NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Quantitative assessments of NEGEM scenarios with TIMES-VTT

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Executive Summary

The aim of Work Package (WP) 8 in NEGEM project is to create a clear and shared medium-to-long-term vision on the realistic and sustainable potentials of negative emission technologies and practises (NETPs) and their role in climate change mitigation at the EU level and globally. The formulation of the final NEGEM vision will be based on NEGEM pathways and storylines to reach the climate goals set in the UNFCCC Paris Agreement. In this report, the NEGEM storylines are described and quantified globally with TIMES-VTT Integrated Assessment Model (IAM), and for Europe with Pan-European TIMES-VTT. The aim of the storyline and scenario formulations is to reflect results created in other NEGEM WPs on the technical, environmental, and social constraints and benefits related to various NETPs. The earlier WP8 work on NEGEM storylines and scenarios has been documented in deliverables 3.9, 8.1, 8.6, and 8.7. The final NEGEM vision will be formulated after stakeholder feedback from the final vision workshop in November 2023.

The NEGEM scenario work has led to formulation of three storylines to illustrate possible alternative futures where deployment of NETPs could take place. All storylines aim for 1.5 °C mitigation target during this century, with an overshoot allowed. They aim to describe realistic potentials of NETPs with emphasis on different techno-economic and/or socio-economic perspectives and development paths that would impact on the potentials. The three storylines are compared with a reference scenario based on Nationally Determined Contributions (NDCs) of the UNFCCC, leading to approximately 2 °C global warming during this century.

Since forecasting the future is practically impossible, the storylines and scenarios can only describe potential trajectories on how the future might unfold. They are not to be interpreted as scenarios forecasting the future or giving specific information on the investments needed for a certain technology or new infrastructures in future. However, they can provide scale and understanding on the magnitude of solutions needed. The scenario work integrates existing and possible development of the future energy and industrial systems, agriculture and forestry, residential and commercial sectors, transport, and the other sectors producing greenhouse gas (GHG) emissions.

The first storyline “Advanced technology and global markets (1.5C-Tec)” illustrates a world with fast and optimistic technological and cost developments, and co-operation between countries and regions, including open markets. NETPs are seen positively and have a full social licence to operate. The second storyline “Nature conservation and biodiversity (1.5C-Env)” describes a world where no further pressure on planetary boundaries is accepted. NETPs are viewed as environmentally and socially problematic, due to environmental concerns related to their large-scale deployment. In addition, significant dietary changes are assumed due to progress towards planetary health diets. In the third storyline “Security and self-sufficiency (1.5C-Sec)”, a continuing multi-crisis mode echoing the current geopolitical situation, climate crisis, and energy crisis is envisaged for the global development. Nations and regions turn more to themselves, leading to conservative technology development of NETPs, and raising security concerns, e.g. on carbon dioxide (CO_2) transport by pipelines.

Traditionally, the 1.5°C mitigation scenarios, such as those described in the IPCC AR6 WG3 (IPCC 2022), have included only a few NETP options: bioenergy combined with CO_2 capture and storage (BECCS), direct air capture and CO_2 storage (DACCS), and afforestation/reforestation. For the scenario modelling here, an expanded portfolio of NETPs is considered, including BECCS, other biomass-based processes combined with CO_2 capture and storage (bio-CCS), DACCS, enhanced weathering (EW), ocean liming (OL), afforestation, reforestation, biochar, and soil carbon sequestration (SCS).

Based on the final global NEGEM scenario runs with TIMES-VTT Integrated Assessment Model we can see that NETPs would be needed to reach global GHG mitigation with a 1.5-2°C target. The 2°C corresponds with the NDCs given by the UNFCCC COP26 in Glasgow in 2021 and, thus, before the current geopolitical crisis. However, the results clearly indicate that moving from the 2°C target to the 1.5°C target leads to much more rapid emissions reductions and much higher mitigation costs even with immediate climate actions, which were assumed in 1.5C-Tec, 1.5C-Env, and 1.5C-Sec scenarios. The scenario results show that a quick transition away from fossil fuels would require strict energy and climate policies to accelerate the transition.

