NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Final NEGEM medium-to-long-term vision

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Executive Summary

The IPCC climate change mitigation scenarios (IPCC AR6, WG3) show that to reach the targets of the Paris Agreement to mitigate global warming to 1.5-2 °C, global carbon neutrality must be reached mid-century. Achieving this target requires rapid and drastic reductions in greenhouse gas emissions in all sectors, as well as serious measures to increase carbon sinks in the land use sector. In addition, negative emission technologies and practices (NETPs) will be needed as a supplementary measure to enable carbon dioxide removal (CDR) from atmosphere.

The policies and regulations that guide the use of NETPs are currently discussed and are taking shape globally and in the European Union (EU). For example, the role of NETPs in the EU 2040 climate target setting is one of the burning questions. Thus, there is a need for **a clear vision of how and to what extent to use NETPs in a sustainable and responsible way to supplement drastic emission reductions.** The NEGEM project has been running since June 2020 and has published a significant amount of multidisciplinary scientific results on the responsible use of NETPs. On the basis of these results, NEGEM brings its contribution to this urgent call for a vision formulation for NETPs.

This report presents the **final NEGEM vision**, which is based on the initial vision in D8.1 (January 2021), its update in D8.7 (November 2022), and the NEGEM results available up to January 2024. It has been developed in co-creation between internal and external stakeholders in two NEGEM vision workshops (December 2020, November 2023). The vision aims to provide insight for policymakers, industrial stakeholders, and scientific community.

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 stakeholders or individuals. For these reasons, this report presents the quantitative estimates on responsible NETPs deployment as ranges, based on NEGEM modelling studies performed with different methods and assumptions. More details on these 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.

A brief and an extensive version of the vision statement have been created to allow exploitation in different formats and for different audiences. The brief version of the final NEGEM vision is formulated as follows:

NEGEM vision, brief version

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 transport 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 enable 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 in order to provide CDR at 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 broader system-level, rather than at country or corporate level.

Key policy-relevant messages from the extensive version of NEGEM vision:

- **Separate policy targets** for 1) greenhouse gas reductions, 2) land use sector (LULUCF), and 3) technical CDR that leads to permanent storage are needed to guarantee balanced contributions for climate change mitigation.
- An **equitable and fair allocation of the CDR targets** between countries and regions is needed.
- The carbon dioxide (CO_2) storage time and vulnerability to intended and/or unintended release of CO_2 are essential. **Permanent CDR** is required to achieve climate neutrality.
- A cost-efficient implementation of CDR is enabled by a large **portfolio of CDR methods** and by international cooperation on CDR regulation, and CO_2 storage and transport systems.
- 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.
- **Technical solutions** such as bioenergy combined with carbon capture and storage (BECCS) and direct air capture and storage (DACCS) start to scale up from 2030-2040, their highest level of deployment likely taking place in the 2060-2070s.
- **Sustainable BECCS** applications could be provided by use of **residual biomass feedstock** and capture of **point source emissions of biogenic CO_2** e.g. from biorefineries and pulp- and paper industry. The BECCS technologies vary from combined heat and power production, to bioliquids and biogases, instead of using BECCS mostly in power plants.
- **Monitoring, verification, and dynamic risk and liability mechanisms are needed** to ensure CO_2 storage.

NEGEM

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Introduction

Task 8.2 of the NEGEM project aims at creating a medium-to-long term *vision for responsible deployment of NETPs* globally and for the EU. The NEGEM vision aims at being applicable to policymakers, industrial stakeholders, and the scientific community. Thus, the vision can support European and global policymaking and strategy development when planning for sustainable and responsible use of negative emission technologies and practices (NETPs).

Based on the NEGEM project plan, the vision is formulated in three stages: 1) a preliminary vision was created in the beginning of the project to guide the work during the project, 2) an update on the vision work was published at the middle of the project, and 3) the final vision is formulated in this report.

As a guideline for the Vision work, the question 'Could *NETPs be a responsible and rational option globally and for the EU?*' is formulated in the project plan. At the beginning of the vision-building work, it was concluded that there are many definitions and different understandings of the term "vision". In general, the work in NEGEM is based on a definition of **a vision that represents a desirable outcome or goal**. It was recognised that the vision for the role of NETPs may differ according to values of individuals or organisations they present, or differences in geographical or stakeholder positions, among other differences. The NEGEM vision has a **European perspective, but the context is global**. Medium-to-long term means the years **2030-2040, and 2050**, respectively.

The initial vision statement, documented in Deliverable 8.1 (January 2021), was based on the discussions between the NEGEM consortium, on the results of Task 8.1 exploring the role of NETPs in alternative climate change mitigation pathways, and on the results of the 1st vision workshop held in December 2020, with external stakeholders (more than 80 participants), and a preceding questionnaire for the participants. The initial vision guided the NEGEM work done during the first stages of the project by concretising the existing expectation and knowledge by the policymakers, stakeholders, and researchers. Several goals were identified for the NEGEM vision in D8.1, such as broad acceptability among stakeholders, inclusion of concrete evidence-based information on the role of NETPs, and environmental sustainability, being instrumental for European policymaking and providing significant contribution in European climate change mitigation efforts.

An update on the vision work and the mid-stage version of the vision were presented in D8.7 (November 2022). This work was done in parallel to the definition of NEGEM storylines and scenarios for global and European scenario modelling using TIMES-VTT and pan-European TIMES models, respectively. The Foresight method for co-creation, namely Futures Wheel (Glenn 2003), was used for creation of the storylines to widely capture possible futures with NETPs. Furthermore, the NEGEM results ready at that time were explored to provide evidence basis for the storylines and the vision. Here, the core value was initially to identify the research-based elements based on research for the vision and the needs for synthesis and harmonisation of individual results to achieve a coherent vision. NEGEM scenarios based on the storylines further concretised the different roles of NETPs quantitatively for the subsequent development of the vision.

The **final NEGEM vision (herein NEGEM vision**) aims at presenting a realistic contribution of NETPs towards reaching the climate goals of the Paris Agreement while respecting planetary boundaries. It is based on NEGEM results available up to January 2024, and thus on the vast evidence bases of the multidisciplinary research work of the NEGEM consortium during the last three and a half years. The final vision development process included internal and external co-creation with a climax of the second vision

workshop organised in November 2023 (over 50 participants). The workshop aimed to incorporate the views of different stakeholders to finalise the vision. The draft version of the final vision and the applicable results of the NEGEM scenario work were presented to the participants. The workshop was designed to gather external stakeholders to provide comments on the vision and its validity. Another goal of the workshop was to increase mutual understanding and build consensus on a medium-to-long term vision.

The core value of the final NEGEM vision is to summarize **NEGEM research results in an exploitable format** by focusing the vision on the findings of the project.

This report is organised as follows. Chapter 1 presents the process of creating the NEGEM vision and the key inputs from the 2nd NEGEM Vision workshop. Chapter 2 summarizes recent NEGEM results and key conclusions applicable to concretise the vision. Chapter 3 presents the final NEGEM vision and its brief version.

1 Process of creating the NEGEM vision

Figure 1 shows the process of developing NEGEM Vision throughout the project. The main milestones have been divided into *Initial NEGEM Vision*, *Updated NEGEM Vision* and *Final NEGEM Vision*. Each of the steps includes the preparation of a deliverable. Noteworthy, external inputs from literature and NEGEM inputs based on results of the project, have played an important role in developing final version of the vision.

The vision process as a whole "aims to create a medium-to-long term vision concluding whether NETPs could be a responsible and rational option globally and for the EU" to reach climate targets.

