experts). The trilogues on the CRCF framework ended in February 2024. At the same time, trilogues for the Net Zero Industry Act were accomplished. In February 2024, Commission’s Communication on EU’s 2040 climate targets and for the Industrial Carbon Management Strategy were published, proposing a 90% net emission saving target for the EU by 2040, and calling for a prominent role for CDR.

With this background, this deliverable aims at summarising the key findings and recommendations of all the work conducted in NEGEM. The scientific methods and detailed results are more extensively described in their respective deliverables and scientific publications. As a NEGEM policy input, this deliverable builds on earlier efforts by the consortium members, such as the work in the Carbon Removals Expert Group by the European Commission, responses to hearings on the EU policies (see the NEGEM Science-Policy Brief) and feeding the results in the annual COP meetings. The NEGEM results summarized in this deliverable aim at bringing science-based inputs for the timely policy discussion in the EU exploring solutions for the above-mentioned and forthcoming challenges. As a summary of the work by the consortium of 16 partner organizations around Europe, this deliverable targets at being valuable, easily accessible, and inspiring entry point into the NEGEM results for the European policymaking.

The report is structured as follows: First, the NEGEM research questions and the multidisciplinary methods used are presented, after which the results on responsible CDR potentials are discussed. Then suggestions for key performance indicators (KPIs) and research, development, and innovation (R&D&I) needs concerning CDR approaches are given. Finally, the NEGEM policy recommendations together with results on commercialization are summarized.

1 Main research questions studied by NEGEM

The main research question studied in the NEGEM project is highlighted in the title of the project "Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways". The project aimed to 'filter' the maximum theoretical deployment potential of carbon dioxide removal (CDR) often portrayed in the climate change mitigations scenarios aiming to limit the global warming to 1.5 -2 °C during this century, such as those by IPCC scenarios (IPCC AR5, IPCC AR6). These theoretical potentials traditionally emerge from the results of "demand-driven" modelling: the optimisation models show the amount of CDR needed to reach the warming targets, without necessarily evaluating the impacts of CDR implementation to environment, and other planetary boundaries than climate change.

In NEGEM, the CDR methods were studied through a set of constraints including techno-economic and environmental limits. The impacts of CDR technologies and practices were analysed through life cycle assessment (LCA), and by "supply-driven" biosphere modelling, to understand the environmental constraints limiting the CDR potentials. In addition, evaluation on commercial barriers and socio-political acceptance was included to reduce the uncertainties associated with CDR and identify more realistic deployment potentials. These results and constraints were considered when defining the storylines for the NEGEM 1.5°C mitigation scenarios.

Furthermore, the project aimed to identify the EU-wide potentials of CDR deployment, along with the relevant governance and financing frameworks. The aim was to produce a more granular knowledge base to inform the ongoing policymaking processes.

The NEGEM research questions were further developed as:

- To what extent is carbon dioxide removal required to achieve climate neutrality?
- At what scale is it feasible to implement CDR methods, given their technical, environmental, economic, and socio-political constraints?
- How to formulate policies and governance structures to optimize the deployment of CDR within the overall climate architecture?

The project framework was illustrated in the beginning of the project as in Figure 1.

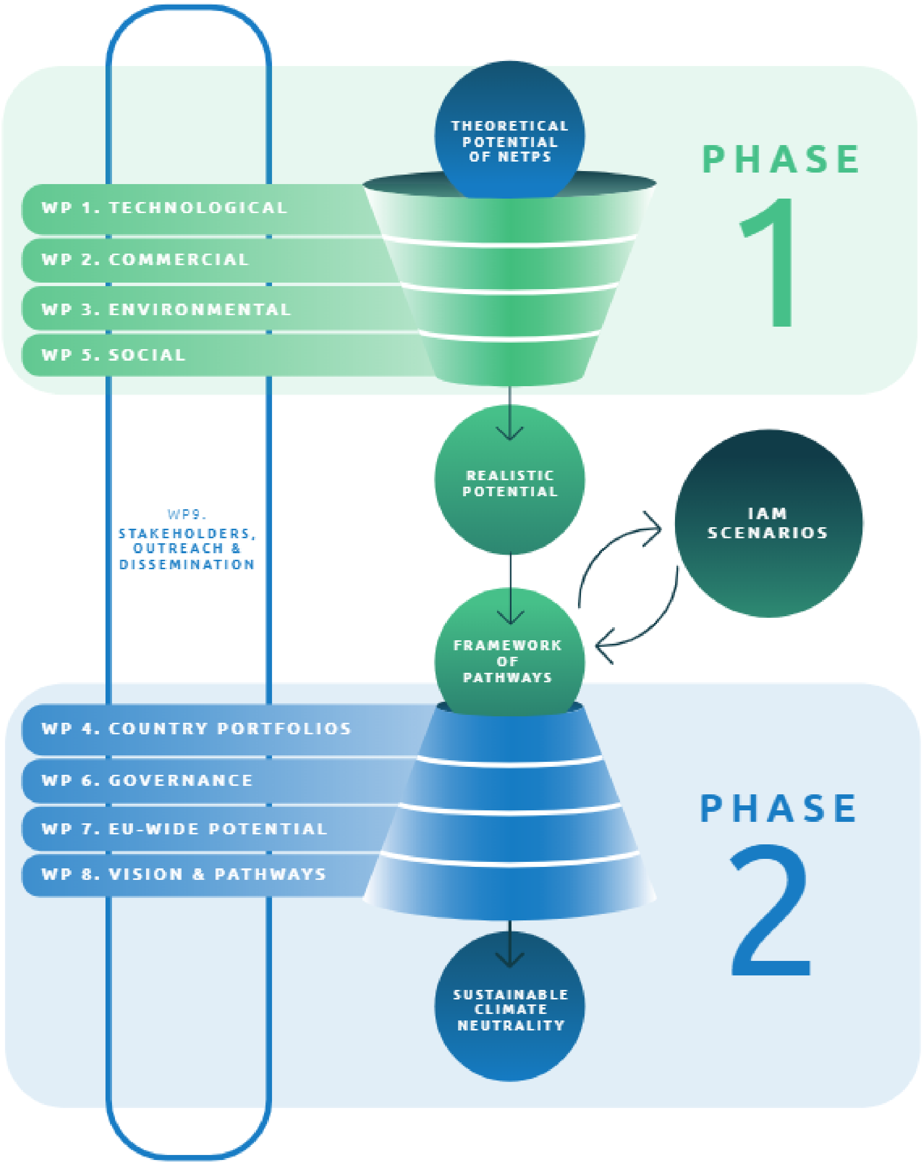

Figure 1. NEGEM framework

A large portfolio of negative emission technologies and practices (NETPs) was included in the NEGEM analysis (Figure 2). In the beginning of the project, a preliminary assessment of these technologies was done based on the literature to recognise the most prominent NETPs for further analysis, and especially, to be included in the extensive life cycle assessment study made in the WP1 (Deliverable 1.1). NEGEM analysis included NETPs such as re- and afforestation, forest management, wood products, soil carbon sequestration, biochar, various alternatives for bioenergy with carbon capture and storage (BECCS) from various biomass feedstock, bio-CCS from biogenic point-source emissions, biochar, direct air capture and storage technologies (low-temperature solid sorbet LTSS-DACCS and high-temperature liquid-sorbent HTLS-DACCS), enhanced weathering (with basalt and dunite), kelp farming, and ocean liming.

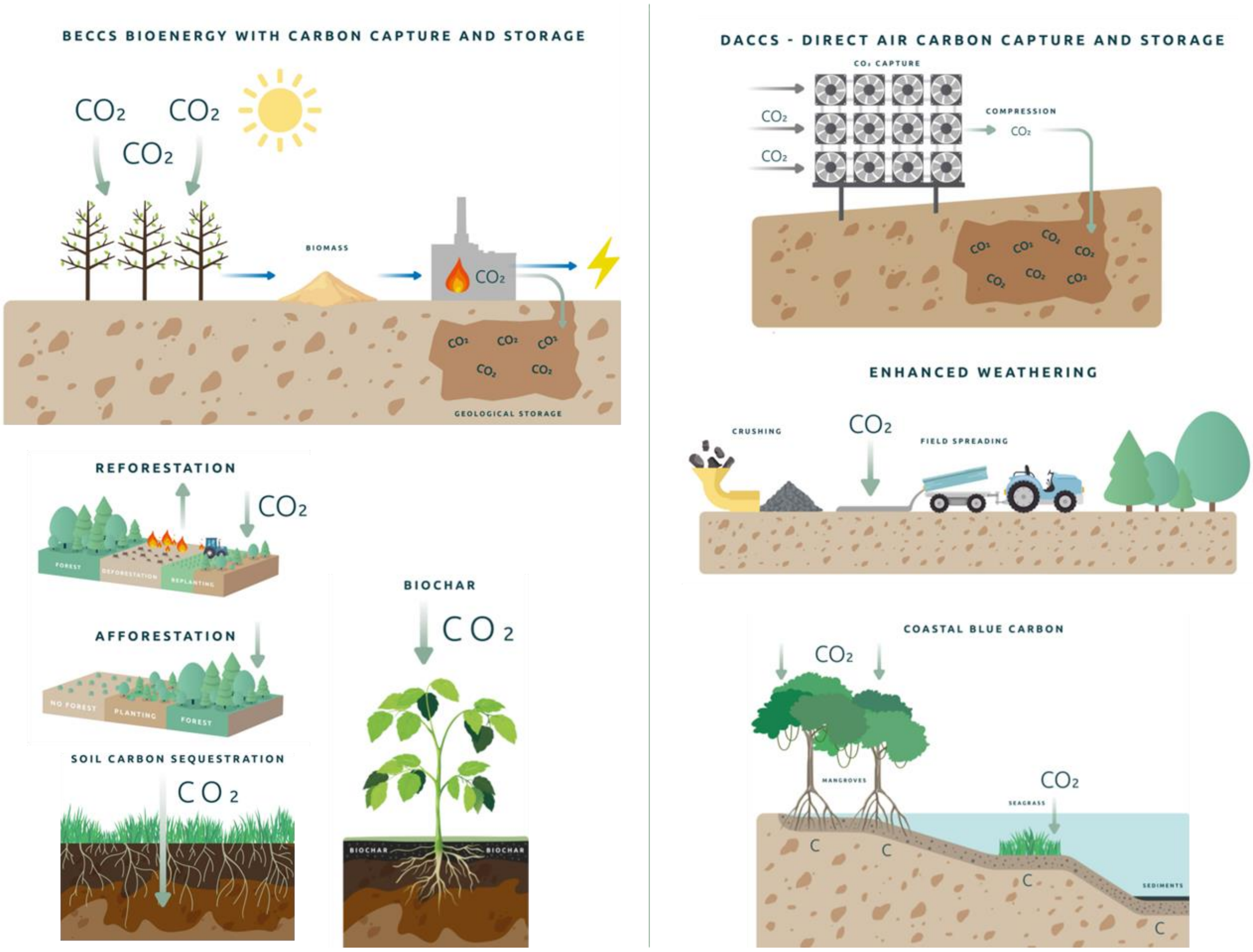

Figure 2. Simplified illustrations used in NEGEM for various NETPs studied.

2 Multidisciplinary methods used

Several research methods were used to study the NEGEM research questions presented in Chapter 1. Figure 3 illustrates the research questions, variety of methods used, and disciplines involved in the NEGEM project. Altogether, the project results are reported in around 70 deliverables and approximately 20 scientific papers (current estimation) (see the NEGEM results page for the list of deliverables and scientific papers already published). One or more of the methods broadly classified in Figure 3 are applied in single studies. The studies, correspondingly, give inputs to one or more of the research questions. The different methods are, hence, not strictly connected to individual research questions. Overall, methods used to reach the NEGEM conclusions can be described as predominantly multidisciplinary.