In the global scenario results, the investments in NETPs are at the highest levels after 2060, but significant amounts of bioenergy combined with carbon capture and storage (BECCS), biochar, soil carbon sequestration (SCS), and enhanced weathering (EW) are deployed as early as 2040, with direct air capture of CO_2 (DACCS) starting to appear in 2050's. This indicates that policies and regulation related to NETPs should be in place in advance. Accelerated actions would be needed in case global GHG emissions would not show rather immediate downturn trend as expected in the scenario runs.

The key messages based on the NEGEM scenario assessment can be summarized as follows:

- NETPs would be needed in gigaton scale to reach the 1.5–2.0°C mitigation goals and no NETP option should be excluded from mitigation portfolios at this stage.
- In the scenario assessments, the GHG mitigation targets were achieved by cost-optimization of the mitigation pathway. The results show that stricter policies and measures to phase out fossil fuels are needed across all GHG mitigating sectors. These measures can include e.g. setting high CO_2 emission taxes, applying regional/international rules for phasing out of fossil fuels, setting very tight CO_2 emission limits in using fossil fuels (i.e. for car manufactures, buildings, etc.), and take-back obligations for fossil fuel producers. In addition, supporting policies are needed to ensure large-scale NETP investments by 2050.
- The global potential for BECCS depends heavily on the assumptions on energy crop potentials. IPCC AR6 WG3 reported a median use of BECCS of approximately 9 $GtCO_2/a$ by 2100, relying largely on energy crops. In NEGEM 1.5-degree global scenarios the contribution of BECCS by 2100 varies from 3 $GtCO_2/a$ in 1.5C-Env to less than 7 $GtCO_2/a$ in 1.5C-Sec. In 1.5-Env scenario, further pressure on planetary boundaries is strictly avoided, so BECCS from energy crops is very limited and BECCS from residues and point-source emissions are emphasised. In 1.5-Sec scenario BECCS from energy crops is enabled by significant land release from pastureland to cultivation of bioenergy crops due to 25% dietary change towards planetary health diets globally.
- In IPCC AR6 WG3 1.5°C scenarios the cumulative removals by 2100 from BECCS vary between 30–780 $GtCO_2$. The removals by BECCS in NEGEM scenarios are around 200–360 $GtCO_2$. The removals by BECCS are moderate due to constraints in use of bioenergy crops, as well as due to an expanded portfolio of NETPs in the modelling. The results show that BECCS application spreads to various technological solutions, for power and heat production, bioliquids and biogases (including hydrogen), instead of traditional assumption to use BECCS mostly in power plants. Deployment of BECCS starts at small scale already in 2030 both in the global scenarios and the European scenarios, the first applications focusing on biofuel conversion where the capture costs are sufficiently low.

- In 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, removals by DACCS vary from around 80 to 240 $GtCO_2$. Deployment of DACCS starts in both global and EU scenarios by 2050. Especially when BECCS is heavily restricted, as in 1.5C-Env scenario, significant removals by DACCS are needed to achieve the climate targets, e.g. globally up to 7 $GtCO_2$/a in 2070. This is despite the relatively high prices of DACCS.

- While the nature-based solutions can be quite competitive and provide multiple co-benefits 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 (i.e. well below 2°C). In NEGEM scenarios, nature-based solutions provide around half of the global removals needed by 2050, and around one third by 2100. Enhanced weathering can also provide a moderate contribution to removals, however further research is needed on its environmental and practical implications.

- In 2020, the European Commission published an impact assessment accompanying the document ”Stepping up Europe’s 2030 climate ambition” SWD (2020) 176 final. It concludes that in the EU the total negative emissions (including the LULUCF sector and NETP options) need to be around 0.5 $GtCO_2$/year by 2050, in order to enable climate neutrality. NEGEM results show significantly higher deployment of NETPs varying from 1.1 to 1.4 $GtCO_2$/year by 2050. NETPs, such as BECCS, are implemented to some extent already in the 2030’s, emphasizing the need to clarify EU regulations for NETPs as soon as possible.

- The EU climate Advisory Board has recommended a 90% greenhouse gas emission reduction target for the EU by 2040 compared with the 1990 emission level. The NEGEM results concerning the CO_2 reductions in Europe indicate that the marginal costs of direct CO_2 emissions reductions would exceed the costs of NETPs deployment when emission reduction levels above 76% are reached.