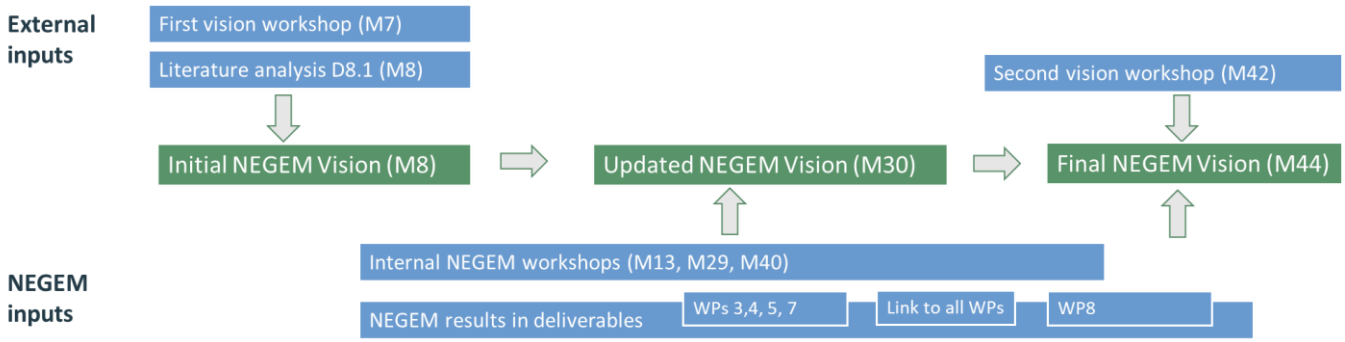

Figure 1 Process of the NEGEM vision work (updated November 2023). The final vision reported in this deliverable is in the stage of M44. It builds on earlier versions and, more importantly, messages from close to complete NEGEM results. Another key cornerstone in completing the Final NEGEM Vision was the second vision workshop held in M42 (November 28, 2023), which included feedback from external stakeholders.

After the publication of the updated NEGEM vision in November 2022 (M30, D8.7), several NEGEM outputs were finalized during M31-M44 that were applied to further develop the vision. The key outcomes of this period include:

- NEGEM science-policy brief summarising common messages of the project for EU policymaking on 2040 climate targets based on NEGEM results as of June 2023.
- Quantitative assessments of NEGEM scenarios with TIMES-VTT (D8.2) were finalised in October 2023.

- Results of different NEGEM WPs (esp. WP3, WP5, WP7) on **barriers and boundary conditions** for the WP8 NEGEM scenario assessments. The results of the WP8 scenario assessments, in turn, shed light on the **holistic picture of the role of NETPs**.
- Internal NEGEM result meeting on September 22nd 2023, to feed the scenario and storyline development for the NEGEM pathways and gathering comments on the quantitative results. The views were considered in the finalisation of the multiple quantitative scenario assessments for the internal validity of the results.
- The 2nd vision workshop with external stakeholders was arranged on November 28, 2023. The workshop was designed to incorporate external views to validate the vision, possibly leading to rewording or smaller to larger fine-tuning of the presented vision.

The final vision and the vision-making process are documented in this deliverable (D8.3). In the context of the NEGEM vision, the purpose of this deliverable (D8.3) is to concretise the vision with close to final NEGEM research results in exploitable formats.

1.1 External inputs for the final vision based on the 2nd Vision workshop

A preliminary vision for NEGEM was produced as an outcome of the 1st vision workshop organised on December 18th, 2020. The 1st Vision workshop aimed at creating of a vision shared with stakeholders. The target of the 2nd NEGEM Vision workshop organised on November 28th, 2023, was set in the project plan to serve validation and approval of vision. Policymakers, industry, NGOs, academia, research and other experts were targeted as participating stakeholder groups to work on the final vision in order to gather a wide set of viewpoints for the vision.

The 2nd NEGEM vision workshop was designed to present and discussing the vision on realistic and responsible potentials for negative emission technologies and practices globally and in Europe. Specifically, the content of the 2nd NEGEM vision workshop highly based on the results of NEGEM project achieved in the project run for three and a half years. As concluding the series of vision workshops, the 2nd vision workshop consisted of four parts, allowing the participants to be informed and co-create on the following topics:

1. Hear the prevalent developments for carbon dioxide removals in the European Union
2. Demonstrate the results of the NEGEM scenarios on realistic carbon removal potentials by NETPs globally and in Europe
3. Present the vision for deployment of NETPs
4. Discuss the implementation of NETPs in existing climate frameworks

In this section, organization of the workshop is documented. In addition, a summary of the discussions, comments and results of the on-line polls designed exploitable for finalising the vision, is presented.

1.1.1 Organisation of the workshop

The 2nd NEGEM Vision workshop was organised as a virtual (Zoom) event on November 28, 2023, 14-16 CET. The second workshop was organised by VTT and gathered more than 50 online participants, and was moderated by Kati Koponen, NEGEM coordinator. Participation in the workshop was open to all; however, experts in different stakeholder groups were particularly targeted to receive broad-based feedback. In addition to NEGEM partners and the external advisory board, invitations were sent to relevant external stakeholder groups, including social media and the distribution of the NEGEM newsletter in collaboration

with NEGEM dissemination partner ETA Florence. Altogether 72 people registered for the event. The geographical coverage was predominantly European, however, there were individual stakeholders also from other continents. Around half of the registered people were classified as research, and a quarter as business, while the rest were divided between policy and public, industrial and NGO stakeholders.

The external registered participants received preliminary material on November 21st (one week before the event), including a draft version of the final NEGEM vision put up by the organising team based on the NEGEM results in use (see Appendix 1). Participants were also briefed about the workshop structure to present the storylines and results of the NEGEM 1.5°C mitigation scenarios, including a large portfolio of NETPs as concrete background information for the vision. A complete report on these published some weeks earlier (D8.2) was provided for participants. Furthermore, in the preliminary material, a target of the workshop was an interactive discussion with questions and polls for the participants based on the presentation of the draft of the final NEGEM vision, was highlighted.

Based on the draft final version of the vision and the applicable NEGEM results presented to the participants, the workshop was designed to gather external stakeholders to comment on the vision and its validity. Building on these guidelines, the workshop was structured around four presentations (Table 1).

Table 1. Agenda of the second NEGEM vision workshop arranged on November 28th, 2023.

14:00 (CET)	**Welcoming words**	Kati Koponen, NEGEM coordinator
14:05	**Carbon dioxide removals – current developments in Europe**	Christian Holzleitner, EC DG Clima
14:20	**NEGEM scenarios on realistic potential for NETPs globally and in Europe**	Kati Koponen & Antti Lehtilä, VTT
14:55	**Presentation of the NEGEM Vision**	Tiina Koljonen, VTT
15:20	**Discussion on the NEGEM vision**	Moderator: Kati Koponen
15:35	**Implementation gap: how NETPs fit existing climate frameworks**	Fabiola de Simone, Carbon Market Watch
15:55	**Closing of the event**	Kati Koponen, NEGEM coordinator

In addition to the presentations of the vision and NEGEM scenarios as its backbone by VTT, the agenda included presentations from Christian Holzleitner from DG Clima of the European Commission, and Fabiola De Simone from NEGEM partner Carbon Market Watch. The purpose of these presentations was to set the vision work in a broader policy context of CDRs being prepared in the EU, and also to reflect the vision with the implementation gaps of NETPs in existing climate frameworks reviewed in selected countries. The latter was built on a recently published NEGEM deliverable (D6.1). All materials and recording of the event are available on the NEGEM website (https://www.negemproject.eu/news/2nd-negem-vision-workshop/).

1.1.2 Viewpoints on the role of NETPs based on NEGEM scenarios and realistic potentials

Reflections on the NEGEM scenario results

As evidence basis for the NEGEM vision, results and background of the NEGEM scenarios and realistic potentials on NETPs based on the results of the project were presented. The presentation raised some detailed questions asked by the workshop participants, dealing with the following topics:

- Soil carbon sequestration potential, bioenergy crop assumptions
- Peak of DACCS in 2070 in the results – the reasons behind?