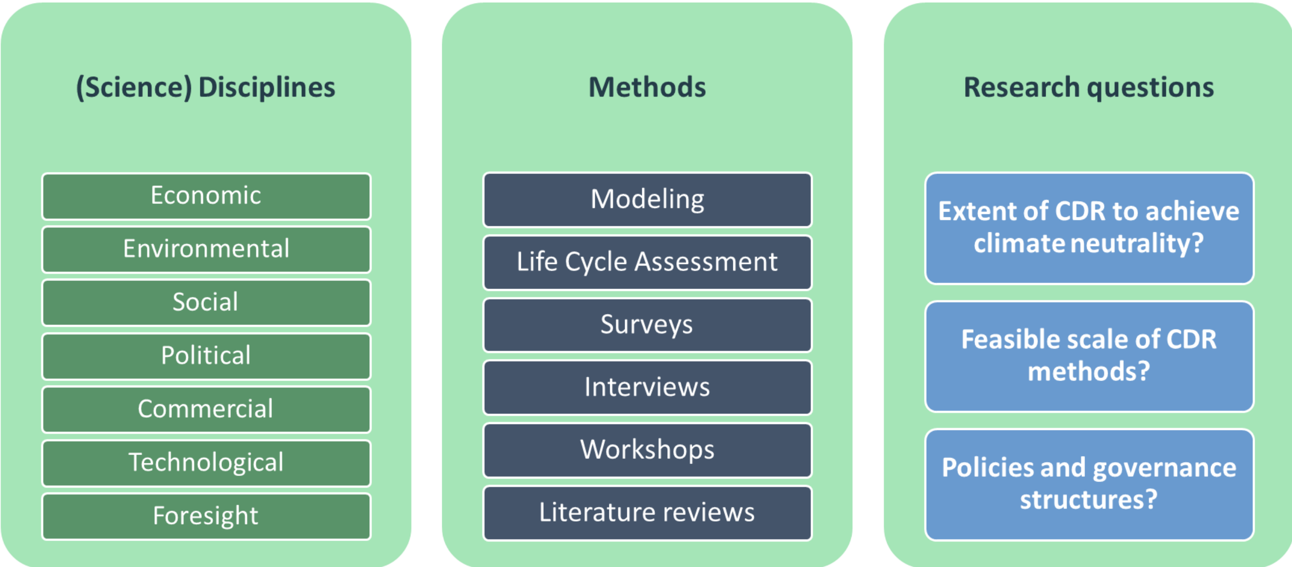

Figure 3. Disciplines and methods used in the NEGEM approach to reach conclusions in the research questions.

Table 1 gives a closer look of the application of multidisciplinary methods in NEGEM. The methods can be further sub-categorized e.g., based on mathematical approach used for quantitative models and assessments, detailed methods and data sources used for literature reviews etc. For such deeper understanding, the methods are explained broadly in the associated deliverables and scientific articles with the results.

Table 1. Overview of methods applied in NEGEM to obtain answers to the research questions studied.

Research questions	Main methods and the role of applying them
To what extent is carbon dioxide removal (CDR) required to achieve climate neutrality?	• **Quantitative modelling** with MONET, JEDI, VTT-TIMES, Pan-European TIMES - creating regional mitigation pathways with volumes of CDR technologies under chosen policy, effort sharing principle, technological assumptions, and environmental constraints • **Workshops** with foresight methods – storyline co-creation for coherent basis of the NEGEM scenario analysis • **Literature reviews**– role of NETPs in existing 1.5°C mitigation scenarios, gathering input data and policy targets for the models
At what scale is it feasible to implement CDR methods, given their technical, environmental, economic, and socio-political aspects?	• **Quantitative modelling** with MONET, JEDI, VTT-TIMES, Pan European-TIMES, LPJmL – technical, environmental, and economic feasibility of CDR • **Life Cycle Assessment (LCA)**– for comparative sustainability assessments on several impacts categories • **Risk management frameworks** to assess risks and impacts of rerelease of carbon storage options • **Interviews, surveys and workshops** - socio-political and economic feasibility • **Expert elicitations** – expert views on CDR potentials, costs, and future developments • **Conjoint analysis – method to** deconstruct and rank the preferences of stakeholders • Document analyses with **text mining and sentiment analysis tools** – positioning of CDR by stakeholders • **Literature reviews**– supporting the assessments
How to formulate policies and governance structures to optimise the deployment of CDR within the overall climate architecture?	• **Workshops**: e.g. CDR for ETS, Financing of ETS, NEGEM vision, NEGEM storylines • **Interviews** • **Literature reviews,** e.g. on existing climate frameworks and accounting rules

Table 2 presents the main characteristics as well as different approaches and scopes of the quantitative modelling tools used in NEGEM. In addition, Deliverable 3.10 shows a detailed summary of the methods applied for the impact assessment of each NETP.

Table 2. The modelling tools used in the NEGEM analysis.

Model	Life cycle assessment (LCA)	LPJmL-model	MONET & JEDI	VTT-TIMES & Pan-European TIMES
Explanation	Life cycle assessment applying ReCiPe 2016 method and SimaPro 9.1.0.8 software	Process-based biosphere model	MONET: whole-system analysis of a least cost portfolio of CDR pathways via a mixed integer linear optimisation formulation, JEDI: model extension to evaluate socio-economic impacts	Whole-system analysis of a least cost portfolio of CDR pathways via bottom-up, technology rich partial equilibrium modelling
Method	Comparison of sustainability performance of NETPs on different environmental and health impact categories	Quantify biophysical potential of vegetation-based NETPs constrained by planetary boundary limits	MONET: Determining the optimal (least cost) co-deployment of CDR pathways to meet regional or national removal targets in different scenarios JEDI: Evaluating the socio-economic impact of the deployment of CDR by estimating the value added to the economy and the employment opportunities created.	Determining the optimal (least cost) co-deployment of CDR pathways to meet 1.5C mitigation scenarios in global and European level
Approach	**Case specific**	**Supply-constrained**	**Demand-driven**	**Demand-driven** (for NEGEM scenarios constraints from LPJmL modelling results were applied for bioenergy feedstock, biochar, and reforestation potentials)
Scope	Product/system: Per unit tCO_2	Global	EU-28	Global, EU-31
Main deliverables	D1.2, 1.3, 1.4,1.5, D3.8	D3.1, 3.2, 3.3, 3.7, 3.10	D4.3, 4.5, 7.2, 7.3	D8.2, D3.9

3 Responsible potentials for NETPs

The NEGEM Science-Policy Brief, and the final NEGEM medium to long-term vision (deliverable 8.3) aimed to summarize the key finding of the project concerning the responsible potentials. In the following, the key conclusions on the responsible deployment of NETPs are given under the two first research questions of NEGEM, based on the policy brief, the final vision, and the latest NEGEM deliverables. After this, the quantitative results are further illustrated in Chapter 3.3. The third research question on policy frameworks is discussed in Chapter 6. As there is an extensive amount of NEGEM results in the almost 70 deliverables, we limit our discussion to the key findings, and the deliverables provide much more extensive conclusions and recommendations. In addition, NETP specific conclusions are given in D6.4 "Carbon negative handbook", where factsheets for each NETP are provided.

3.1 To what extent is carbon dioxide removal required to achieve climate neutrality?

The key NEGEM conclusions is that to meet the climate goals of the Paris Agreement, drastic, immediate, and sustained reductions in greenhouse gas emissions are needed. To keep the warming at 1.5-2 °C, carbon dioxide removal (CDR) technologies and practices are needed but should only be relied on as a supplementary measure to emission reductions. **The smaller the residual emissions, the lower the demand for CDR.** It is not clear, which of the impacts of the climate change are reversible, and thus emission avoidance is more beneficial than emission removal.

When evaluating various CDR options, the carbon dioxide (CO_2) storage time and vulnerability to intended and/or unintended release of CO_2 are essential. One of the NEGEM key conclusions is that **technical solutions with storage at geological time scale providing permanent CDR, are needed to reach climate neutrality** (Allen et al. 2022). Industrial level deployment of these technologies, such as BECCS and DACCS, should start latest in 2030's in order to provide CDR at gigaton scale in 2050.

On the other hand, **nature-based CDR methods, such as reforestation, can provide substantial synergies between climate change mitigation and international targets for nature restoration** (i.e. the Kunming-Montreal Global Biodiversity Framework) and broader sustainable development goals (Deliverable 3.6). Thus, their implementation can be justified from several perspectives and should be accelerated immediately, especially when co-benefits can be linked to targets of nature restoration and Sustainable Development Goals.

In any case, dependence on CDR should be kept to a minimum. As the amount of permanent carbon removals is likely a scarce resource, and Net-Zero is ultimately a global target, counterbalancing of residual emissions should be achieved at a broader system-level (Deliverable 6.5). Furthermore, the separation of the CDR solutions in nature-based and technical solutions is rather unclear, and classification based on the permanence of CO_2 storage (geological vs. temporary) would be more useful.

3.2 At what scale is it feasible to implement CDR methods?

3.2.1 Environmental aspects

As described in Chapter 2 NEGEM studied the environmental constraints for NETPs with several methods. First, NEGEM accomplished a comprehensive life cycle assessment (LCA) study of altogether 36 different CDR configurations. The results show that **none of the CDR methods comes without side-effects and trade-offs** (Figure 4). On the other hand, also low risk options with recognisable co-benefits, and especially forestation options, soil carbon sequestration and several DACCS options were found as effective with few trade-offs (Cobo et al. 2023, Deliverable 3.8). Enhanced weathering was at first considered a promising option, but based on subsequent studies later in the project, doubts were raised on the CO_2 sequestration efficiency and the toxicity impacts of the weathering process, which could significantly worsen the LCA results. **The main conclusion of the LCA study was that to balance the environmental and health impacts a portfolio of NETPs is needed.**

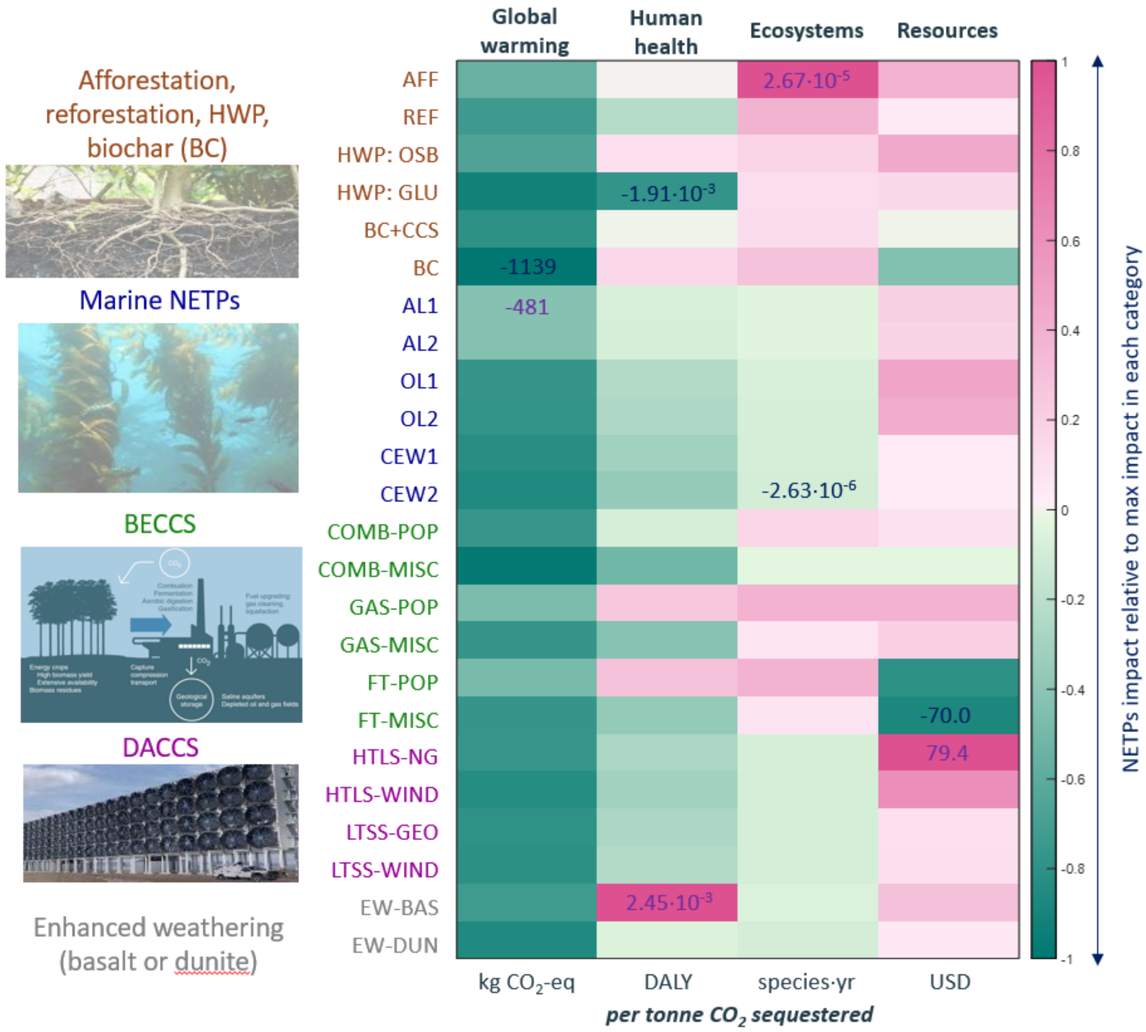

Figure 4. LCA results for the various NETPs studied reflecting the trade-offs (see Deliverable 3.8)