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1 Introduction

To reach the 1.5°C target for global warming agreed in the Paris Agreement, drastic and rapid greenhouse gas (GHG) emission reductions are needed. The current and expected pathways of emission reductions, according to the Nationally Defined Contributions (NDC) given under the Paris Agreement, are not in line with the target to mitigate global temperatures to 1.5-2°C. Thus, emission reductions need to be accelerated during this decade (IPCC AR6, 2022). The recent assessment by the International Energy Agency projects that demand for coal, oil, and natural gas will all peak during this decade even without any additional climate policies. However, this development alone is not enough to reach the 1.5 °C goal (IEA 2023).

One of the key messages of IPCC AR6 WGIII report is that deploying negative emission technologies and practises (NETPs) will be essential to globally reach net-zero GHG emissions. NETPs cannot replace emission reductions but are needed to support climate change mitigation actions.

The IPCC outlines three complementary roles for NETPs:

1) To supplement emission reductions and accelerate climate change mitigation;
2) To achieve net-zero by balancing out residual CO_2 and non-CO_2 greenhouse gas emissions;
3) To exceed annual GHG emissions and achieve 'net-negative' emissions globally to draw down global temperatures.

NETPs include several technical and nature-based solutions (NEGEM Deliverable 1.1,). Technical solutions include, for example, direct air capture and CO_2 storage (DACCS), bioenergy or other biomass-based process combined with CO_2 capture and storage (BECCS and Bio-CCS), enhanced weathering (EW), and ocean-based solutions, such as ocean liming (OL). Nature-based solutions include e.g., afforestation, reforestation, biochar, soil carbon sequestration (SCS), and seaweed cultivation and sinking.

The need for NETPs varies enormously in the economically optimized climate stabilization scenarios that limit warming to 1.5°C included in the IPCC AR6 WG3 report, depending on the speed and rate of emissions reductions accomplished in each scenario. In these scenarios, the cumulative global net-negative emissions including NETPs are 20–660 $GtCO_2$ by 2100 (of which the share from the AFOLU sector is 20-400 $GtCO_2$). By 2100, the cumulative removals by BECCS vary between 30-780 $GtCO_2$ and removals by DACCS vary between 0-310 $GtCO_2$. However, it should be noted that only some scenarios include a NETP portfolio, which is also one reason behind the above large variations. As an example, the IPCC AR6 WG3 scenarios generally include BECCS, DACCS, and af-/reforestation, whereas the other NETP options are included in the assessments to a lesser extent.

In 2020, the European Commission published an impact assessment accompanying the document "Stepping up Europe's 2030 climate ambition" SWD (2020) 176 final. It concludes that in the European Union (EU) the total negative emissions (including the LULUCF sector and NETP options) need to be around 0.5 $GtCO_2$/year by 2050, in order to enable climate neutrality. NEGEM has studied possible CDR targets for Europe based on a cumulative need for 687 Gt of global CDR by 2100 defined in some IPCC 1.5°C scenarios. Different effort-sharing principles (namely responsibility, capacity, and equity principles) were tested to allocate the global target for CDR to different regions. The cumulative target for EU28 varied from 32 Gt by 2100 (based on the equity principle) to 325 Gt by 2100 (capacity principle) (see D4.3).

In the IPCC AR6 WG3 scenarios, the need for NETPs is defined based on economic optimisation and can be described as “demand based”. The aim of the NEGEM project is to understand the realistic, supply based potentials for responsible deployment of NETPs. In this report, the final NEGEM storylines are described and quantified with global and European Integrated Assessment Models (IAMs), TIMES-VTT and Pan-European TIMES-VTT, respectively. The aim of these storylines and scenarios is to collect results created in the other NEGEM WPs on the technical, environmental, and social constraints and benefits related to various NETPs (e.g. D1.5, D3.7, D3.9, D5.4). The scenario work integrates existing and possible development of the future energy and industrial systems, agriculture and forestry, residential and commercial sectors, transport, and the other sectors producing greenhouse gas (GHG) emissions. Another aim of the NEGEM scenarios is to widen the portfolio of NETPs applied in scenario modelling. In addition to BECCS, DACCS, and af-/reforestation, here also biochar, soil carbon sequestration, enhanced weathering, and ocean liming are included in the scenarios. In different storylines, variations in assumed constraints for different NETPs are applied.