- Pros and cons of treating the technology options in the same market
- Economic optimum between deep reductions in GHG and deployment of NETPs
- Allocation of NETPs outside Europe and its financial implications
- Existing vs additional biomass flows use for BECCS

The above points provide an exploitable checklist for vision documentation and communications of the NEGEM vision, scenarios, and other results.

Risks and uncertainties

After inspired by the presentation on NEGEM scenarios and realistic potentials on NETPs, risks and uncertainties related to application of (i) technology-based NETPs, Figure 2, left, and (ii) nature-based NETPs, right, were asked from participants with on-line polls.

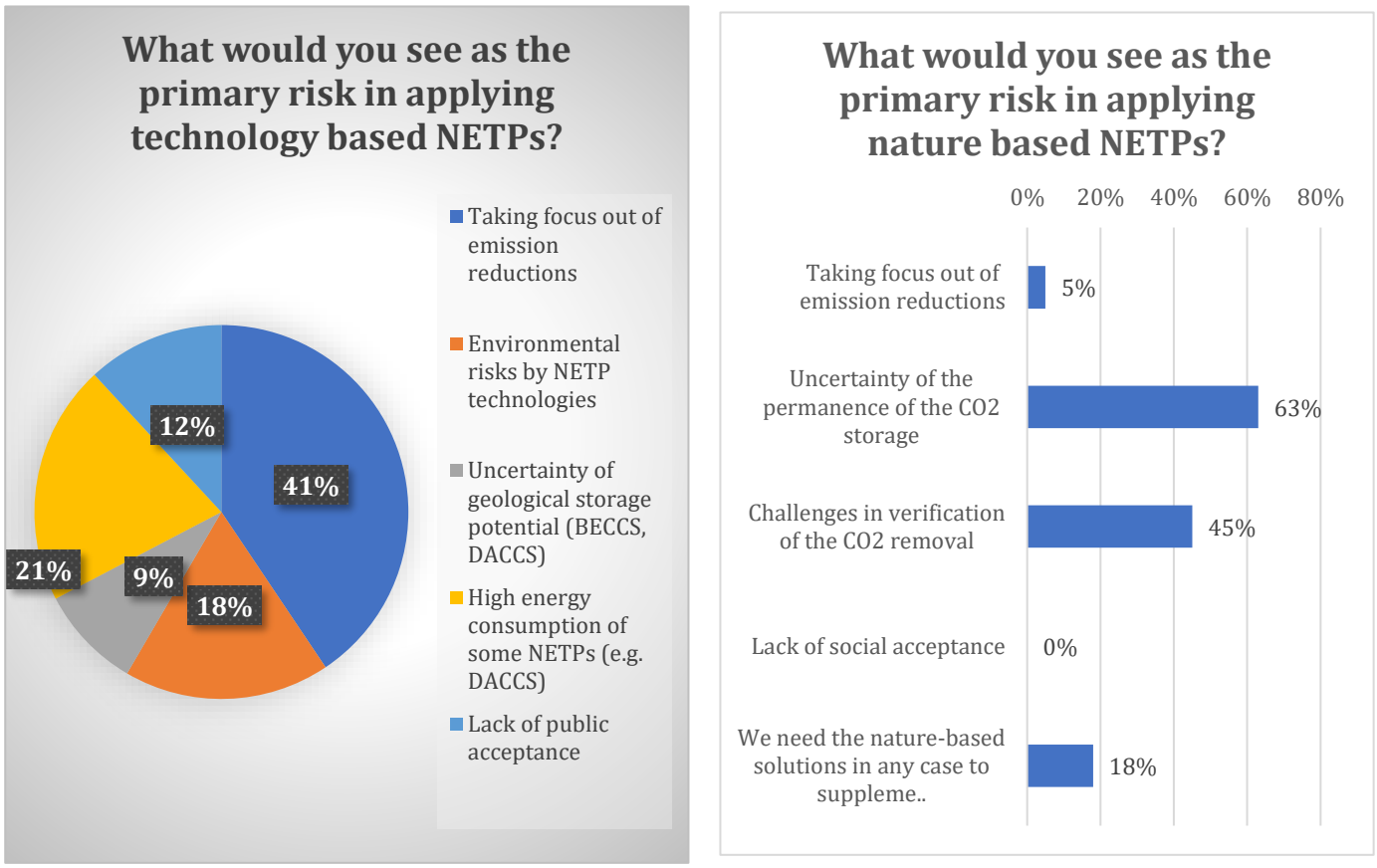

Figure 2. On-line poll results on the risks of technology-based NETPs (left) and nature based risks (right, multiple choice allowed[1]).

With technology-based NETPs, the risk of taking the focus out of emission reductions was considered the primary by 41% of the respondents, followed by the high energy consumption of some NETPs (21%) and the environmental risks of NETPs (18%). Uncertainty of permanence of the CO_2 storage and challenges in verification of the CO_2 removal appear as the primary risks based of nature-based NETPs on the views of workshop participants (multiple choice question). The risk of applying them to take the focus out of

[1] A multiple-choice version of the question was launched by the moderator by accident and should have been in the same format as the poll for technology based NETPs.

emission reductions was not seen as high as with the technological NETPs by the participants. Also, there is a clear signal in the social acceptance not considered a primary risk with nature-based solutions.

In the chat, the consistency of the risk of taking focus out of emission reduction could be more relevant for technology-based NETPs was questioned, as the nature-based NETPs are generally low-cost options. However, it was recognized that the potential of NBS (Nature-based solutions) is limited, so the other options come into play anyway. Furthermore, there was a view that the permanence and monitoring issues with nature-based solutions could limit their usability, suggesting that the priority hierarchy is correct.

Key insights for the vision

The risk of NETPs taking focus out of emission reductions is addressed in the NEGEM vision by stating the need for drastic emission reduction and the supplementary role of NETPs vision (see Chapter 3). In addition, the vision highlights the need for separate policy targets for emission reductions, land use sector, and for CDR. It clearly states the need for permanent CDR to reach carbon neutrality. Social acceptability should be ensured by continuous interaction and system approach in regulatory planning.

After the workshop, the need for monitoring, verification, and dynamic risk and liability mechanisms to ensure the liability of CO_2 storage was added to the extended version of the vision.

1.1.3 Viewpoints on the NEGEM vision

After presenting the draft NEGEM vision, the participants were asked the following questions about barriers and policy instruments (Figure 3).