Second, **environmentally constrained global biomass potentials for BECCS** were studied with the biosphere model LPJmL5-NEGEM (Deliverables 3.2, 3.6, 3.7). In the climate stabilization scenarios from Integrated Assessment Models included in IPCC's AR6 (IPCC 2023), the need for CDR is largely covered by BECCS from dedicated bioenergy crops, the medium demand for BECCS being around 9 $GtCO_2$/yr in 2050 (D8.1). However, these rates result from economic optimization balancing emission reductions and CDR, yet with limited representation of environmental constraints. In NEGEM, a "supply-driven" assessment of the global BECCS and reforestation potentials was done by excluding further transgression of terrestrial planetary boundaries and ensuring that forest ecosystems are not converted to biomass plantations. The study focused on land areas outside current agricultural land. The planetary boundaries evaluated were freshwater use, nitrogen flows, land-system change and biosphere integrity. Significant limitations to

BECCS and reforestation CDR potentials on non-agricultural land were recognised when planetary boundaries other than climate stabilization were included in the assessments (Figure 5). (Deliverable 3.2)

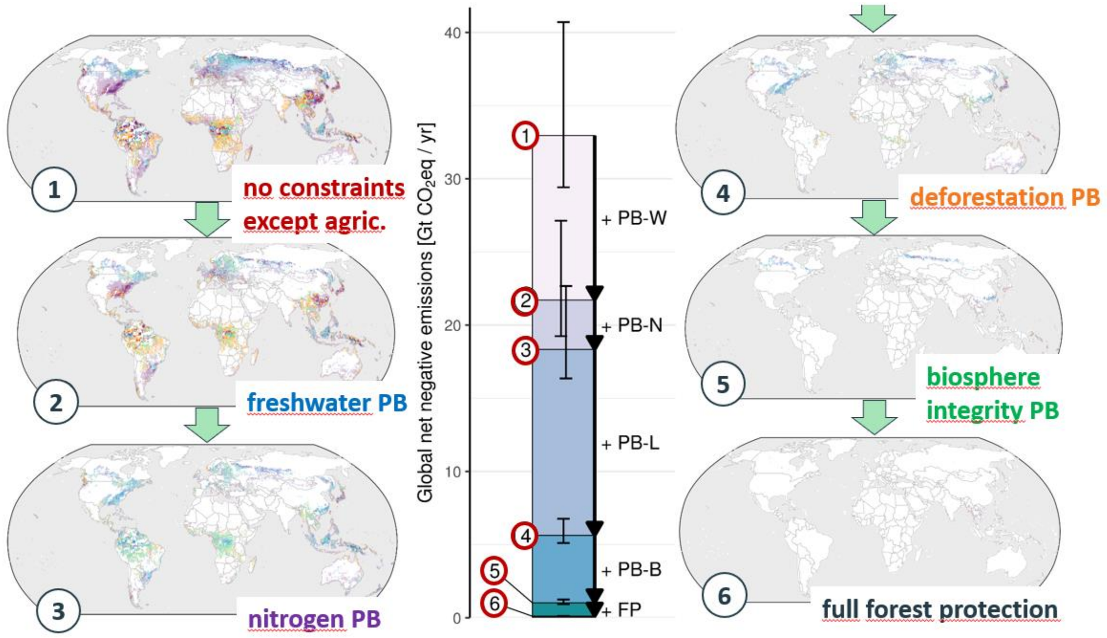

Figure 5. BECCS potentials outside current agricultural land when no further pressure on planetary boundaries for freshwater use, nitrogen flows, land-system change and biosphere integrity is accepted (see Deliverable 3.2). PB=planetary boundary for W=water, N=nitrogen, L=deforestation, B=biosphere integrity, FP=full forest protection.

This led to the conclusion that to free land area for BECCS or reforestation, **significant transformations of the agricultural sector would be needed**, for example, as a result of dietary changes (reduced meat consumption). In addition, the current agricultural land should be more efficiently yet sustainably used, including crop yield increases, innovative farming practices (e.g., intercropping, double cropping, cover cropping, agroforestry), and the use of waste and residue streams across all agricultural and forestry value chains for BECCS.

Global dietary changes, e.g., by following the EAT-Lancet planetary health diet, could free up substantial amounts of land from current agricultural use, mainly from pastures, for BECCS or reforestation purposes. Depending on the level of global shift to the new diet regime (25, 50 or 100% change), the intensity of land management, and the carbon removal efficiency, the additional global BECCS potentials could range from 1.7 to 18.5 $GtCO_2$/yr – yet, the higher end potentials would severely increase pressures on water stress and environmental boundaries for nitrogen, water and biosphere integrity. By contrast, reforestation on pastures was simulated to remove 1.5 to 4.3 $GtCO_2$/yr while serving both climate stabilization and nature restoration, thereby synergistically contributing to getting back into a safe operating space regarding multiple planetary boundaries. (D3.7) Furthermore, solutions such as biochar and soil carbon sequestration could enhance resilience of natural or anthropogenic systems to extreme events due to climate change (D3.4).

As an outcome from the LCA and biosphere modelling results, a **large portfolio of NETPs was applied in the scenario modelling** towards 1.5°C mitigation targets to balance the impacts of various NETPs. The scenario modelling by TIMES-VTT and PET-TIMES showed that to reach the 1.5°C mitigation targets, the **full portfolio of NETPs came into use**. The technical CDR solutions such as BECCS and DACCS scaled up from 2030-2040's, their highest level of deployment likely taking place in the 2060-2070's (Deliverable

8.2). The constraints from the LPJmL modelling were applied for BECCS, biochar, and reforestation potentials. Sustainable BECCS applications (e.g. 2-4 $GtCO_2$/yr around 2050 globally) combined energy crops, residual biomass feedstock (forest and agricultural residues), and capture of point source biogenic CO_2 emissions e.g. from biorefineries and pulp- and paper industry. According to the modelling results, the **BECCS technologies varied from combined heat and power production, to bioliquids and biogases, instead of using BECCS mostly in power plants** (D8.2). The BECCS potentials were in line with the estimated potentials by the MONET model of around 2 $GtCO_2$/yr of BECCS by 2050 (Chiquier et al. 2022).

The TIMES-VTT scenarios with strict environmental constraints for BECCS potential (based on the LPJmL modelling results) showed **significantly increased need for DACCS technology** (see Figure 6 1.5-Env scenario). This on the other hand increased the **need for renewable electricity** dramatically, as the energy needs for DACCS needed to be covered with increased wind and solar power, in addition to the demand for the clean energy transition (D 8.2).

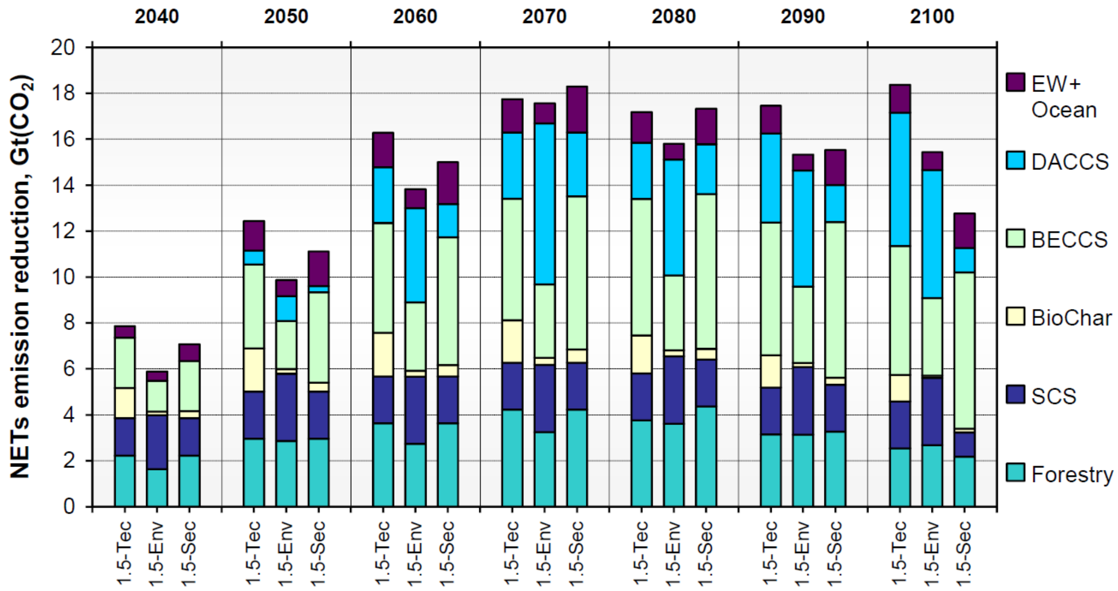

Figure 6. NEGEM 1.5C scenario results for global contributions of different NETPs with TIMES-VTT modelling. 1.5Tec, 1.5-Env, and 1.5-Sec scenarios represent the three storylines studied. (See deliverable 8.2)

The NEGEM modelling results with TIMES-VTT showed that **a large portfolio of CDR methods, would enable the most cost-effective mitigation pathways** (D8.2). In addition, international co-operation is key for the usage of **biomass resources, CO_2 transportation networks, and geological storage facilities** in an efficient manner (Chiquier et al. 2022, Deliverable 8.2).

NEGEM made a preliminary assessment of the **key non-renewable resource chains** (rare metals and minerals) in the context of large-scale deployment of CDR. (Deliverable 3.9) The results showed that the clean energy transition may be constrained by a supply of cobalt and neodymium, which are important metals in batteries and wind power installations (IEA 2023). In addition, copper and silver are used in significant amounts. Availability of these metals could potentially limit long-term investments in clean energy technologies. In addition, the mining operations create pressure on water quality, local pollution, and may include social and equality problems, as the mining often takes place in in the Global South (Koljonen et al. 2024).

Finally, NEGEM studied **non-CO_2 GHG removal** solutions for methane (CH_4) and nitrous oxide (N_2O) through metal-catalytic oxidation, photocatalytic oxidation and biological oxidation. The conclusion was that low concentration of CH_4 and N_2O may limit these approaches on the basis of cost and energy requirements. For example, more emissions could be generated from energy use than could be removed at certain concentrations of GHGs. Thus, it remains an open question if non-CO_2 removal techniques will prove effective at creating a negative emission, and commercially viable at scale; all the options studied require further research and development. (Deliverable 2.3).

3.2.2 Economic aspects

The cost estimates for NETPs vary in literature and can be very case and location specific. For example, the costs of different BECCS technologies may vary significantly, depending e.g. on the biomass feedstock used, the scale and location of the plant, and the concentration of the CO_2 in the given flue gas stream. Many of the NETPs are still in the development phase without experience on large scale applications. Thus, **the costs of different NETPs are inherently uncertain**. NETPs database collected in the beginning of the NEGEM project included information on the costs of different NETPs and their components (Deliverable 4.1). At the end of NEGEM project, an updated literature review on NETP price estimates for 2050 was made (Havukainen 2024). Figure 7 shows the average estimates and ranges found from the literature, specific for 2050.

The expert elicitations made in NEGEM showed **that even experts can have very different estimations on the price development of various NETPs** (Deliverable 5.4). As BECCS and DACCS technologies will have a central role in providing permanent carbon dioxide removals, NEGEM conducted altogether 34 expert elicitations to evaluate the current and future price development for these technologies (21 DACCS experts and 13 BECCS experts were interviewed) (see Deliverable 5.4). The elicitation results suggest that by 2050, the average costs for DACCS will fall to 280 €/tCO_2 and for BECCS to 153 €/tCO_2 (current assumptions were 581 €/tCO_2 for DACCS and 172 €/tCO_2 for). However, these averages hide a wide divergence in views among experts, particularly for DACCS, for which the best estimates could vary from 100 to 1100 €/tCO_2. For BECCS the best estimates varied from 120 to 350 €/tCO_2.

Most DACCS experts believed that economies of scale and better materials will reduce the costs. For BECCS, the result was a bit opposite, and the experts believed that BECCS might struggle to scale up given the distinctive characteristics of each plant. In addition, the biomass feedstock was seen to become even more expensive than the current prices, e.g. due to increasing demand. A stable, decarbonised energy system for Europe was seen necessary, to reduce uncertainties linked to energy costs for DACCS and guarantee the revenue streams for BECCS, respectively (see Deliverable 5.4).