The final aim of NEGEM Work Package (WP) 8 is to create a clear and shared medium-to-long-term vision on the sustainable potentials of NETPs and their role in climate change mitigation at the EU level and globally. The formulation of the final NEGEM vision will be based on NEGEM pathways and storylines to reach the climate goals set in the UNFCCC Paris Agreement. The earlier WP8 work on NEGEM storylines and scenarios has been documented in deliverables 3.9, 8.1, 8.6, and 8.7. The NEGEM scenario work started with creation of a preliminary NEGEM vision, literature analysis of the role of NETPs in GHG mitigation, and the selection of the publicly available emission scenarios (D8.1). The first TIMES-VTT scenario results were reported in D3.9, which studied global demand, supply and trade-offs for selected metals and minerals in global mitigation pathways. Modelling of the global scenarios was largely based on definitions and GHG emission pathways reported in the IIASA database (IIASA 2022) for the IPCC AR6 WG3 report. However, TIMES-VTT database for NETPs was updated and extended based on results from WP1, WP3, WP4 and WP7 of NEGEM as well as on recent literature on NETPs and other GHG mitigating technologies. In D8.6 a summary of the formulation and quantification of the preliminary NEGEM storylines was given in addition to the preliminary scenario results for the selected global NEGEM scenarios. Deliverable 8.7 “*Updated NEGEM Vision”* gave additional information for the storyline and scenario formulation process, which have been a part of the vision making process. For this final scenario report (D8.2), the latest NEGEM results from other WPs have been included both qualitatively for the storyline descriptions and quantitatively to the scenario assumptions. The data flows are described in section 3.3.

The NEGEM scenario work has led to the formulation of three storylines to illustrate possible futures where deployment of NETPs could take place. All storylines aim for 1.5 °C mitigation target and aim to describe realistic potentials of NETPs with emphasis on different aspects that would impact on the potentials from techno-economic and/or socio-economic perspectives. Since forecasting the future is practically impossible, the storylines can only describe potential trajectories on how the future might unfold. They are not to be interpreted as scenarios forecasting the future or giving specific information on the amounts of certain technology needed in future. However, they can provide understanding on the magnitude of solutions needed.

The first storyline is called “Advanced technology and global markets (1.5C-Tec)” which illustrates a world with fast and optimistic technological and cost development, and co-operation between countries including open markets. NETPs are seen positively and have full social licence to operate. The second storyline “Nature conservation and biodiversity (1.5C-Env)” describes a world where no further pressure on planetary boundaries is accepted. NETPs are viewed environmentally and socially problematic, due to environmental concerns related to their large-scale deployment. Unlike in 1.5C-Tec scenario, significant dietary changes are assumed due to progress towards planetary health diets. In the third storyline “Security and self-sufficiency (1.5C-Sec)”, a continuing multi-crisis mode echoing the current geopolitical situation, climate crisis and energy crisis, is envisaged for the global development. Nations and regions turn more to themselves, leading to conservative technology development and acceptance of NETPs, and heightened concerns related CO_2 transport and storage. As a reference scenario, a mitigation pathway, which includes NDCs that represents 2 °C global warming during this century, is included.

This deliverable 8.2 concentrates on reporting the key assumptions on NETPs in the NEGEM storylines and in scenario modelling, as well as the global and European scenario results. The analysis of the results will continue also in the following deliverables 8.3 on NEGEM vision and 8.4 on final recommendations. The contents of the D8.2 is organised as follows: Chapter 2 includes a description the NEGEM storylines, including a summary of the foresight methods used. Chapter 3 describes the TIMES-VTT IAM and Pan-European TIMES-VTT models used for the global, and European scenarios analysis, respectively. It also describes the assumptions on NETPs potentials added to the models. Chapter 4 presents the results of the scenario modelling globally and in Europe (EU-31). In addition, results are compared to earlier results from other NEGEM WPs. Chapter 5 shortly describes the sensitivities and challenges in the modelling, and future research needs. In Chapter 6, the key findings and policy relevant messages are highlighted.