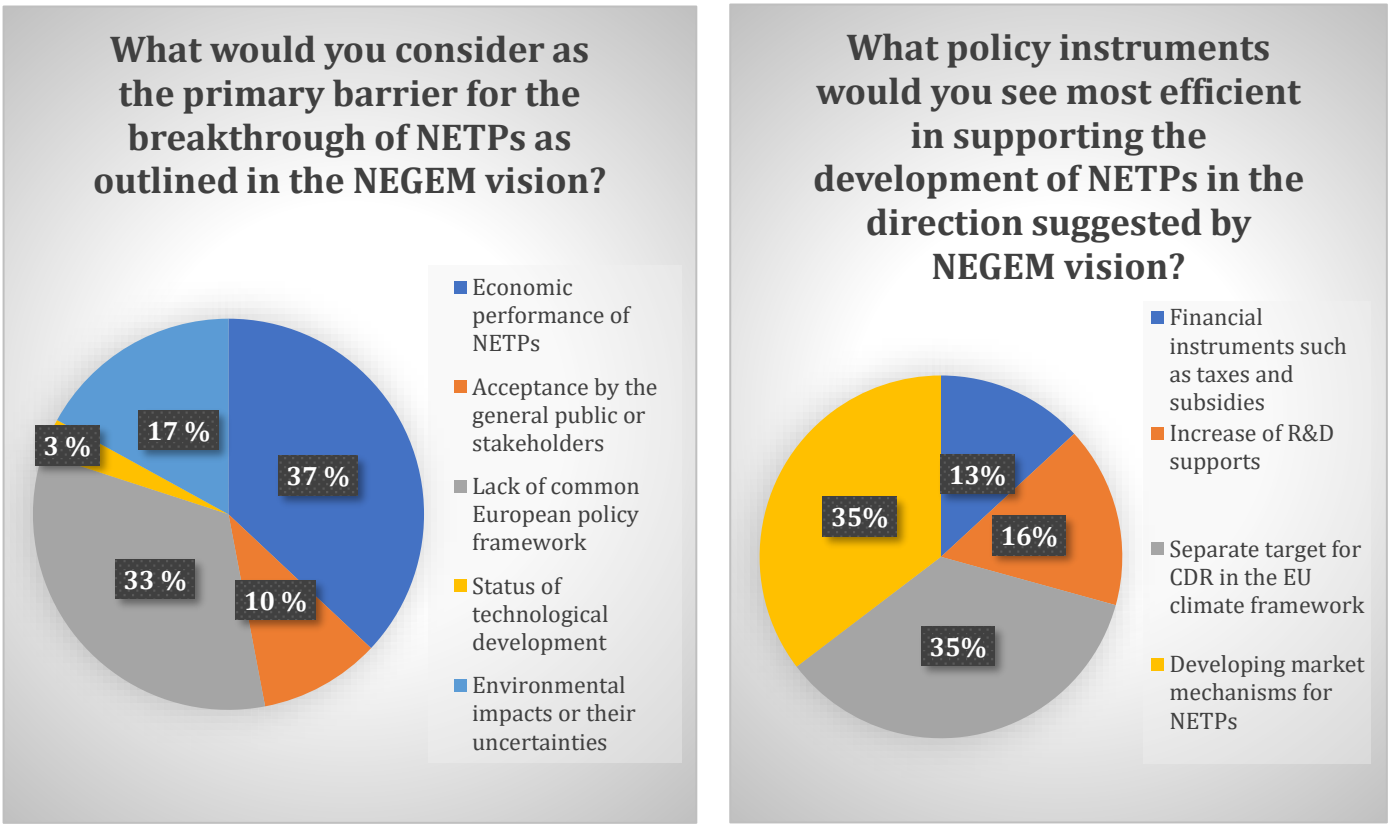

Figure 3. On-line poll results on the primary barriers (left) and policy instruments (right) relevant for the NEGEM vision.

Interestingly, the shares of the two most primary barriers considered, i.e. economic performance of NETPs (37%) and lack of common European policy framework (33%) were exactly identical to those in the first vision workshop in December 2020 (see D8.1). The share of Status of technological development was 3% in the 2nd vision workshop poll, whereas it was 10% in the 1st vision workshop polls. Hence, one could suggest a trust in technological development not appearing as a barrier having increased over the lifetime of the project. However, these thoughts must be only seen as speculative discussion, as participants of the workshop were not the same.

Regarding policy instruments, it was suggested that applying separate targets for CDR in the EU climate framework (35%) and developing market mechanisms for NETPs (35%) are the most efficient to support NETPs in the direction of vision. The figure on market mechanism option is in line with the first vision workshop result of 33%, respectively. The option on the EU climate framework was formulated more generally in the first vision workshop ("Developing common European climate frameworks") and recorded a smaller share of 12% back then. Hence, the result may be interpreted as a signal of the view of workshop participants on the importance of separate targets. The growth of the climate framework option appears to have happened at the expense of the option 'Financial instruments such as taxes and subsidies" the share of which had diminished down to 13% from 36%, respectively. Again, thoughts on development of preference order of options over time must only be only seen as speculative discussions, as participants of the workshop were not the same.

Key insights for the vision

After the workshop, the need for continuous research and development efforts (R&D) and need for commercialisation mechanisms was added to the vision to address the barrier of economic performance of NETPs.

1.1.4 Discussion on the draft of final vision

The participants were asked to reflect if they identified anything lacking from the vision. Accordingly, the following answers were suggested to be added to the vision to develop it further:

- A need to continue investing on developing the technologies, as most are still on low Technology Readiness Level (TRL).
- Country/regional perspective, best destinations for NETPs.
- An approach to certification and MRV (Measurement, Reporting, and Verification); despite separating reductions from removals in targets, tailored funding, etc. could be agreed on, the 'paperwork' could be done in an integrated way.

Key insights for the vision

After the workshop, the need for continuous research and development efforts (R&D) and need for commercialisation instruments were added to the vision to address the comment on the TRL levels. The country / regional perspective referred to the ambiguity of the earlier version of the vision mentioning "international co-operation" needed. This was clarified after the workshop as "global co-operation". A statement on monitoring and reporting was added to the extensive description of the vision after the workshop.

1.2 Feedback from the NEGEM External Advisory Board

The 7th NEGEM General Assembly meeting was organised online in December 2023. The draft of the vision was presented there to the NEGEM partners and members of the NEGEM External Advisory Board, who were present at the meeting. Feedback on the draft vision from the EAB included:

- Need to state that the nature-based CDR should be the first to be implemented, and technical solutions will be needed if this is not sufficient.
    - In the vision, the different roles of nature-based solutions and technical solutions are highlighted. In addition, the comment was addressed in the extensive vision by adding the statement based on NEGEM scenario modelling (D8.2) that thea implementation of nature based methods should accelerate immediately.
- The strong synergies that can be provided by reforestation were questioned in some cases. For example, the biodiversity impacts of presenting new tree species to the regions could be less positive.
    - This was addressed by removing the word 'strong' from the phrase "Nature-based CDR methods provide ~~strong~~ synergies between climate change mitigation and international targets for nature restoration and broader sustainable development goals'.

- A comment on the use of term “nature based” was also made after the meeting. It is can be considered to be not accurate, as none of the methods is really provided by nature itself. Also the classification to nature based and technology based options is not clear. This has been discussed also within the NEGEM consortium, and in the NEGEM policy brief it was stated that it would be more useful to classify the NETPs based on the permanence of the CO_2 storage provided. However, the term “nature based” was kept in the vision, as it is currently widely use in the EU policy, which is the main target for the vision.

2 NEGEM results as an evidence basis for the vision

In this chapter, the NEGEM results published between June 2023 and January 2024 are summarised under the research questions defined for the project in the project plan. A similar exercise with the earlier NEGEM results was made for the Deliverable 8.7, and for NEGEM science-policy brief[2] in June 2023, thus the focus here is on the results published after that. The inputs from the science-policy brief are considered for the vision formulation and are supplemented by the recent results.

The inclusion of the NEGEM results in a summarised format in this deliverable helps identify the key questions for sustainable and realistic potentials of NETPs. This, in turn, helps to create coherent key messages of the whole project and, therefore, paves the way towards a maximally shared vision of NEGEM consortium and external stakeholders, supported by evidence. Figure 4 illustrates the process of creating the NEGEM vision based on the results from the project and with co-creation with external experts.