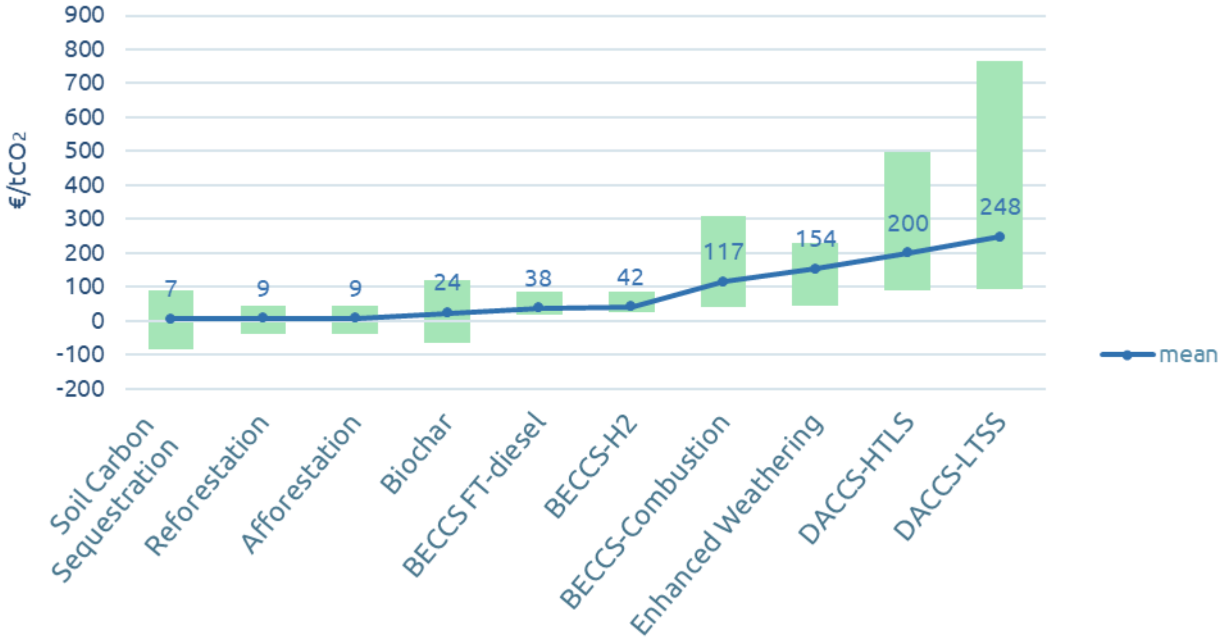

Figure 7. The unit costs per ton CO_2 removed range for NETPs in 2050 (exchange rate from dollars 0.9206, 2024 average). The low cost for BECCS from FT-diesel and H_2 production comes from the assumption, that almost pure CO_2 streams are available in the process and can be cheaply captured. (See literature sources in Annex 2)

3.2.3 Socio-political aspects

NEGEM studied the **social license to operate** for different CDR methods and found that it varied across sectors and geographies (Deliverable 5.1). For example, NGOs and companies can have varying/opposing views on the acceptability of different CDR solutions. Most firms favored technological solutions such as BECCS and DACCS, whereas NGOs more commonly favored nature-based solutions. However, **interaction between different stakeholders** had an effect in changing perceptions. (Deliverable 5.3) Tensions between the goals of carbon dioxide removal and other high-priority social or environmental goals were found out, thus a **systems perspective needs to be adapted when designing the legislation or regulations.** (Deliverable 5.2)

Furthermore, NEGEM studied which NETP features were most valued across different stakeholder profiles, and thus their relative importance in shaping stakeholder preferences (Deliverable 5.6). To do so, the research undertook a conjoint analysis study, a research method designed to deconstruct and rank the preferences of participants by presenting them with a series of options that vary across a set of defined dimensions. The following five dimensions were assessed: cost per ton of CO_2 captured associated with these technologies, permanence of the CO_2 captured, type of storage (biological or geological), resource use, and project proponent. The results revealed that **both groups prioritized permanence of CO_2 removal as the paramount dimension**, and private sector respondents assigned it even greater importance, accounting for 42% of their decision-making process, as opposed to 35% for NGO stakeholders (Figure 8).

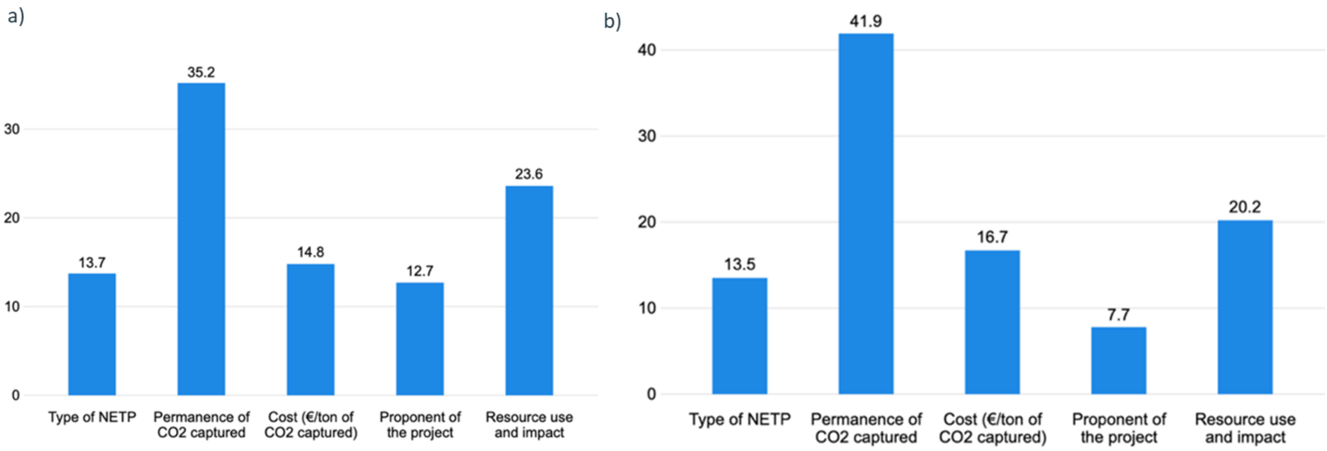

Figure 8. Importance of each dimension for a) NGO respondents, b) private sector respondents. Private sector stakeholders (73 responses), associated with environmental NGOs (66 responses). (see Deliverable 5.6)

NEGEM accomplished **a wide public survey during the fall 2023, with over 6000 respondents from 6 different countries** (Germany, Spain, Finland, Lithuania, The Netherlands, and Poland). The study concentrated on public perceptions on DACCS and af-/reforestation. Across all surveyed nations, respondents consistently viewed af-/reforestation as more acceptable than DACCS, however remaining neutral about DACCS. Perceptions of positive consequences for nature, future generations, climate mitigation, and broader environmental impacts heavily favored af-/reforestation. **Countries with high cumulative emissions and strong financial capacity were seen as having a greater responsibility and thus the fairness of implementing NETPs within their borders was viewed favorably.** Respondents strongly expressed the need for the involvement of citizens in NETP development. This includes being informed, having a voice in the process, and sharing decision-making power with experts and governments. (Deliverable 5.5)

In addition to the surveys and interviews, **socio-economic impacts** associated with deploying CDR at the national scale were studied with the MONET model. Two scenarios were evaluated: (i) the “Cost” case study minimized the total system cost, whereas (ii) the “Jobs” case study maximized the direct value added (DVA) of the system (Deliverable 7.4). To meet CO_2 removal targets of the EU-28, the “Cost” scenario prioritizes deployment of cheaper NETP such as AR, biochar and BECCS, resulting in a lower average CDR cost. These biomass-based CDR methods are expected to increase gross value added (GVA) in the agricultural and forestry sectors. The “Jobs” case study prioritizes technical CDR methods such as DACCS which tends to increase DVA and years of employment in economic sectors such as manufacturing, construction, utilities, and scientific R&D (Figure 9). These case studies demonstrated that inter-regional supply chains are deployed, which creates jobs across different regions. This **highlights the value of intra-European collaboration in delivering EU-level CDR targets.** Hence, collaboration amongst the EU member states can create **economic opportunities across the different regions and industries**.

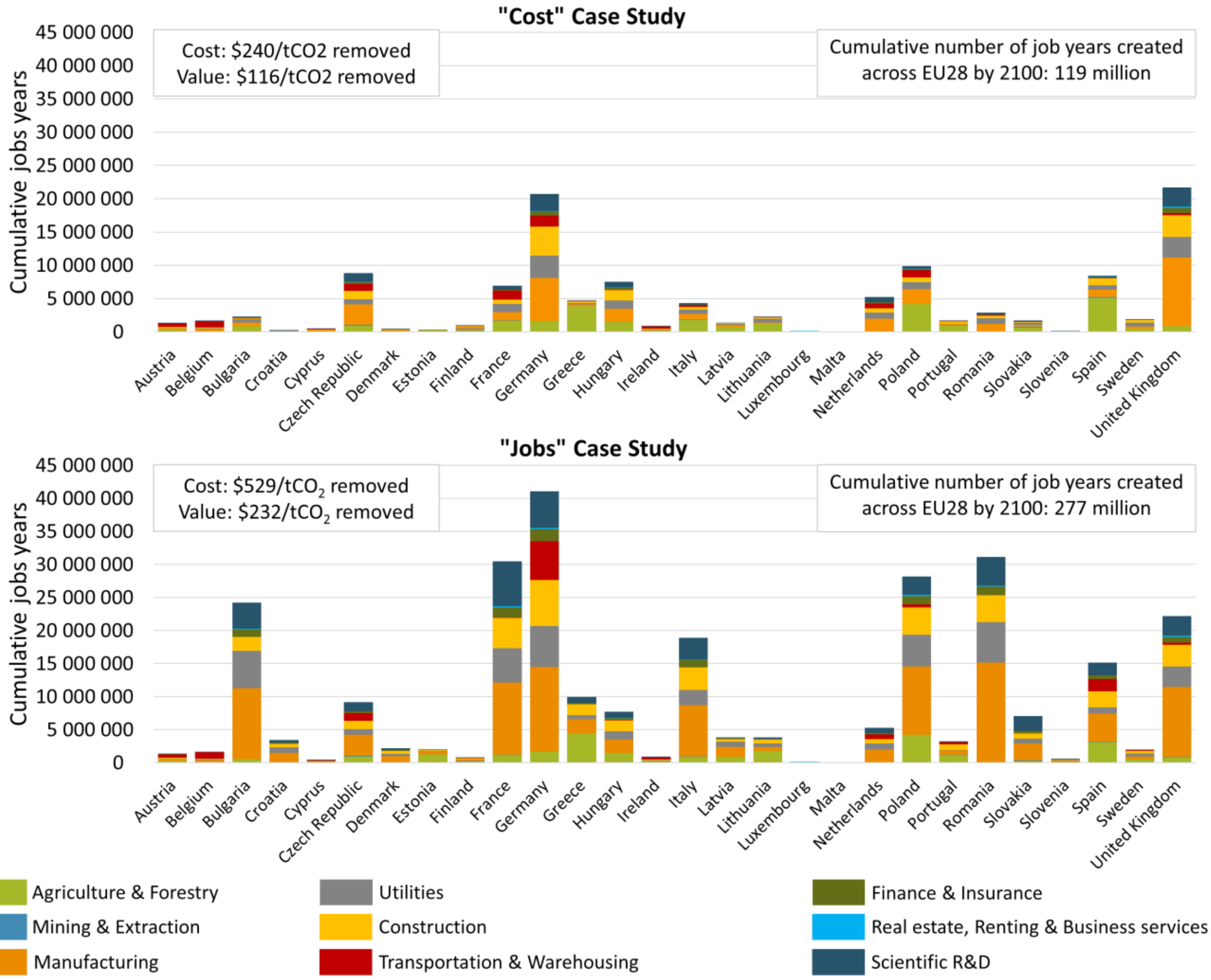

Figure 9. Cumulative number of job years created between 2020 to 2100 in the EU-28 for the (top) "Cost" case study, and (bottom) "Jobs" case study. "Cost" scenario prioritizes AR, biochar and BECCS, "Jobs" prioritizes DACCS. Note: the number of job years does not represent the number of people but rather the years of employment required to deliver the scenario. (Deliverable 7.4)

3.3 Quantitative results from NEGEM

According to the NEGEM results, there are still considerable uncertainties with quantitative assessments for NETPs potentials and deployment, and the vision for the desired level of deployment may differ depending on stakeholder or individual. For these reasons, this report presents the quantitative estimates on responsible NETPs deployment as ranges (see Figure 10), based on NEGEM modelling studies performed with different methods and assumptions (see Annex 1 for a summary). Additional details on the results can be found from the relevant deliverables. The quantitative results should not be seen as consensus targets for the single NETPs deployment suggested by the project. However, the quantitative values give some evidence-based indication of the foreseeable potentials for NETPs in order to reach the 1.5-2 ° C mitigation target.

The results in Figure 10 show that the NEGEM ranges are below the median values from IAMC AR6 scenarios database reflecting the IPCC's 1.5C scenarios, for all NETPs. This shows that taking into account the environmental constraints e.g. for BECCS clearly reduces the potentials available. On the other hand, the potentials for single NETPs e.g. in TIMES-VTT modelling are lower, as a large portfolio of NETPs is taken into use, thus reducing the demand for a single NETP.