2 Description of NEGEM storylines

2.1 Methods

The aim of the NEGEM project is to analyse the realistic and sustainable potentials of the NETPs for 1.5 °C mitigation pathways. Thus, we wanted to create alternative storylines with different development paths for global and EU economies, technology developments, and peoples' behaviour. In these storylines the operating environment, including the techno-economic and socio-economic potentials for the NETPs differ from each other. Scenario storyline or pathway formulation is an important step in the whole scenario planning process aiming at mutual understanding and dissemination in the end of the scenario project. Therefore, the NEGEM storylines were formulated in collaboration with NEGEM partners and the NEGEM External Advisory Board (EAB) to ensure that we combine the knowledge acquired in the project. The method for formulating storylines in the collaborative effort of the NEGEM consortium, including detailed analysis of the workshops and other steps, were described in D8.6 and D8.7, so here we present just a short summary on key goals and milestones of the process. The NEGEM framework shows the information flows and schematics for storyline and scenario formulations (Figure 1).

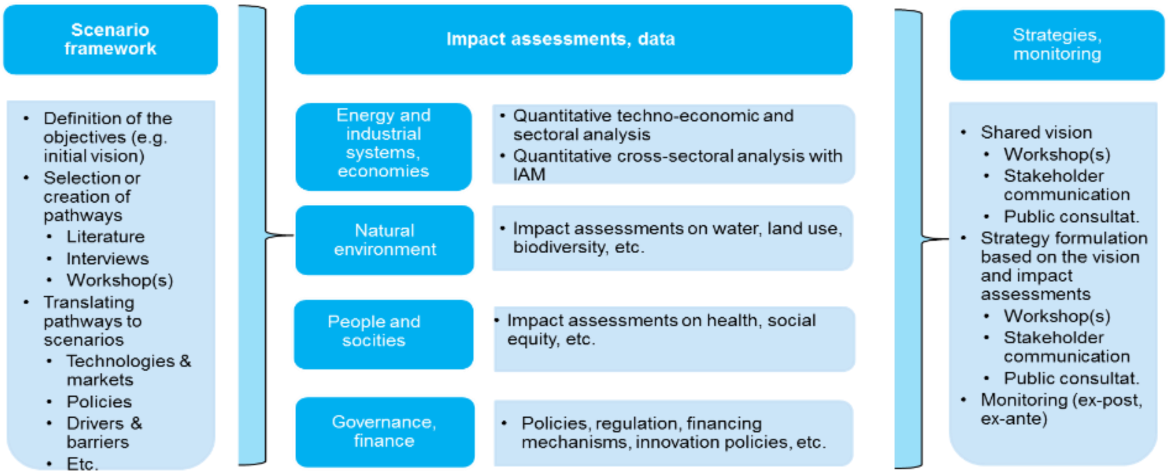

Figure 1. NEGEM framework showing the elements constituting the NEGEM scenario and vision work.

There are several foresight methods to support the systemic formulation of storylines and related scenarios created with quantitative modelling. In NEGEM, Futures Wheel approach (Bengston 2015) was applied in the initial creation of the storylines that took place in the NEGEM General Assembly in Espoo, Finland, in October 2022. Futures wheel is a participatory “smart group” or “mind-mapping” foresight method that provides a description of a future based on the consequences of an event or trend. The method is thus flexibly applicable in various sectors of society and in many types of questions. Notably, VTT has experience in applying Futures Wheel method with quantitative modelling, including projects creating low-carbon pathways for society (e.g. Dufva et al. 2013). In the case of NEGEM, futures with negative emissions and practices were considered the central trends of the futures studied, correspondingly.

After the workshop on October 6th, 2022, the storylines were developed in an iterative process with quantitative modelling and further dialogue between the NEGEM partners. On September 22nd, 2023, the draft storylines and quantitative scenario results were presented in a specific on-line meeting arranged for the whole NEGEM consortium. The scenario process has aimed at updating the scenarios and incorporating the latest NEGEM results and insights from the consortium. In NEGEM, WP3 has especially focused on natural ecosystem and its planetary boundary limits while WP2, WP4, WP6 and WP7 have mostly considered techno-economic systems with policies and measures. WP1 has a more holistic approach on sustainability using the life cycle assessment approach while WP5 is about social systems, including public and stakeholder perceptions.

The basic question in storyline formulation for this analysis is how to take advantage of all the NEGEM results and findings and, especially, how to quantify all the relevant perspectives, boundary conditions, and other features for quantitative scenario modelling. In the case of WP8, the quantitative modelling builds on TIMES-VTT integrated assessment models with both global and European levels captured in this report. Here, we are combining the Futures Wheel approach with a scenario method to paint a picture of future conditions in a narrative format. The initial storylines have been described in earlier deliverables 8.6 and 8.7. In Chapter 3, an updated description for each storyline is given to adjust to the latest NEGEM results and some new findings from literature. Furthermore, the updated storylines have been elaborated to avoid overlapping, to maximize variability in the NETP futures studied, and to maintain consistency with quantitative modelling. Streamlining the initial storylines based on brainstorming of individual groups makes them also more applicable for dissemination purposes.