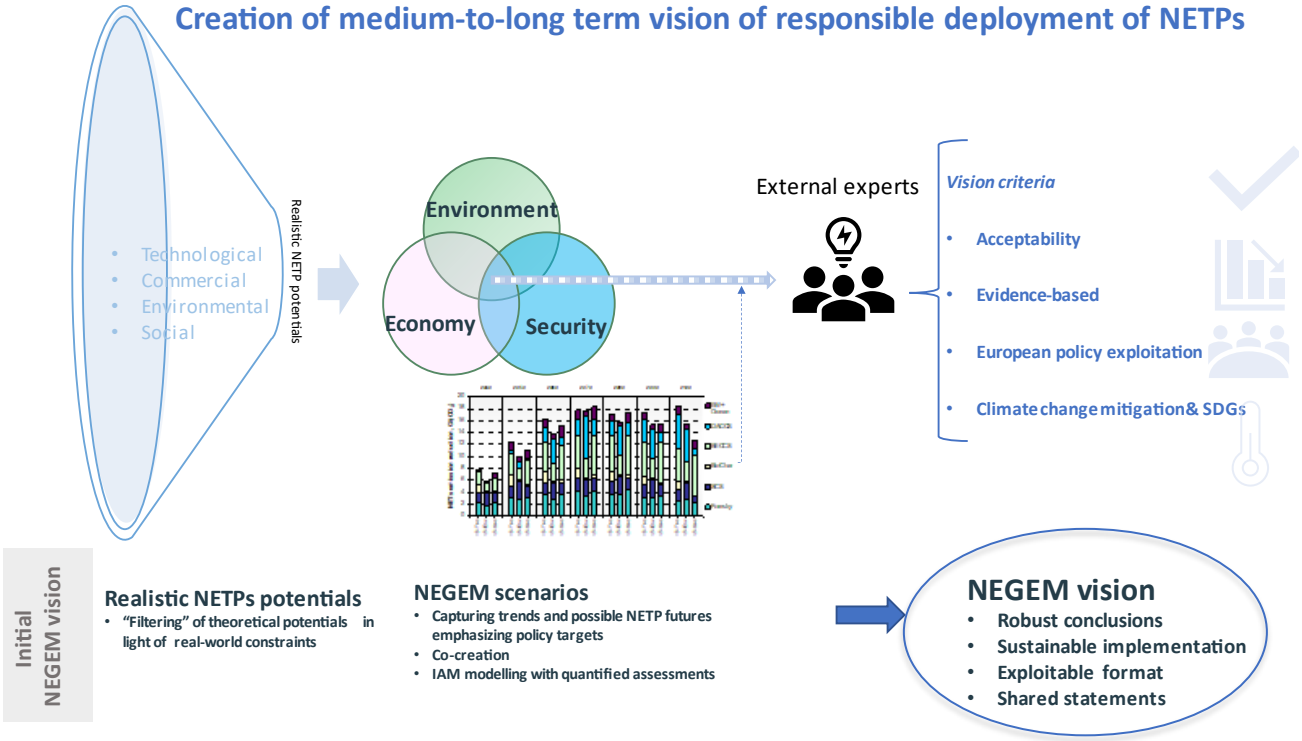

Figure 4. Process of creating the NEGEM vision.

[2] https://www.negemproject.eu/wp-content/uploads/2023/08/NEGEM-Policy-Brief-2040-Target.pdf

2.1 At what scale is it feasible to implement CDR methods, given their technical, environmental, economic, and socio-political aspects?

Here, the recent key results on technical, environmental, and socio-political aspects are summarised. **The highlighted key conclusions are reflected in the vision statements (Chapter 3).**

2.1.1 Key conclusions on environmental aspects

The key results on environmental aspects are reviewed based on D3.10 'Report on synoptic assessment of global theoretical NETP potentials', which summarises the work done in WP3 (and in WP1 LCA analysis by D3.8). WP3 assessed the most critical impacts and side effects associated with the large-scale deployment of NETPs with respect to the stability of the Earth system, ecosystem functionality, human health and resource availability. The results from WP3 are based on several methodologies, including spatially explicit, process-based biogeochemical modelling of key environmental functions under NETP deployment by LPJmL NEGEM model (D3.2/3.3/3.7), life cycle analysis addressing diverse impact dimensions (D3.8), integrated assessment modelling focussing on non-renewable material flows by VTT TIMES model (D3.9), and literature reviews for selected marine NETPs (D3.5) and for the potential contribution of Nordic forests to climate stabilisation (D3.6).

The WP3 synopsis concludes that "every NETP assessed (re-/afforestation, forest management, BECCS, biochar sequestration, Direct Air Capture and Carbon Storage (DACCS), enhanced weathering, coastal blue carbon, and ocean alkalinization) shows **trade-offs** with at least one impact dimension. To mitigate the effects of individual stressors from specific NETPs, the **CDR portfolio** should be diverse considering the NETPs' multidimensional constraints and differences in the readiness as well as the reliability of CO_2 storage. However, **forest restoration stands out with the most cobenefits,** aligning with global targets for both nature restoration (e.g., the Kunming-Montreal Biodiversity Framework) and climate stabilisation (e.g. the Paris Agreement). However, **carbon sequestration within forests is reversible** and may be threatened by increased fire frequencies under climate change. In addition, the feasibility of reforestation is intricately linked to large-scale food system transformations. Releasing land for reforestation or other natural climate solutions can be achieved most effectively through a **diet shift** reducing meat consumption.' (D3.10)

Other main conclusions from D3.10 as stated by the authors in the deliverable:

- "Careful implementation of a **portfolio of NETPs** is needed, taking the various dimensions of Earth system functioning and SDGs into account in a holistic approach.
- CDR from natural climate solutions is **saturable and reversible** and thus less suitable for compensating residual fossil emissions, but their role in restoring, fostering and protecting the natural carbon sink remains indispensable for Earth system stability.
- The realistic potential for low-impact biomass-based CDR is small unless realized in a sustainable, **ecologically responsible manner** on current agricultural land or by considerately utilizing biomass side streams. NETPs relying on biomass feedstocks (wood products, biochar, BECCS) can have severe environmental impacts if based on feedstock production on large-scale and intensively managed plantations.

- There are substantial uncertainties regarding sustainable NETPs potentials, i.e. wide ranges in the upper ceiling estimates for reforestation (1.6–4.3 $GtCO_2eq\ yr^{-1}$), land- and calorie-neutral biochar sequestration (0–2.03 $GtCO_2eq\ yr^{-1}$) and BECCS supplied by biomass side streams plus current bioenergy plantings (1.7–7.0 $GtCO_2eq\ yr^{-1}$)."

❖ As the key conclusion is **the uncertainty in the NETPs potentials** with minimal environmental impacts, the vision states that the **dependence on CDR should be kept in minimum**.

In addition, new results from the LCA analysis of WP1 (still in preparation) suggest that the potential for enhanced weathering, which was considered somewhat prominent in the earlier deliverables (e.g. D3.8), could be significantly lower based on recent experimental findings (Buckingham et al. 2022, Amann et al. 2020). The low mineralisation rate achieved in field experiments, in comparison to the theoretical rates used for the earlier LCA, would increase the amount of mineral needed and thus affect all the LCA impact categories negatively, thus severely reducing the potential of EW to provide CDR. **Therefore, in accordance with the NEGEM approach building on realistic potentials, EW is not particularly mentioned in the vision**, even though it was included in the earlier scenario modelling.

2.1.2 Key conclusions on technical and economic aspects

D5.4 'Final report on expert elicitation for NETPs' studied quantitative and qualitative insights from 34 expert elicitations – 21 DACCS experts and 13 BECCS experts were interviewed. The key conclusion was that there is a high uncertainty about the future costs and deployment scale of both technologies.

Key conclusions as stated by the authors in the deliverable:

- "The experts' best estimates suggest that, by mid-century, costs will fall to an average value of EUR 280/tCO_2 for DACCS and EUR 153/tCO_2 for BECCS (current assumptions are EUR 581/tCO_2 for DACCS and EUR 172/tCO_2 for BECCS). However, these 'averages' hide a wide divergence in views among experts, particularly for DACCS.
- Most DACCS experts do believe that in the future new and better materials as well as economies of scale will reduce the costs of the technology although they differ widely in their assessment of the overall cost implications. By contrast, experts believe that BECCS, while currently significantly cheaper than DACCS, might struggle to scale up given the distinctive characteristics of each plant.