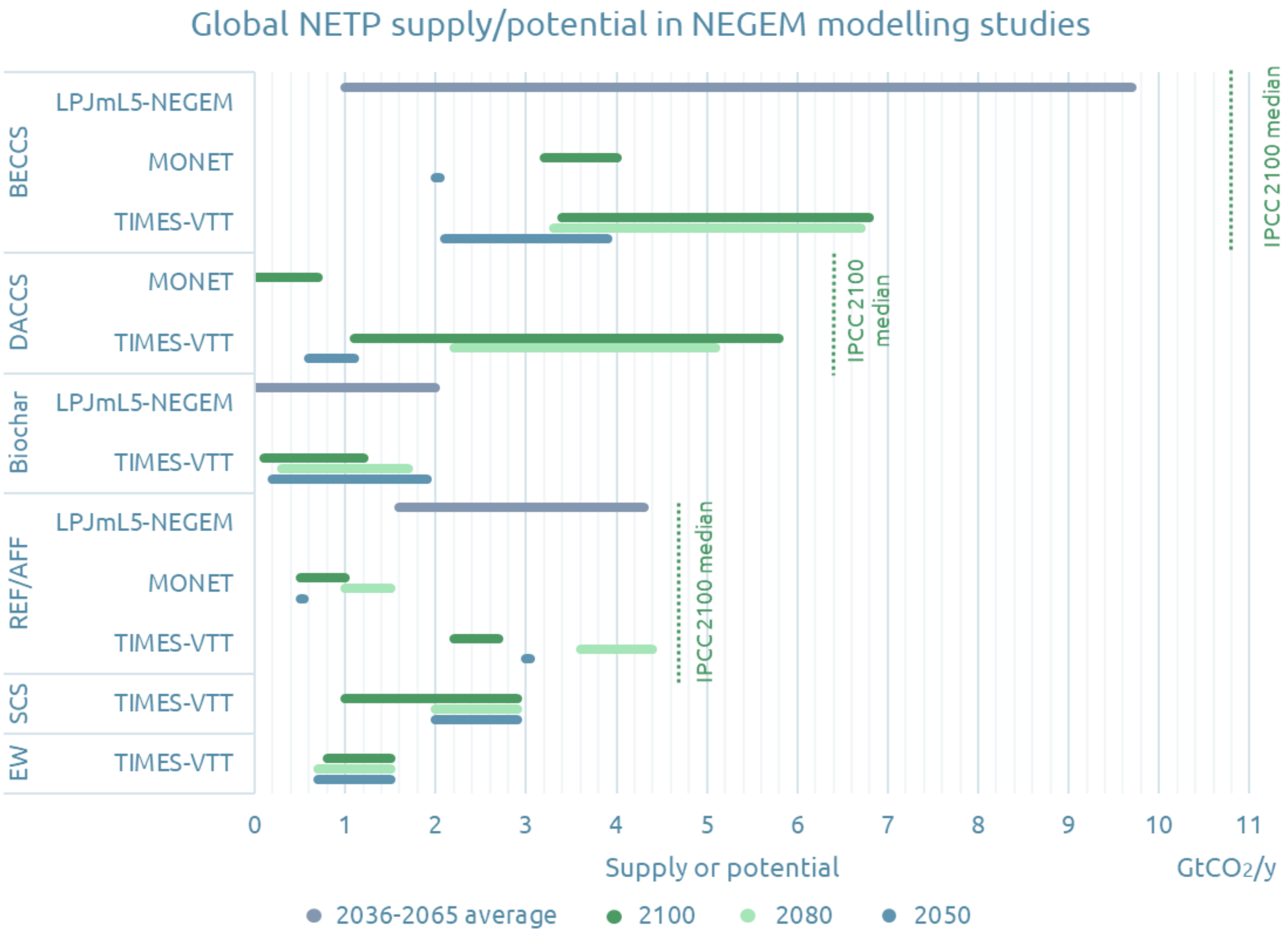

Figure 10. Supply or potential for various NETPs based on the NEGEM modelling studies. LPJmL5 model is a process-based biosphere model, providing supply-based results, whereas TIMES-VTT and MONET (results from D8.2, and Chiquier et al. 2022, respectively) are optimisation models providing demand-based results. The high-end results by LPJmL for BECCS and afforestation would require 100% global dietary changes to release agricultural land for NETPs. (See Annex 1 for references and further explanations and Table 2 for model descriptions.)

Figure 11 illustrates the yearly and cumulative NETP potentials in the EU-31 at 2050 by PET-TIMES modelling (D8.2).

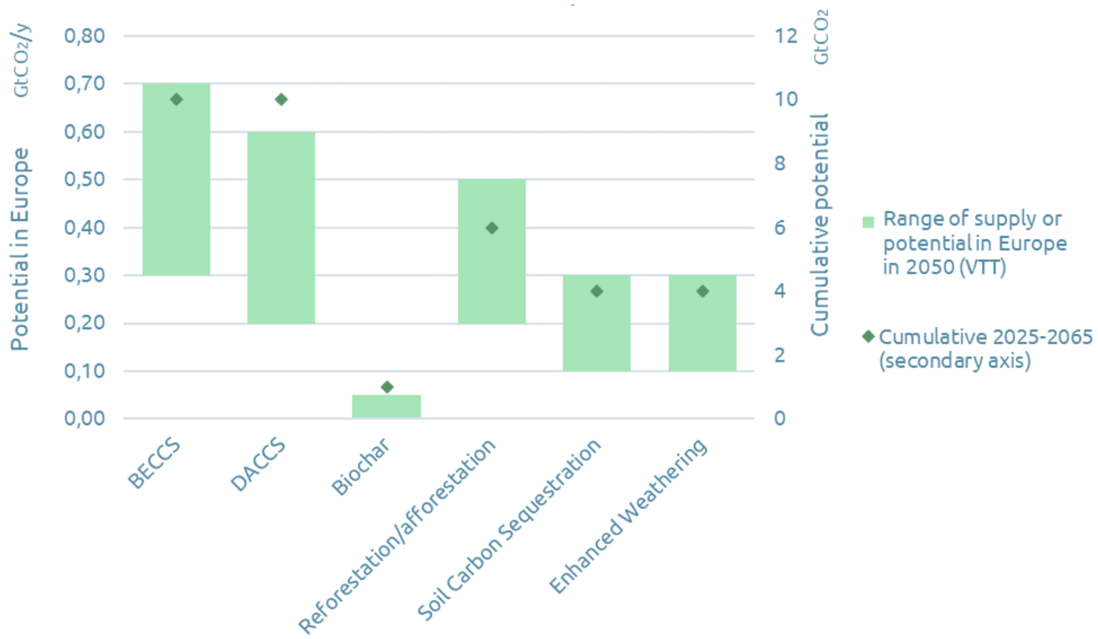

Figure 11. Potential for NETPs in EU-31 at 2050, by PET-TIMES modelling. (Deliverable 8.2). Note that biochar potential here refers to calorie-and-land neutral biochar (D3.10), and e.g. residual feedstock are used only for BECCS and not for biochar. (See Annex 1)

4 Suggestions for KPIs

Key performance indicators (KPIs) can be used to express the progress toward or the achievement of a goal as precisely as possible. There may be more than one possible indicator to assess the progression towards a certain goal, in complex issues. Possible KPIs can be assessed against several criteria suggested in literature, e.g. Relevance, Completeness, Availability, Measurability, Reliability, Familiarity, Non-redundancy and Independence (see more detailed in Correia et al. 2019 based on van Rooijen & Nesterova 2013 and Bosch et al. 2017).

During the NEGEM project, a set of key performance indicators was used by Cobo et al. 2023: a) The technology readiness level, b) The maximum annual global GGR potential, c) The cost of removing 1 tCO_2-eq., d) The number of negative trade-offs (identified by LCA), e) The number of co-benefits (identified by LCA). These indicators were used to evaluate the global potentials and trade-offs for various NETPs.

The KPIs presented below, are rather designed for the goal of implementation of the NETPs. Reflecting the multidisciplinary approach of the NEGEM project, the proposed KPIs are classified under five categories, including technical and environmental performance, as well as social, security and governance aspects. For each proposed KPI, Table 3 gives ideas for ex-ante indicators for planning and ideas for ex-post monitoring, reporting, verification and liability. Both qualitative and quantitative indicators are applied. Some of the proposed indicators are simpler to use and less uncertain than others. Moreover, some KPIs are relevant for all NETPs whereas others are used only for specific NETPs. However, all of them merit consideration when planning for implementation of NETPs. KPIs proposed here do not cover specific issues related to ocean-based NETPs, such as transboundary issues, and specific issues for ocean ecosystems (see deliverable 3.5 on ocean-related NETPs).

Table 3. Key performance indicators for NETPs. Grey color means that further definition, method development, or data collection is needed for the indicator/monitoring. "Quality" refers to the quality of e.g. risk management plan (is the plan up to commonly agreed standards/procedures, if these exist).

KPI	Ideas for ex-ante indicators for planning (unit/valuation criteria in parentheses)	Ideas for ex-post monitoring, reporting, verification and liability
Technical performance		
Permanence of CO_2 storage	• Expected storage time (years) • Does the project have a plan for monitoring leakage over storage duration? (yes/no, what is the quality of the plan) • Does the project have a liability mechanism to guarantee permanence of temporary storage over planned time? (yes/no, what is the quality of the plan)	• Leakage from permanent geological storage is monitored and quantified (e.g. target for a leakage rate below defined % per year) • Realization of temporal storage is monitored and verified: e.g. by field measurements, forest inventories, remote sensing practices, etc. • The liability mechanisms to guarantee the duration of a temporal storage (e.g. re-/afforestation) are monitored and verified
Physical risk of reversal	• Evidence/science-based risk of reversal (low, high, medium) • see D6.4	• The reversals are monitored as above
CO_2 removal efficiency	• The life cycle greenhouse gas emissions per ton of CO_2-eq. removal, when all inputs to the CDR process are included, e.g. energy, chemicals, fertilizers, etc., as well as leakages from the process (tCO_2-eq./tCO_2 removal) • see D3.8	• The LCA emissions are monitored and verified • E.g. the GHG criteria in the RED3 directive (EU/2023/2413) for bioenergy sets an example on how LCA based indicators can be reported, monitored, and verified
Timing for removal	• The payback time for the removal, i.e. time it takes that the removals are higher than the emissions due to creating removal, taking into account e.g. the speed of sequestration, life cycle emissions, and the impacts e.g. on forest C stocks due to biomass harvest for BECCS (years) • see Chiquier et al. 2022	• Monitoring of the exact payback time can be challenging in many cases and will require further developments
Environmental performance		
Resources use	• LCA indicators on resources use occurring during the life cycle: e.g. land area (ha/tCO_2 removal), energy (MWh/tCO_2 removal), water (l/tCO_2 removal), fossil (€/tCO_2 removal) & other resources per tCO_2 removal	• The LCA indicators are monitored and verified • The local conditions are monitored, and changes in vulnerabilities are recognized

	• Consumption of rare metals and minerals per tCO_2 removal (t/tCO_2 removal) • Need for fertilizers (e.g. t/ha) • Regional vulnerability at the location of the project (e.g. high/low vulnerability on droughts, increased land use intensity, etc.) • see D3.8,3.9	
Emissions to environment	• LCA indicators on environmental impacts occurring during the life cycle, when all inputs to the CDR process are considered: emissions on land/water/air (e.g. ppm/tCO_2 removal) • Regional vulnerability at the location of the project (e.g. high/low vulnerability of watersheds, biotopes, etc.) • see D3.8	• The LCA indicators are monitored and verified • The local conditions are monitored, and changes in vulnerabilities are recognized
Biodiversity/biosphere integrity	• LCA indicator: species loss/year, as a contribution to the planetary boundary of genetic biosphere integrity • Human appropriation of net primary productivity as a contribution to the planetary boundary of functional biosphere integrity • Does the NETP support the internationally agreed restoration targets? (Kunming-Montreal targets) • see D3.3	• LCA indicators for biodiversity are monitored and verified • The nature restoration targets (Kunming-Montreal targets) are monitored and verified
Environmental co-benefits	• Does the NETP support the internationally agreed restoration targets? (Kunming-Montreal targets) • Yield increases (t/ha) • Resilience of soils and ecosystems to climate extremes (e.g. water holding capacity) • see D3.4	• The nature restoration targets (Kunming-Montreal targets) are monitored and verified • Yields are monitored • Soil quality is monitored and verified, e.g. by measurements of water holding capacity
Economic performance		
Cost of CO_2 removed	• Planned cost of removal, e.g. based on a feasibility study / investment plan (€/tCO_2 removal, be specific if gross or net cost is used)	• The actual costs are reported and monitored