The following storylines describe the actions taken to reach a NETPs applying society in 2050 describing the societal changes required and technological solutions implemented. The socio-economic developments and key drivers are described for each storyline. The storylines each aim at highlighting one corner of the uncertainty space for a given perspective providing three distinctive narratives.

2.2 NETPs included in the scenarios

The IPCC AR6 WG3 mitigation scenarios for 1.5-2.0.°C mitigation have typically limited the NETPs included to bioenergy with carbon capture and storage (BECCS), re- and afforestation and direct air capture and storage of CO_2 (DACCS) (IPCC 2022). This work includes an expanded portfolio of NETPs, considered as promising in the NEGEM project (Figure 2). In addition to the above NETPs also biochar, enhanced weathering (EW) and soil carbon sequestration (SCS) have been included in the modelling based on NEGEM results and recently reported data from literature. Also, ocean based NET methods are included in one of the scenarios based on collaboration with the OceanNETs H2020 project and data exchange.

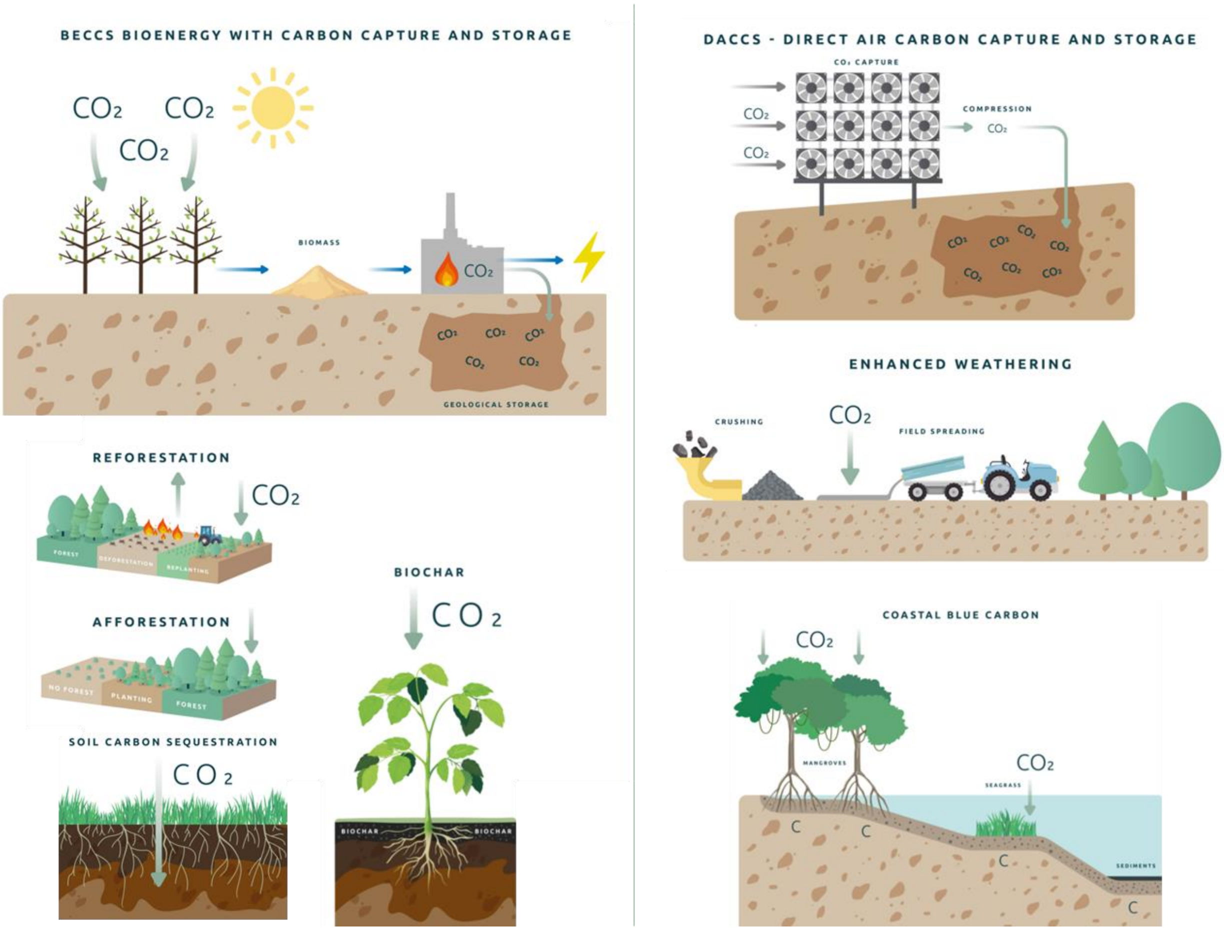

Figure 2 Simplified illustrations of various negative emission technologies and practises among those studied in NEGEM.

2.3 Description of the alternative storylines to reach the 1.5 °C mitigation target

As described above, three alternative storylines were created:

1. Storyline focusing on more optimistic technology development of the NETPs and its market based implementation;
2. Storyline focusing on global environmental sustainability and lifestyle changes not to overshoot planetary boundaries;
3. Storyline focusing on security and self-sufficiency because of geopolitical fragmentation and regional markets.

Based on all three storylines a robust scenario should be achievable through combining the scenarios, representing a more realistic potential of NETPs and feeding the final NEGEM vision, which will be reported in D8.3 (Figure 3).

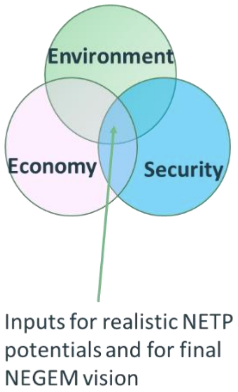

Figure 3. Three NEGEM storylines will create a framework for the assessments of the realistic potentials of NETPs and final NEGEM vision.

All storylines aim to describe the realistic potentials of NETPs with emphasis on different determinants of techno-economic and/or socio-economic feasibility. For example, they all include limitations for large-scale implementation due to environmental concerns on NETPs (e.g. assumptions on land-based biomass potential is based on more strict assumptions on land-use and its change). In the Environment scenario, these constraints are, however, the most emphasised.