❖ Policymakers must prioritize securing a stable green energy system to reduce uncertainties linked to energy costs for DACCS and revenue streams for BECCS respectively.These results are reflected in the vision, with the **need for continuous Research and development (R&D)** to reduce the economic uncertainties. Furthermore, **a schedule is provided for the implementation of NETPs beginning in 2030,** giving a vision for the need to accelerate the R&D efforts. On the other hand, due to the uncertainty in the NETPs costs (in addition to other uncertainties), **the vision states that the dependence on CDR should be kept in minimum**.

D4.5 'Member State specific pathway for NETP deployment' studied the overall technical and commercial potential to deploy NETPs at the EU member state level, considering the more mature NETPs. It concluded that a cost-effective deployment pathway will be reliant on technologies with a lower degree of risk (higher certainty on performance), and this is more likely to be expected in the case of engineered removals such as BECCS and DACCS. The analysis suggested that the EU member states and the UK have sufficient combined NETP potential to meet a cumulative CO_2 removal quota of approximately 81 Gt CO_2-

eq by 2100, apportioned based on a 'responsible' share of the IPCC P3 pathway[3]. The resulting optimal **cost NETP portfolio** is mostly comprised of BECCS (73%), afforestation (20%), biochar (5%) and enhanced weathering (2%) (DACCS does not appear as a cost-efficient solution, as it's price is assumed to stay at level of \$400 – 600/t CO_2 captured).

- D4.5 concluded that the capacity to deliver higher CO_2 removal quotas will be mainly constrained by **the availability of CO_2 storage** as opposed to technology supply or build rate constraints. This is now reflected in the vision with a statement on the limited storage potential. This conclusion also emphasises the need to establish **cross-border collaboration** and the development of supportive policy frameworks to effectively implement these technologies, and is addressed in the vision with the need for global co-operation.

D8.2 "Quantitative assessments of NEGEM scenarios" aimed at estimating the sustainable contribution of NETPs in the 1.5°C mitigation scenarios modelled by TIMES-VTT IAM assessments with a representation of all greenhouse gases (GHGs). To incorporate variability and possible futures, varying NEGEM scenarios were studied, based on three different storylines, "Economy", "Environment" and "Security". These scenarios delineate the roles of different NETPs and, thus, different deployments of NETPs. Importantly, the scenarios aimed at capturing barriers and boundary conditions to model more realistic and sustainable potentials of NETPs on a global and EU scales. For this attempt, the results of all the NEGEM Work Packages (WPs) were considered. In particular, the results of WP3 on environmental impacts, WP7 on multidimensional potentials, and WP5 on the perspectives of stakeholder groups were applied in the scenario assessments.

The key conclusions of D8.2:

- NETPs would be needed on a gigaton scale to achieve the mitigation goals and **no NETP option should be excluded from mitigation portfolios at this stage**. However, the realistic removal potentials and environmental impacts of some NETPs, e.g. enhanced weathering, will still need further careful investigations before large scale application.
- The results show that **stricter policies** and measures are needed in all GHG emitting sectors.These could include e.g. phase out of fossil fuels.
- Furthermore, **supporting policies are needed to ensure large-scale NETP investments by 2050**.
- The global potential for BECCS depends heavily on assumptions on energy crop potentials. **BECCS application spreads to various technological solutions, for power and heat production, bioliquids and biogases (including hydrogen), instead of the traditional assumption of using BECCS mostly in power plants.** The deployment of BECCS starts at a small scale already in 2030 both in the global scenarios and in the European scenarios, the first applications focussing on biofuel conversion where the capture costs are sufficiently low.

[3] The "Responsibility" principle for effort sharing relates the liability for global warming with a responsibility for its solution, by accounting for both current and cumulative historical greenhouse gas (GHG) emissions of countries in absolute terms as the measurement indicator. See deliverable 4.3.

- DACCS appears in all scenarios despite its relatively high price (around 200 €/tCO_2 at minimum), meaning that its deployment is cost-optimal. This is because the emission reduction measures also become expensive when carbon neutrality is approached.
- While nature-based solutions can be quite competitive and provide multiple cobenefits for biodiversity and biosphere integrity, under the assumed storylines the combined potential of biochar, soil carbon sequestration, and af-/reforestation still seems far from sufficient for keeping the temperature change within the planetary boundary for climate change well below 2°C (let alone the planetary boundary for climate change of 350 ppm CO_2 in the atmosphere corresponding to about 1°C warming). In NEGEM scenarios, nature-based solutions provide around half of the global removals needed by 2050, and around one third by 2100.

❖ Based on the D8.2 results, the vision especially **states the need for stricter climate policies to keep the dependence on CDR at a minimum**. The vision calls for the **portfolio** of NETPs to reach an optimal sustainable and cost solution. The vision states that according to the NEGEM scenarios, implementation of nature based solutions should accelerate immediately. Technical solutions such as BECCS and DACCS start to scale up from 2030-2040's, their highest level of deployment taking place in the 2060-2070's. The vision also states that BECCS should be applied over wider range of technologies.

2.1.3 Key conclusions on social aspects

D5.5 "Public awareness and assessments of NETPs: The results of a series of cross-national public surveys" studied the public opinion on NETPs (namely af-/reforestation (AR) and DACCS) with a cross-national public survey. The aim was to understand the public acceptability of NETPs and the factors influencing the public acceptability, such as perceived consequences of NETPs, perceived fairness of implementing NETPs in a country, and perceived responsibility and perceived capacity of a country to implement NETPs. In total, 6,818 participants in six European countries (that is, Germany, Spain, Finland, Lithuania, The Netherlands, and Poland) completed an online questionnaire, approximately 1,000 participants in each country.

Key conclusions as stated by the authors in the deliverable:

- "Overall, people thought that CO_2 emissions should primarily be reduced by producing more renewable energy (37%), followed by **behaviour change** (24%), and to a lesser extent by using nuclear energy and implementing NETPs.
- Participants wanted the general public to be informed about the development of NETPs, to be able to express opinions and to co-decide with governments and experts about NETPs. Participants thought to a lesser extent that the public should decide themselves about NETPs.
- AR was perceived as more acceptable and having more positive consequences (i.e., for nature and the environment, future generations, effectiveness in limiting global warming, and effects on other mitigation efforts) compared to DACCS. The results were rather similar across the six countries. Overall, people were rather positive about AR and quite neutral about DACCS, with no large division between opponents or supporters.
- Acceptability was strongly related to perceived **fairness of implementing NETPs** in a particular country, which in turn depended on the extent to which people consider that country responsible for CO_2 emissions and capable of implementing NETPs (i.e., has the knowledge and resources to implement AR and DACCS). Specifically, participants indicated that it would be fairer and acceptable if a particular country with high CO_2 emissions and sufficient knowledge and resources would implement both NETPs."

- The results of D5.5 show that people are also ready for behaviour changes, which are considered a primary measure in comparison to NETPs by the respondents. The vision calls for **behaviour changes,** e.g. in reduced consumption and in dietary changes. To respond to the demand for fairness in NETPs implementation, the extensive vision states that an **equitable and fair allocation of CDR targets** between countries is needed.

2.2 How to formulate policies and governance structures to optimise the deployment of CDR within the overall climate architecture?

Here the recent key results on policies and governance structures are summarised. **The bolded key conclusions are reflected in the vision statements (Chapter 3).**

D2.4 "Classification of NETPs against appropriate commercialisation instruments" studied the risks and atmospheric impacts associated with different carbon storage types (e.g. afforestation, biochar, and geological CO_2 storage) and the effectiveness of current risk management practices. It also provided policy-relevant insights for designing long-term risk and liability mechanisms. Balancing the ongoing fossil CO_2 emissions with carbon storage options that are unable to effectively store carbon for timescales comparable to the indefinite climate impact of CO_2, mainly due to the **high risk of re-release**, raises concerns about the long-term sustainability of net zero.