Cost of liability mechanism / of replacing the C storage in case of reversal	• Does the project have a liability mechanism in place? (yes/no, quality) • What is its cost of the liability mechanism (€/tCO_2 removal)? • see D2.4	• The realised costs of the liability mechanisms are monitored over time
Liability in case of not being able to deliver the removal in the first place	• Does the project have a liability mechanism in place for a case where the project fails to provide removals, e.g. due to technical problems? (yes/no, quality of the mechanism)	• The implementation of the removal project is monitored to verify success of removals • In case of failed removals, the implementation of liability mechanism is monitored
Co-products creating economic value	• Are there co-products for the NETP, such as heat/power/fuel in case of BECCS (yes/no) • Revenue from the co-products (€/tCO_2 removal)	• The revenue from co-products could be monitored
Social aspects		
Health impacts (direct and indirect)	• LCA indicators for health (e.g. DALY/tCO_2 removal) (see D3.8) • Information on use of chemicals, pesticides, etc. during the NETP value chain (e.g. amount of chemicals used, health risks associated)	• The direct health impacts throughout the NETP value chain are monitored • Monitoring the indirect health impacts e.g. through climate change mitigation specific to NETPs may be impossible
Impact on local jobs	• Jobs created (e.g. jobs / job years) • see D7.4	• The actual jobs created in NETP installations and through the value chain are monitored
Affordability of the NETP / cost for the society	• Risk of high costs for society could be evaluated based on the net cost of removal (€/tCO_2 removal), cost of initial investment (M€), etc. • On the other hand, also the benefits from climate change mitigation should be accounted for	• Monitoring the costs for the society could be challenging, as it might be difficult to account for the benefits created by NETPs through climate change mitigation
Link to energy poverty (i.e. energy intensive NETPs consume a lot of energy)	• Energy input needed (MWh/tCO_2 removal) (see resources use) • Vulnerability of the region to energy poverty (high/medium/low)	• The actual energy consumption of NETPs installations and impacts on the local energy system are monitored and verified
Impact on food systems (e.g. need for dietary changes / risk of competition with food production / positive impacts on yields)	• Land area needed (ha/tCO_2 removal) (see resources use) • Vulnerability of the region for risks to food security (high/low) • Does the NETP support yield increases? (yes/no, t/ha) • Are dietary changes needed to enable NETPs with land use requirement for biomass	• Monitoring the impacts on food systems could be challenging as impacts specific to NETPs could be difficult to separate from impacts due to other drivers

	production / af-/reforestation? (yes, no, scale) • see D3.2, 3.7 & 3.10	
Acceptability (e.g. perceived fairness / consequences on nature and the environment, etc.)?	• Ex-ante public perception studies with surveys, interviews, local workshops, etc. • see D5.5	• Monitoring and reporting public perception with surveys, interviews, local workshops, etc.
Security aspects		
Vulnerability to external interventions	• Need for pipelines, intermediate CO_2 storages or terminals, CO_2 transportation by boat, etc. may increase the risk for external interventions (quantity of infrastructure associated to risks) • Does the project have a risk management plan to prevent external interventions? (yes, no, quality)	• Any events of external interventions are monitored and reported • Risk management plans are monitored and verified over time
Vulnerability on disturbances in the energy system / energy supply constraints, e.g. using energy for NETPs vs. other uses	• Vulnerability to disturbances in the energy system can be evaluated based on the energy input (MWh/tCO_2 removal) (see resources use) • Is there an energy output from the removal process? (if yes → positive impact to energy system resilience) • Risk of overloading grids	• Disturbance situations in energy systems and their impact to CO_2 removal are monitored • The amount of energy produced in the NETP facility is monitored and verified
Forest fires	• The location of the projects, vulnerability of the region to forest fires? (high/medium/low) • Proximity of the project to habitation (km) • Does the project have a forest management and risk management plans in place? (yes/no, quality)	• The forest fires are monitored, and the rate of loss of carbon storage is verified and reported • The functioning of the liability mechanism in the case of forest fire is monitored • Number of accidents due to forest fires is monitored
Leaks from onshore CO_2 storage	• Evidence based risk of leakage from onshore geological storage (e.g. low/high/rate of leakage per year) • Has the project identified vulnerable points in the logistic chain and monitoring system at place? (yes/no, quality)	• The onshore storages are monitored over time • Accidents due to leakages are monitored and reported
Water sufficiency	• Water input needed (l/ tCO_2 removal) (see resources use) • The location of the project and the regional vulnerability for water scarcity / droughts	• The water consumption during the NETPs value chain is monitored and verified

	• Does the project have a plan for adaptation e.g. to droughts. (yes/no, quality)	• The local developments on the water conditions (e.g. increased risks of droughts) are monitored
Governance aspects		
Contractual risk of reversal (e.g. due to a governance change in future or need for intergenerational monitoring)	• Does the project have a long-term plan for monitoring the storage over generations? (yes/no, quality)	• The storage permanence is monitored and verified over generations
CO_2 transportation between nations	• Is there a need for international CO_2 transportation? (yes/no) • Transport distances (km)	• International CO_2 transportation is monitored and verified
Biomass transportation between nations	• Need for international biomass transportation (yes/no) • Transportation distance (km), vehicles & emissions (gCO_2/km) • Is there a sustainability certification for biomass (yes/no, quality of the certificate)	• International biomass transportation is monitored • Transportation emissions are monitored • Sustainability certification of biomass is monitored

5 R&D&I priorities

Based on NEGEM analyses and results, what R&D&I (Research, Development, and Innovation) priorities could be indicated or even recommended? To answer this question, discussion is divided into several dimensions as follows.

First, NEGEM results identify R&D&I needs both in technological and systemic challenges. Technological questions concern a particular NETP or its sub-processes. Systemic challenges affect many NETP solutions simultaneously, such as the question of design of commercialization mechanisms, or lack of information on wider environmental impacts.

Second, the areas identified based on NEGEM results differ according to the phase of R&D. R&D instruments of impact can be significantly different for technologies close to commercial maturity or taking their early steps in research. The scale of Technology Readiness level (TRL) as defined by the European Commission, can be applied to classify the technologies[2] to analyze this dimension. Nascent technologies (*TRL 1: basic principles observed, TRL 2: technology concept formulated, TRL 3: experimental proof of concept*) can be defined as being in research phase. Solutions in deployment phase appear promising in the NEGEM results but are not yet proven full-scale (TRL 7-9). The development phase in between might include e.g. validation of technology in lab (TRL 4-6). Deliverable 1.1 indicated TRL ratings

[2] TRL definitions: h2020-wp1415-annex-g-trl_en.pdf (europa.eu)

for the detailed NETP concepts selected for the NEGEM studies, and the data from D1.1 has been utilized in the aggregated assessments below.

Within the multidisciplinary approach of NEGEM, many knowledge gaps have been identified for NETPs with varying TRLs. Hence, these areas appear as potential for further R&D&I activities. The priority areas for R&D&I could be justified based on potential to achieve Paris Agreement goals, highlighting the European perspective and the EC's target to efficiently allocate the R&D&I measures. Modeling exercises completed in NEGEM give certain indications on the potential, considering the constraints for NETPs concluded by the project.

Based on the above discussion, Table 4 suggests a framework for mapping of R&D&I priority areas divided in systemic R&D needs, technological R&D needs, the relative stage of R&D as parts of the innovation process, and potential role/significance from European perspective based on NEGEM results. For example, based on NEGEM WP1 results on technological assessments, low risk options to the environment with co-benefits could be recognized, and especially forestation options, soil carbon sequestration and several DACCS options with different technological readiness were found as interesting (Cobo et al. 2023). Simultaneously, the DACCS exploitation appeared as a key technology in scenario assessments, with AR and SOCS also in notable role (D8.2). These results could be used to justify R&D investments in these areas.

Regarding the research needs for different NETPs, the NETP Handbook (D6.4) factsheets have been utilized as a central source for summarizing the R&D needs of all the technologies presented in Table 4, complemented with other NEGEM results. To finalize the Table, the R&D&I ideas from NEGEM were subsequently completed, commented and elaborated by VTT's technology experts on CDR.

Placing the systemic R&D needs in the TRL scale of Table 4 is not straightforward, as they typically include or involve several technologies. Below, those who have direct connection to particular NETPs technology, have been positioned correspondingly, whereas the generic systemic R&D needs have been assessed only for their significance (in vertical direction).

Self-evidently, the placements and definitions of R&D&I areas in Table 4 are only indicative. In real-life determination of priority public R&D&I areas, the potential overlaps or synergies of the EU, national and regional levels should be considered. It must be underlined that allocation of scarce public R&D resources always calls for choices. With uncertainties as elementary characteristic in research, should we invest in solutions close to market but with limited potential or in basic research stage but with larger potential? How to consider the competitive situation of different NETP solutions? Also, political emphases such as prominent industrial sectors of a country or conflicting interests between the EU countries, cannot be ignored in analysis of practical choices, even though the textbook examples underline the principle of technology neutrality in R&D priorities. Despite the strategic questions above are left to public decision-makers, the format of Table 4 aims to give justified guidance for the R&D&I priorities and instrument design based on NEGEM results, considering the potential and significance of technologies from the European perspective and technological readiness.

Table 4 Classification of R&D&I needs for priorities based on NEGEM results. See more detailed description of the technologies in D6.4. ***Blue colour for technological questions, Green colour for systemic questions.***

		R&D&I needs with NETPs
Role / significance from European perspective based on NEGEM results: HIGH	Deployment ~TRL 7-9	**DACCS:** • Process optimization and novel configurations to bring costs down • Scaling up the technology, modular concepts • Minimization of other environmental impacts, esp. with amine-functioned solid adsorbents **Bio-CCS:** • Demonstration & implementation (technologies are in different developments stages, e.g. combustion to produce power is more mature than production of hydrogen from gasification or FTL pathways) • Point source applications (e.g. in existing pulp and paper industry or CHP plants). • Economically feasible BECCS options for medium and small-scale point sources • Availability & accounting of non-plantation based feedstocks **CO_2 capture:** • Energy integration of CO_2 capture in pulp & paper industry • Energy-efficient CO_2 capture systems tailored for each industry sector **CO_2-storage:** • Availability of CO_2 storage facilities, infra • Cross-boundary transportation of CO_2 • Leak risk management (permitting & monitoring) **AFF/REF:** • Impacts of climate warming on the ability of forests to grow and store carbon
	Development ~TRL 4-6	**DACCS:** • Heat transfer: contactor design and heat exchangers **Biochar:** • Reactivity in different storage mediums • 1) novel monitoring insitu of biochar reactivity and 2) model development and validation of reactivity and physical spreading based on novel monitoring. • Interaction between biochar and soil properties: influence on carbon loss, water-holding capacity, and ecosystems
	Research ~TRL 1-3	**DACCS:** • Sorbents for DACCS concepts: sustainability, scalability, capture efficiency, heat transfer • New applications of DACCS, e.g. not reliant on sorbents
	Systemic questions: • Harmonized country-level databases on NETPs potentials • CO_2 storage facilities, international co-operation, cross-boundary transportation of CO_2, risks • Monitoring systems and standards • Standardised LCA procedures for the different approaches to ensure comprehensive accounting of carbon flows and GHG emissions along the entire value chain. • Governance structures, regulation, incentive mechanisms, foreseeable price / financial incentives for a European CDR market • Acceptance of NETPs extensively in regional, technological and stakeholder respects • Non-GWP environmental & societal impacts	

		R&D&I needs with NETPs
Role /significance from European perspective based on NEGEM results: MEDIUM	Deployment ~TRL 7-9	**AFF/REF:** • Climate feedbacks for non-CO_2 GHG effects: Volatile organic compounds, evapotranspiration, albedo changes **SCS:** • Potentials (soil type, climate, management practices) • Impacts on soil functioning and soil properties: influence on carbon loss, water-holding capacity, and ecosystems • Balance between biodiversity and climate impacts • Monitoring by remote sensing
	Development ~TRL 4-6	**Enhanced Weathering:** • Mineralization efficiency in real life • Toxicity impacts • New methods for EW: use of catalysts or organisms such as lichen or mosses • Accurate measuring methodologies **CO_2-storage:** • Storing CO_2 by mineralization, e.g. in mining waste **CO_2 mineralisation:** • Increase mineralisation yield • Reduce energy cost • Product & by-product utilisation, e.g. extraction of valuable metals • Logistics optimisation (transportation of CO_2 vs. all solids vs. some solids) • Systematic mapping and testing of suitable secondary raw materials (chemical and mineralogical compositions, quantities, locations)
	Research ~TRL 1-3	
	Systemic questions: • Compatibility between land based NETPs in the modelling studies to avoid double counting of land use (e.g. use of land for biochar, soil carbon, EW) • Establishing baseline (or business as usual) carbonation and/or avoided emissions of alkaline industrial waste streams (e.g. carbonation of ashes and slags, amount of emissions saved by replacing clinker in cement)	
		R&D&I needs with NETPs
Role / significance [...]: LOW	Research ~TRL 1-3	• Ocean alkalinization • Non-CO_2 GHG removal solutions for methane (CH_4) and nitrous oxide (N_2O) through metal-catalytic oxidation, photocatalytic oxidation and biological oxidation
	Systemic questions: • Cross-boundary, governance, liability questions for ocean based methods	

6 Governance structures

In this Chapter, the third and final NEGEM research question "How to formulate policies to optimise the deployment of CDR within the overall climate policy architecture?" is discussed.

6.1 Key policy recommendations

To be able to invest in CDR, stakeholders need clear, long-term regulation and greater certainty. (Deliverable 5.2) Thus, there is an urgent need for clear and coherent CDR definitions (see Deliverable 6.2), policy frameworks and accounting rules internationally, to enable the sustainable implementation of various CDR options.

As the NEGEM results have shown, **CDR methods and their supply chains are complex systems, which can have transboundary implications for different jurisdictions**, especially with regards to carbon accounting. CDR systems can affect land usage, energy systems, the rights of local communities, and human health (Deliverable 6.1). This highlights the need for **comprehensive governance frameworks**, which should be developed to recognize **specific features of different CDR methods**. NEGEM went through several international and EU policy frameworks and concluded that they all require further development on how to address CDR and to achieve their climate goals (Deliverable 6.1). In addition, no comprehensive accounting framework for CDR exists, but, as a start, relevant parts in UNFCCC and EU frameworks were identified (Deliverable 6.3).

In its Science-Policy Brief and final NEGEM medium to long-term vision (Deliverable 8.3) NEGEM provided several policy recommendations, based on the findings of the project work. One key recommendation throughout the project was that in the short- to medium-term **separate targets and governance frameworks for emission reductions and CDR** are required to ensure that net-emissions are more quickly reduced (Reiner et al, 2021). In EU climate policy, such a separation is included in the European Climate Law, where the contribution of the land-sink towards the net emission reduction target of 55% by 2030 is capped to 225 $MtCO_2e$. However, the discussion has now started on the EU 2040 targets. In June 2023, NEGEM provided some key recommendations for the public consultation organized for setting the EU 2040 climate target, including the recommendation **three separate targets for emission reductions, land sink sequestration and permanent carbon removals (Table 5)**.

The key feature for the CDR **accounting frameworks is that they must account for the storage permanence** (Mac Dowell et al. 2022)**.** Separate policy instruments and targets are needed for nature-based CDR and permanent CDR, recognising e.g., different permanence of storage and vulnerabilities to unintended releases of carbon.

In addition, **policy measures should encourage CDR with minimal impacts on planetary boundaries**. As shown by the NEGEM results (Deliverables 3.2, 3.6, 3.7), large scale CDR measures can put pressures on several planetary boundaries, such as fresh water, land system change, and biosphere integrity.

In addition, **responsible effort sharing** globally and in the EU is needed (Deliverable 4.3). The NEGEM public survey showed that from the public perspective it would be fairer and more acceptable if countries with high CO_2 emissions and sufficient knowledge and resources would implement CDR approaches (Deliverable 5.5).

Table 5. NEGEM key recommendations for the EU 2040 policy consultation (June 2023).

Key messages on the role of CDR for EU's 2040 climate policy from the NEGEM Science-Policy Brief:

- **Establish separate targets for GHG reduction and CDR for 2040**
  - By 2040 emissions should be close to zero in many sectors, including the energy sector. In addition to targets for deep and sustained emissions reductions, a specific target for CDR is needed for 2040.
  - Establish **separate targets for GHG reduction, the LULUCF sector, and technical CDR that leads to geological storage**.
  - An "equitable and fair" allocation of emission reduction and carbon dioxide removal targets between EU Member States is needed, while also considering the EU's responsibilities at a global level.

- **For the 2050 climate neutrality target the role of CDR is likely important**, especially considering the possibility for a degrading forest carbon sink in the EU.
  - Industrial level deployment of CDR methods should start latest in 2030's in order to provide CDR at scale in 2050.
  - However, dependence on CDR should be kept to a minimum.

- **Recognize the different roles of nature-based and technical solutions.** The CO_2 storage time and vulnerability to intended and/or unintended release of CO_2 is essential.
  - Technical solutions with geological-timescale storages provide permanent CDR and are needed to reach climate neutrality.
  - Nature-based methods are needed as they provide strong synergies between climate change mitigation and international targets for nature restoration (i.e. the Kunming-Montreal Global Biodiversity Framework), and broader sustainable development goals given their benefits e.g. for biodiversity and soil quality.

- **Enable co-operation** between Member States and outside EU for CDR (e.g. CO_2 transportation & geological CO_2 storage).

- **Agreement on CDR regulation** is needed as soon as possible, in order to establish a clear investment horizon for stakeholders.

6.2 Commercialisation

In addition to the policy frameworks, NEGEM studied the market-based, public procurement, and fiscal policy mechanisms for CDR (Hickey et al. 2023, Deliverable 2.1). The findings proposed that the **current mechanisms are severely under-resourced** and provide too little incentive to enable a CDR portfolio that could support achievement of net zero targets. The current mechanisms mainly support paying modest sums for established afforestation and soil carbon sequestration methods, while **mechanisms to support permanent geological CDR remain largely underdeveloped**.

The effectiveness of different risk management frameworks for securing carbon storage, such as buffer accounts and ton-year accounting frameworks, was studied (Deliverable 2.4). The findings indicated that buffer accounts may be significantly undercapitalized. Additionally, the study highlighted that ton-year accounting could be an ineffective risk management framework when evaluating carbon storage options on timescales relevant to fossil fuel CO_2 emissions, as it is unable to approximate the short- and long-term climate impact of rereleased CO_2 over time. Composite carbon storage offsets through a combination of different carbon storage types were studied (Deliverable 2.2. and 2.4). The primary policy recommendation was that **dynamic risk and liability mechanisms can offer an effective way to facilitate the liability of stored carbon and transition to lower risk storage over time,** but need to be robustly designed and implemented.

NEGEM organized two workshops on the CDR commercialization from the European perspective, first one on the Consideration of greenhouse gas removals in the Emission Trading Systems (ETS) (April 2022), and another on the Financing mechanisms for NETPs (February 2024). The workshop on the role of CDR in emission trading systems provided a wide discussion on the topic without providing a clear consensus. It concluded that **a successful CDR deployment will need a broader suite of policies than just ETS inclusion**. However, ETS inclusion could, in time, offer deployment support, and create a supportive business environment (e.g. on monitoring, reporting and verification, accounting standards, environmental and social standards) although many questions remain as to how this could be achieved without compromising environmental integrity. More work is needed to understand and quantify the equivalence of different carbon removal approaches, and one solution could be to focus on like-for-like links (i.e. nature-based CDR offsets for land-use emissions; geological CDR offsets for fossil fuel emissions). The timing is also important; **For a successful link between CDR and ETS, the CDR market would need to be ready for ETS and the ETS would need to be ready for CDR**. The readiness of CDR requires, among other things, a sufficiently small differential between CDR costs and ETS prices, and a sufficient track record of CDR in terms of storing carbon safely and permanently, as well as the ability to reliably quantify and monitor carbon flows and storage reversals. The readiness of ETS relates to the resilience of regulatory arrangements, cap setting processes and market stability mechanisms to absorb substantial volumes of CDR without deterring emission reductions. (see Fankhauser et al. 2022)

The second workshop on “Long-term financing mechanisms for implementing and operationalizing the EU CRCF” (see Deliverable 9.3) gathered academic, technical and political experts to discuss on potential mechanisms to implement the EU Carbon removals certification framework (CRCF), the associated benefits and pitfalls, and pave a way forward on financing options and relevant public policy. Also here, discussion seemed to produce more questions than to find concrete solutions. However, the CRCF was viewed as the first step in building a CDR “taxonomy”. CDR was mentioned several times as a public good, the financing of which remains still an open question. The collective themes from the discussion were (listed in Deliverable 9.3):

- **Working with uncertainty**: Financing tools need to accommodate uncertainty surrounding success and failure in projects, and the physical uncertainty in quantification of carbon flows or ecosystem co-benefits within each project.
- **Learning-by-doing**: There is a need for action now despite a lot of uncertainty surrounding expensive technologies, in particular for novel carbon removal activities. Flexibility for financing mechanisms is needed to absorb the risk of project failure, adapt to new approaches and use failure as a learning tool to reduce the uncertainty in the technologies and build confidence in investment.
- **De-risking:** Financing tools should provide long-term stability, acknowledge and reduce the risk for long-term investments, instilling trust and confidence in upscaling removals.
- **Purpose:** Clarification is needed on why carbon flows need to be quantified and what certifications will be for. This is an important element to consider in the development of methodologies.
- **Complexity**: Financing tools need to accommodate a diverse range of complex activities that do not happen in isolation. All options need to be considered: adaptation of or embedding into existing trade/industrial policy, development of new funding pillars, broad or targeted funding.

7 Final words

NEGEM results show that a multidisciplinary approach is essential to understand the wider systemic impacts of CDR, to guide in their sustainable implementation, and to guarantee their acceptability among stakeholders and citizens. NEGEM consortium has accomplished a significant amount of research on different negative emission technologies and practices over the four years of project work. Many of the results are being prepared for publication as peer-reviewed academic journal articles. These results are a valuable source for the EU policymakers, researchers, and other stakeholders for the years to come. The authors want to thank all the NEGEM partners for their excellent work and commitment to the project!

In February 2024, the EU Commission's Communication and Impact Assessment on the EU's 2040 climate target illustrated a need for industrial carbon removals of around 50-70 Mt/year, and for LULUCF net removals of 320 Mt/year by 2040. This sets a clear role for the CDR in the upcoming EU policy. In February 2024, also the EU Carbon Removals Certification Framework (CRCF) merged from the trilogue discussions. It is still unclear how the CRCF framework will be used in the overall EU climate policy framework, with the finer details relevant for application such as refining definitions and setting standards for methodologies still to be determined in CDR Expert Group. In addition, a revision of EU ETS will take place in 2026, with role of CDR to be clarified. NEGEM findings and recommendation can be used to guide and shape the upcoming European CDR policies and have already been exploited e.g., by the Commission CDR expert group.

The NEGEM vision was created to pave the way towards responsible deployment of Negative Emission Technologies and Practices (Deliverable 8.3) and summarises the key conclusions.

NEGEM vision

To meet the climate goals of the Paris Agreement, drastic, immediate, and sustained reductions in greenhouse gas emissions are needed. To keep the warming at 1.5-2 °C, carbon dioxide removal (CDR) technologies and practices are needed but should only be relied on as a supplementary measure to emission reductions. The smaller the residual emissions, the lower the demand for CDR.

Technical solutions with storage at geological time scale provide permanent CDR, which is needed to reach climate neutrality. Nature-based CDR methods provide synergies between climate change mitigation and international targets for nature restoration and broader sustainable development goals. To respond to environmental and social challenges, a portfolio of CDR methods is needed to balance the impacts. A large portfolio of CDR methods together with global co-operation will enable cost-effective mitigation pathways. International co-operation allows the usage of CO_2 transportation and geological storage facilities in an efficient manner.

Responsible CDR implementation, balancing between the targets for climate change mitigation and protection of other planetary boundaries, is guided by science-based evidence, and clear and transparent policy and monitoring frameworks. Continuous interaction between different stakeholders, as well as a system perspective in regulation design, will guarantee a social licence to operate for CDR methods. A growing number of regions, countries, businesses, and other stakeholders need to form CDR visions within broader visions for climate neutrality, while enabling continuous R&D efforts and establishing commercialisation mechanisms for CDR methods. Industrial level deployment of CDR methods should start in the 2030's to provide CDR at gigaton scale in 2050. However, dependence on CDR should be kept to a minimum. As the amount of permanent carbon removals is likely a scarce resource, counterbalancing of residual emissions should be achieved at a system-level.