'In conclusion, the study emphasises the importance of **effective risk management frameworks** and highlights the limitations of certain types and combinations. By addressing these considerations, policymakers can develop more comprehensive and effective regulation of carbon storage portfolios that minimise the risks associated with CO_2 release and contribute to long-term climate stability. The primary policy recommendation of this analysis is that dynamic **risk and liability mechanisms**, such as buffer accounts, can offer an effective way to facilitate the liability of stored carbon and transition to lower risk storage over time.

- Based on D2.4, a clear statement on the need for monitoring, verification, and risk and liability mechanisms to ensure the liability of CO_2 storage was added to the extensive version of the vision.

D5.4 "Final report on expert elicitation for NETPs" concluded that "costs, as well as **policy and regulations**, are the most relevant limiting factors for the implementation BECCS and DACCS. Experts believe that policy instruments should reduce the investment burden to promote the deployment of these technologies by integrating them into existing tools, such as the emission trading scheme. Without a concrete framework that defines how negative emissions are accounted for, disposed of and paid for, investors will have limited incentives to provide the initial capital needed to scale up these technologies."

- Based on D5.4, the need for clear policies and regulations, as well as for commercialisation mechanisms, is stated in the vision.

D6.1 "How do NETPs fit in existing climate frameworks?" studied the role of CDR in the existing climate frameworks, such as global frameworks (CORSIA, Kyoto CDM), EU policies, and in 11 national or subnational jurisdictions: Australia, California, Denmark, Finland, France, Germany, New Zealand, Sweden, Switzerland, the United Kingdom, and the United States.

The key conclusion was that all the policy frameworks analysed were inadequate and require further development if they are to address CDR and achieve their climate goals. The study recommended the establishment of robust and **dedicated governance frameworks** for carbon . These must make clear that carbon removals currently fulfil a secondary climate function and that their **role should be to supplement urgent and rapid emissions reduction.**

- "Dedicated frameworks also need to introduce realistic legally binding targets for CDR that complement rather than substitute emissions reductions. Although the use of nature-based methods as removals can lead to a false equivalency between short-term storage and long-term emissions, if natural sinks are taken into account then separate targets for technological removals and natural carbon sinks should be set in such a way that reflects the different timescales, benefits and risks involved. Fixed and separated targets for nature-based CDR alongside targets with milestones for technological CDR would not only provide measurable indicators of progress, but also provide transparency on the amount of residual emissions that can be tolerated towards reaching climate neutrality and net-negative emissions.
- Beyond accurately defining carbon removals, policymakers should implement **robust accounting rules, methodologies, and sustainability requirements** for CDR based on careful consideration of implications and impacts to ensure real, sustainable removals. This can also help address the risks of relying on vulnerable natural sinks by ensuring accurate accounting of both sequestered and (re-)released greenhouse gases.
- While **reducing emissions must remain the absolute priority** in the coming years and decades when addressing climate breakdown, **carbon removals will become increasingly important over time**."

❖ The vision highlights the additional role of CDR and the need for clear regulations.

D6.5 The publication "Who should use NETPs?" studied the questions who should use the limited amount of NETPs. Two key aspects were identified: 1) the deployment of NETPs i.e., who should use natural resources to remove and store carbon, and 2) the use of the negative emissions generated by these activities i.e., who should use the NETPs to counterbalance their emissions? A key conclusion was that responsible implementation and expansion of NETPs should be strategic and consider the efficient use of limited natural, engineering, and economic resources, the CDR efficiency, and storage permanence.

Key conclusions as stated by the authors in the deliverable:

- The expectations surrounding the role NETPs will play in achieving net-zero targets need to be carefully managed because **the amount of permanent carbon removals is and will remain a scarce resource**.
- All sectors will need to undergo **drastic decarbonisation**, and most sectors requiring full decarbonisation.
- The best use of physical, financial, and social resources is to reduce atmospheric concentrations of GHGs by **reducing emissions in the first place**.
- Although capacity may be limited, CDR will be essential to reach net-zero targets to counterbalance what is designated as residual GHG emissions.
- Instruments and mechanisms must ensure that the NETP allocation has a credible and verifiable impact that aligns with **sustainable resource use and sustainable development goals** and does not exert additional pressure on planetary boundaries.

- Use of NETPs should generate a clear benefit to societies by ensuring **counterbalancing of emissions is achieved at a system-level, rather than simply at the individual level.**

❖ Based on D6.5 the conclusion on counterbalancing the residual emissions at system level was added to the vision.

2.3 Quantitative estimations on NETPs potentials

Several modelling tools have been used in the NEGEM project to study the responsible potential for different NETPs globally and in Europe. Table 2 presents a synthesis on the global NETP potentials based on NEGEM modelling results from WPs 3, 4, 7, and 8. The results are based on different modelling tools, assumptions, and methods (see explanation). They should not be seen as consensus targets for single CDR technologies suggested by the project. However, the quantitative analysis give some evidence-based indication of the order of magnitude of CDR achievable to make the NEGEM vision more concrete.

The NEGEM results are compared to potential ranges of various NETPs given by IPCC (AR6 WG3). In addition, they are compared to the median values of NETPs potentials in the IAMC 1.5°C Scenarios Database (IIASA 2019), which were analysed in Deliverable 8.1. The scenario database, hosted by IIASA, contains results for around 350 1.5°C scenarios which include NETPs.

Table 2. 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 .

NETP	Technology specification	Global	Global	Europe	Europe	Applied methodology and notes	Deliverable
		Supply or potential [$GtCO_2/y$]	**Cumulative supply or potential [Gt CO_2]**	**Supply or potential [$GtCO_2/y$]**	**Cumulative supply or potential [Gt CO_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, assuming minimal management intensity.	D3.7, PIK
	Biomass: Current bioenergy, residues, bioenergy crops, point-source biogenic CO_2 emission	**2050:** 2.1-3.9 **2080:** 3.3-6.7	**2025-2100:** 185-360	**EU-31 2050:** 0.3-0.4	**EU-31 2025-2065:** 10	Cost-optimised results from TIMES-VTT NEGEM mitigation scenarios to reach 1.5°C target with a large portfolio of NETPs. Full	D8.2, VTT

	Technologies: BECCS from power and heat, bioliquids, and biogases (including hydrogen) production	**2100:** 3.4-6.8			(averaged over three scenarios)	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	
	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 scenarios database for DACCS		**2050:** 0.05 **2100:** 6.4				(median of 8 scenarios)	D8.1, VTT
NEGEM DACCS	DACCS (High-temperature liquid sorbent processes)	**2050:** 0.6-1.1	**2025-2100:** 50-220	**2050:** ~0.2-0.4	**EU-31**	Cost-optimised results from TIMES-VTT and Pan-	D8.2, VTT

		2080: 2.2-5.1 **2100:** 1.1-5.8			**2025-2065:** 10 (averaged over three scenarios)	European TIMES NEGEM scenarios Cost of DACCS drops to around 200 €/t CO_2 in high-end potentials and stays around 350 €/t CO_2 for low-end potentials.	
	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:**	**2025-2100:** 15-115	**2050:** ~0-0.05	**EU-31 2025-2065:** 1	Cost-optimised results from TIMES-VTT and Pan-European TIMES NEGEM scenarios. Potentials based	D8.2, VTT

		0.3-1.7 **2100:** 0.1-1.2			(averaged over three scenarios)	on Land- and calorie- neutral biochar (see D3.10). No residual biomass used for biochar.	
					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

The supply based BECCS potentials from bioenergy crops (D3.7) vary remarkably depending on the assumptions on the global land use. The high-end values assume a radical (100%) global diet change towards the Planetary Health Diet (with reduced meat consumption), thus releasing pasture land for bioenergy crop cultivation. However, with these high-level potentials a trade-off between CDR provision and other sustainability goals would be created, and even the scenarios assuming minimal management (e.g. no irrigation) have an effect on the biosphere integrity (D3.3). Thus, the lower end potentials can be seen as more responsible, and were applied for the NEGEM mitigation scenarios in D8.2. In comparison to the mitigation potentials per year proposed by the IPCC AR6 WG3 report Table TS7, the potentials reflected by the NEGEM mitigation scenario results (D8.2, Chiquier et al. 2022) are towards the mid- or lower end of the IPCC range. When compared to the median values derived from the IAMC 1.5°C scenarios database, the NEGEM mitigation scenario values for BECCS for 2050 are at the same level, staying however at lower level for 2100.