For preparing this report, the following deliverables have been taken into consideration:

D#	Deliverable title	Lead Beneficiary	Type	Dissemination level	Due date (in MM)
D1.1	Justification of NETPs chosen for the NEGEM project	ETH	R	CO	6
D1.2	Comprehensive sustainability assessment of terrestrial biodiversity NETPs	ETH	R	PU	12
D1.3	Comprehensive sustainability assessment of marine NETPs	NIVA	R	PU	16
D1.4	Comprehensive sustainability assessment of Bio-CCS NETPs	VTT	R	PU	12
D1.5	Comprehensive sustainability assessment of geoengineering and other NETPs	ICL	R	PU	24
D2.1	Quantitative survey of commercialisation mechanisms	UOXF	R	PU	18
D2.2	Interactions and trade-offs between nature-based and engineered climate change solutions	UOXF	R	PU	17
D2.3	Assessment of incentives for non-CO2 NETPs, relative permanence of NETPs and their implications	UOXF	R	PU	24.5
D2.4	Classification of NETPs against appropriate commercialisation instruments, including options for trading multiple technologies under a single instrument such as the ETS	UOXF	R	PU	36
D3.1	Upgraded LPJmL5 version	PIK	R	PU	12
D3.2	Report on Global NETP biogeochemical potential and impact analysis constrained by interacting planetary boundaries	PIK	R	PU	24
D3.3	Global assessment of NETP impacts utilising concepts of biosphere integrity	PIK	R	PU	36

D3.4	Report on effects of climate extremes on NETP potentials and impacts, also considering potentials of management improvements	PIK	R	PU	46
D3.5	Literature assessment of ocean-based NETPs regarding potentials, impacts and trade-offs	NIVA	R	PU	24
D3.6	Case study on impacts of large-scale re-/afforestation on ecosystem services in Nordic regions	NIVA	R	PU	24
D3.7	Global impacts of NETP potentials on food security and freshwater availability, scenario analysis of options and management choices	PIK	R	PU	36
D3.8	Report on comparative life-cycle sustainability assessment of NETPs for impacts on human health, ecological functions and resources	ETH	R	PU	24
D3.9	Report on assessment of impacts on key non-renewable resource chains: case study on global demand, supply and trade-offs for selected metals and minerals in global mitigation pathways	VTT	R	PU	25
D3.10	Report on synoptic assessment of global theoretical NETP potentials	PIK	R	PU	41
D4.1	NETP database	ICL	OTHER	PU	9
D4.3	Member State Targets	ICL	R	PU	17
D4.5	Member State specific pathway for NETP deployment	ICL	R	PU	36
D5.1	NETP analogues and Social License to Operate	UCAM	R	PU	18
D5.2	Stakeholder views on the business case for NETPs	UCAM	R	PU	24
D5.3	Stakeholder views on NETP governance	UCAM	R	PU	18
D5.4	Final Report on Expert Elicitation for NETPs	UCAM	R	PU	36

D5.5	Public awareness and assessments of NETPs: Results of a series of cross-national public surveys	RUG	R	PU	42
D5.6	Final Report of Stakeholder Survey: Solving NETPs Trade-Offs	UCAM	R	PU	46
D6.1	How do NETPs fit in existing climate frameworks?	CMW	R	PU	39
D6.2	Principles for carbon negative accounting	CMW	R	PU	18
D6.3	Global governance of NETPs - global supply chains and coherent accounting	BELLONA	R	PU	30
D6.4	Carbon negative handbook	BELLONA	R	PU	46
D6.5	Who should use NETPs? Managing expectations for NETP demand: Considerations for allocating carbon dioxide removals	BELLONA	R	PU	42
D7.2	Extended MONET-EU	ICL	R	PU	17
D7.3	MONET-EU-JEDI tool	ICL	R	PU	24
D7.4	Value of intra-member state collaboration	ICL	R	PU	46
D8.1	Stocktaking of scenarios with negative emission technologies and practises. Documentation of the vision making process and initial NEGEM vision	VTT	R	PU	8
D8.2	Quantitative assessments of NEGEM scenarios with TIMES-VTT	VTT	R	PU	41
D8.3	Final NEGEM medium-to-long—term vision	VTT	R	PU	44
D9.3	Full-day workshop on financing tools for NETPs	BELLONA	R	PU	45
	NEGEM Science-Policy Brief	NEGEM	R	PU	https://www.negemproject.eu/wp-content/uploads/2023/08/NEGEM-

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Annex 1. Data from NEGEM modelling studies

Data from NEGEM modelling studies, illustrated in Figure 10 and Figure 11

Table A1. NETP supply/potential in NEGEM modelling studies in comparison to potentials by IPCC AR6 WG3 report Table TS7, and IAMC 1.5°C Scenarios Database by IIASA. Table is from D8.3 on NEGEM final vision (see the deliverable for more discussion on values).

NETP	Technology specification	Global	Global	Europe	Europe	Applied methodology and notes	Deliverable
		Supply or potential [$GtCO_2/y$]	**Cumulative supply or potential [$GtCO_2$]**	**Supply or potential [$GtCO_2/y$]**	**Cumulative supply or potential [$GtCO_2$]**		
IPCC BECCS potential		0.5-11					IPCC AR6 WG3 Table TS7
Median value from IAMC 1.5C scenarios database for BECCS		**2050:** 3.3 **2100:** 10.8				(median of 266 scenarios)	D8.1, VTT
NEGEM BECCS	Biomass: Bioenergy crops Technologies: BECCS from power / liquid fuel production	1-9.7 (30y average in 2036-2065 climate)				Supply based results from LPJmL-NEGEM land use modelling. For high-end potentials, land is released from pasture land to bioenergy crops production due to a 100% global dietary change,	D3.7, PIK

						assuming minimal management intensity.	
	Biomass: Current bioenergy, residues, bioenergy crops, point-source biogenic CO_2 emission Technologies: BECCS from power and heat, bioliquids, and biogases (including hydrogen) production	**2050:** 2.1-3.9 **2080:** 3.3-6.7 **2100:** 3.4-6.8	**2025-2100:** 185-360	**EU-31** **2050:** 0.3-0.4	**EU-31** **2025-2065:** 10 (averaged over three scenarios)	Cost-optimised results from TIMES-VTT NEGEM mitigation scenarios to reach 1.5°C target with a large portfolio of NETPs. Full global energy system modelled. Bioenergy crops availability for BECCS is based on D3.7 results. Scenarios for EU-31 based on the Pan-European TIMES model	D8.2, VTT
	Biomass: Bioenergy crops on marginal land, residues Technologies: BECCS for power production	**2050:** ~2 **2100:** 3.2-4	**2020-2100:** 186			Cost-optimised results by MONET mitigation scenarios to reach 1.5°C target, with BECCS, Afforestation and DACCS included.	Chiquier et al. 2022 (ICL)
	Biomass: Bioenergy crops on marginal land, residues Technologies: BECCS for power production				**EU 28** **2020-2100:** 59	Cost-optimised results by MONET model with BECCS, Afforestation, DACCS and EW, to reach a burden sharing target of 81 $GtCO_2$ removal by EU-28 by 2100.	D4.5, ICL
IPCC DACCS		5-40					IPCC AR6 WG3 Table TS7
Median value from IAMC 1.5C		**2050:** 0.05				(median of 8 scenarios)	D8.1, VTT

scenarios database for DACCS		**2100:** 6.4					
NEGEM DACCS	DACCS (High-temperature liquid sorbent processes)	**2050:** 0.6-1.1 **2080:** 2.2-5.1 **2100:** 1.1-5.8	**2025-2100:** 50-220	**2050:** ~0.2-0.4	**EU-31** **2025-2065:** 10 (averaged over three scenarios)	Cost-optimised results from TIMES-VTT and Pan-European TIMES NEGEM scenarios Cost of DACCS drops to around 200 €/tCO_2 in high-end potentials and stays around 350 €/tCO_2 for low-end potentials.	D8.2, VTT
	DACCS (High-temperature liquid sorbent processes, Low-temperature solid sorbent process)	**2100:** 0-0.7				Cost-optimised results by MONET. The costs of DACCS would need to be below 100$/t$CO_2$ to be implemented by the model	Chiquier et al. 2022 (ICL)
	DACCS (High-temperature liquid sorbent processes, Low-temperature solid sorbent process)				**EU-28** **2020-2100:** 0	Cost-optimised results by MONET. Total cost of DACCS is estimated to be $400 – 600/t$CO_2$ captured. Thus, it is not deployed in the results.	D4.5, ICL

IPCC Biochar		0.3-6.6					IPCC AR6 WG3 Table TS7
NEGEM Biochar		0.0-2.0				Land- and calorie- neutral biochar. No residual biomass used for biochar.	D3.10, PIK
		2050: 0.2-1.9 **2080:** 0.3-1.7 **2100:** 0.1-1.2	**2025-2100:** 15-115	**2050:** ~0-0.05	**EU-31 2025-2065:** 1 (averaged over three scenarios)	Cost-optimised results from TIMES-VTT and Pan-European TIMES NEGEM scenarios. Potentials based on Land- and calorie- neutral biochar (see D3.10). No residual biomass used for biochar.	D8.2, VTT
					EU-28 2020-2100: 4	Cost-optimised results by MONET.	D4.5, ICL
IPCC Re-/ af-forestation		0.5-10					IPCC AR6 WG3 Table TS7
Median value from IAMC 1.5C scenarios database for Re-/ af-forestation		**2050:** 3.8 **2100:** 4.7				(median of 51 scenarios)	D8.1, VTT
NEGEM Re-/ af-forestation	Only reforestation	1.6-4.3 (30y average in 2036-2065 climate)					D3.10, PIK

	Re-/afforestation	**2050:** 3 **2080:** 3.6-4.4 **2100:** 2.2-2.7	**2025-2100:** 200-230	**2050:** ~0.2-0.3	**EU-31 2025-2065:** 6 (averaged over three scenarios)	Cost-optimised results from TIMES-VTT and Pan-European TIMES NEGEM scenarios	D8.2, VTT
	Re-/afforestation	**2050:** ~0,5 **2090:** 1-1.5 **2100:** ~0.5-1	**2020-2100:** 65			Cost-optimised results by MONET.	Chiquier et al. 2022
	Re-/afforestation				**EU-28 2020-2100:** 16	Cost-optimised results by MONET.	D4.5, ICL
IPCC Soil carbon sequestration		0.6-9.3					IPCC AR6 WG3 Table TS7
Median value from IAMC 1.5C scenarios database for Soil carbon/biochar		**2050:** 3.6 **2100:** 3.5				(1 scenario)	D8.1, VTT

NEGEM Soil carbon sequestration		**2050:** 2-2.9 **2080:** 2-2.9 **2100:** 1.1-2.9	**2025-2100:** 130-190	**2050:** ~0.1-0.2	**EU-31 2025-2065:** 4 (averaged over three scenarios)	Cost-optimised results from TIMES-VTT and Pan-European TIMES NEGEM scenarios. SCS data from literature.	D8.2, VTT
IPCC Enhanced weathering		2-4					IPCC AR6 WG3 Table TS7
Median value from IAMC 1.5C scenarios database for Enhanced weathering		**2050:** 1.2 **2100:** 2.5				(1 scenario)	D8.1, VTT
NEGEM Enhanced weathering		**2050:** 0.7-1.5 **2080:** 0.7-1.5 **2100:** 0.8-1.5	**2025-2100:** 45-100	**2050:** ~0.1-0.2	**EU-31 2025-2065:** 4 (averaged over three scenarios by 2065)	Cost-optimised results from TIMES-VTT and Pan-European TIMES NEGEM scenarios. EW data from literature. Energy demand included.	D8.2, VTT
					EU-28 2020-2100: 2	Cost-optimised results by MONET.	D4.5, ICL

Annex 2. Sources of the literature review for NETP costs

Table A2. Sources of the literature review for NETP costs in Figure 7.

Technology		Estimates from literature ($/tCO₂)	Estimates from literature converted to € (€/tCO₂)[a]	Mean of all cost estimates ($/tCO₂)	Mean of all cost estimates converted to € (€/tCO₂)
DACCS					
	LTSS-DACCS	101,4-225,5[1(b,c]	84-199[d,e]	268,89	248
		170-730[2]	157-672		
		193,2[3]	178		
	HTLS-DACCS	111,1-250,3[1(b,c]	93-222[d,e]	217,17	200
		100-440[2]	92-405		
		200,8[3]	185		
Enhanced weathering					
		50-200[4]	46-184	166,83	154
		157-194[5]	145-179		
		max. 200[6]	max. 184		
BECCS					
	Gasification to H_2	28,7-63,9[3]	26-59	45,65	42
		30-60[4]	28-55		
	FT Gasification	20-40[4]	18-37	41,5	38
		30-76[7]	28-70		
	Combustion	88-288[4]	81-265	126,65	117
		46,6-84[3]	43-77		
Afforestation/Reforestation					
		5,0-50[4]	4,6-46	9,63	9
		-40-10[6]	-37-9		
		16,4[3]	15		
Biochar					
		30-120[4]	28-110	26,23	24
		(-70)-(-60)[6]	(-64)-(-55)		
		4,4-133[3]	4,1-122		
Soil Carbon Sequestration					
		0-100[4]	0-92	7,5	7
		-45 - 100[12]	-41-92		
		-90 - (-20) [6]	-83-(-18)		

1) (Lux et al., 2023) 2) (Young et al., 2023) 3) (Baker et al., 2020) 4) (Fuss et al., 2018) 5) (Beerling et al., 2020) 6) (Hepburn et al., 2019) 7) (Shahbaz et al., 2021) 8) (Roe et al., 2019) 9) (Cobo et al., 2023) 10) (Hanssen et al., 2020) 11) (Austin et al., 2020) 12) (Smith et al. 2023)

a) Converted to € from $ with exchange rate 0.9206 (2024 average) b) Originally presented in € c) 10$/tCO₂ storage cost added d) Not converted, originally in € e) The storage cost added in $, not presented in this column

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