In the IPCC AR6 WG3 1.5°C scenarios the cumulative removals by 2100 from BECCS vary between 30–780 $GtCO_2$. The cumulative removals by BECCS in the NEGEM D8.2 are around 185–360 $GtCO_2$. The reduced reliance on BECCS in the NEGEM scenarios occurs due to constraints in use of bioenergy crops, as well as due to an expanded portfolio of NETPs in the modelling.

For DACCS the NEGEM scenario values from D8.2 are significantly higher than those of D4.5 or Chiquier et al. 2022. This is due to a more optimistic assumption on cost development, i.e. cost of DACCS varies from 200-350 €/ t CO_2 captured in D8.2, instead of $400 – 600/t CO_2 captured in D4.5. When comparing the D8.2 values to IPCC and IAMC database values, the level of DACCS deployment is significantly higher in 2050 but stays at lower level for 2100. In the IPCC AR6 WG3 1.5°C scenarios, the cumulative removals by 2100 from DACCS vary between 0–310 $GtCO_2$ across the scenarios. In the NEGEM scenarios (D8.2), removals by DACCS vary from around 50 to 220 $GtCO_2$.

The demand proposed for NETPs by the IPCC 1.5°C scenarios is at gigaton scale already in 2050, and e.g. around 10-12 Gt CO_2 by NEGEM 1.5°C scenarios (D8.2). This can be compared to the current carbon dioxide removals, 2 $GtCO_2$/yr, of which major part comes from conventional management of land and only a minor share, 0.002 $GtCO_2$/yr, results from methods such as BECCS and DACCS (Smith et al. 2023). Thus, as stated in the NEGEM vision, it is evident that clear policy frameworks and commercialisation mechanisms are needed to accelerate the use of NETPs.

3 Final NEGEM vision

The aim of the NEGEM vision is to set the ground for a clear, shared, medium-to-long-term vision on NETPs. Here, vision is defined as a desirable outcome or goal, focussing on sustainable NETPs potentials and on their role in contributing to climate targets. Naturally, as the project is funded by the EU, relevancy for European policymaking is particularly targeted. However, the context of the vision is global. As desired futures on NETP deployment evidently differ between stakeholders and individuals, essentially, the vision serves as a common legacy of the NEGEM project for Europe.

To meet the climate goals of the Paris Agreement, drastic and immediate greenhouse gas emission reductions are needed. To keep the warming in 1.5-2 °C, carbon dioxide removal (CDR) technologies and practises are needed but should only be relied on as a supplementary measure to emission reductions. Putting a strong emphasis on phasing out fossil fuels, and reducing demand for goods and energy in a globally equitable way, as well as changing the eating habits towards the Planetary Health Diet, could lower the demand for CDR. The smaller the residual emissions are, the lower the demand for CDR.

Separate policy targets for (1) greenhouse gas reductions, (2) land use sector (LULUCF), and (3) technical CDR that leads to permanent storage are needed to guarantee the balanced contributions for climate change mitigation. Technical CDR solutions with geological-timescale storages will provide permanent CDR and are needed to reach the climate neutrality. Nature-based methods for CDR are essential, as they will provide synergies between climate change mitigation and international targets for nature restoration and broader sustainable development goals. The carbon dioxide (CO_2) storage time and vulnerability to intended and/or unintended release of CO_2 is essential.

The responsible deployment of CDR is restricted by planetary boundaries and none of the CDR options comes without environmental trade-offs. However, several co-benefits are recognised for the nature-based methods regarding e.g. soil quality, biosphere integrity, and nature restoration targets. Significant changes in current agricultural sector, such as global dietary changes towards Planetary Health Diets, could release current pastureland to prevent natural land to be converted for CDR methods, with reforestation providing the most environmentally sustainable use of of this land.

Sustainable BECCS applications could be provided especially by use of **residual biomass feedstock** and capture of **point source emissions of biogenic CO_2**, e.g. from biorefineries and pulp- and paper industry. The BECCS technologies vary from combined heat and power production, to bioliquids and biogases (including hydrogen), instead of using BECCS mostly in power plants.

CDR solutions in development, such as **DACCS**, could provide substantial removal potentials when applied with abundant carbon neutral energy systems, but more research and piloting is needed to enable responsible large scale implementation.

To respond to the environmental and social challenges, a portfolio of CDR methods is needed to balance the impacts. A large portfolio of CDR methods together with **international cooperation** on CDR regulation, CO_2 transport, and utilisation of CO_2 storage resources, can enable a cost-efficient CDR implementation. An equitable and fair allocation of CDR targets between countries is needed.

Commercial and public instruments to finance and support CDR implementation should enable the scale of CDR needed. Monitoring, verification, and dynamic risk and liability mechanisms to ensure the **liability of CO_2 storage** are needed. Continued support for R&D of CDR methods at early development stages should enable their rapid ramp up. A **social licence to operate** for CDR methods is achieved through

continuous interaction between decision makers, different stakeholders, and general public. Systems perspective is adapted for regulation planning.

NEGEM project provides estimations on responsible CDR potentials globally and in Europe based on NEGEM impact assessments and scenario modelling (see Table 2). The removals are provided by a large portfolio of CDR methods, and all CDR options should be considered in mitigation portfolios at this stage. According to the NEGEM scenarios, implementation of nature based solutions should accelerate immediately, especially when co-benefits can be linked to targets of nature restoration and Sustainable Development Goals. Technical solutions such as BECCS and DACCS start to scale up from 2030-2040's, their highest level of deployment likely taking place in the 2060-2070's. 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, rather than at country or corporate level.**

Brief 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 transport 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 enable 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 in order to provide CDR at 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 broader system-level, rather than at country or corporate 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)
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
D3.5	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
D4.5	Member State specific pathway for NETP deployment	ICL	R	PU	36
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
D6.1	How do NETPs fit in existing climate frameworks?	CMW	R	PU	39
D6.5	Who should use NETPs? Managing expectations for NETP demand: Considerations for allocating carbon dioxide removals	BELLONA	R	PU	42
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
D8.7	Updated NEGEM vision	VTT	R	PU	30
	NEGEM Policy-brief	NEGEM	R	PU	https://www.negemproject.eu/wp-content/uploads/2023/08/NEGEM-Policy-Brief-2040-Target.pdf

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Appendix 1

Draft vision presented in the 2nd Vision workshop, November 2023

Draft version of the final vision

To meet the climate goals of the Paris Agreement, drastic and immediate greenhouse gas emission reductions are needed. To keep the warming in 1.5-2 °C, carbon dioxide removal (CDR) technologies and practises are needed but should only be relied on as a complementary measure to emission reductions. The smaller the residual emissions are, the lower the demand for CDR. Nature-based CDR methods provide strong synergies between climate change mitigation and international targets for nature restoration and broader sustainable development goals. Technical solutions with geological-timescale provide permanent CDR, which is needed to reach climate neutrality. To respond to the environmental and social challenges, a portfolio of CDR methods is needed to balance the impacts. A large portfolio of CDR methods together with international co-operation will enable cost-effective mitigation pathways.

Responsible CDR implementation, balancing between the targets for climate change mitigation and protection of other planetary boundaries, should be guided by a clear and transparent policy framework. Continuous interaction between different stakeholders, as well as systems perspective in regulation design, will enable a social licence to operate for CDR methods. A growing number of regions, countries, businesses, and other stakeholders need to form their own CDR visions for climate neutrality.