Since forecasting the future is practically impossible, **the storylines can only describe potential trajectories on how the future might unfold**. They are not to be interpreted as scenarios forecasting the future or giving specific information on the amounts of certain technology needed in future. However, they can provide scale and understanding on the magnitude of solutions needed under different techno-economic and socio-economic conditions.

2.3.1 Advanced technology and global markets (1.5C-Tec)

The advanced technology and global markets (1.5C-Tec) storyline entails a very rapid NETP scale-up by 2050, which is enabled by various business models, effective international co-operation and open markets, and effective climate policies. The rapid technology development will pull down the costs of the

NETs technologies as there would be incentives to invest in solutions that are more expensive with early innovation funds. Low-cost finance would also allow fast-track deployment of the large-scale investments.

There would be a fundamental transformation of the energy system. The current energy system and industry relying on fossil fuels would need to be transformed with renewables, CCS, NETPs, and carbon capture and utilisation (CCU). To enable efficient deployment of NETPs, regional portfolios would be optimized depending on location, and cooperation would be key for exploiting regional advantages. Strong system integration of NETs with low fossil carbon future would take place.

The main climate policy mechanism would be a high and increasing global carbon price. Moreover, global integration of regional emission allowance markets would be realized with a cap-and-trade system. Nature based solutions would be promoted in a variety of mechanisms, not just carbon markets.

Advanced international co-operation would enable large, distributed CO_2 transport and storage networks to be in place. International co-operation would also facilitate the development of policy regimes enabling ocean-based carbon removal methods to be used in a way that does not conflict with environment and other ocean related activities.

High-income countries support the new technology implementation in the low-income countries and ensure clean energy access for all. Distributive fairness principles are agreed on at the global level, implicating more even distribution of resources and welfare.

Continued discussion between different stakeholder groups, such as business, NGOs, regulators, and citizens, would have paved the way for common understanding and acceptance of different NETPs (D5.3). Thus, in the 1.5C-Tec scenario NETPs have a full social license to operate.

Main characteristics of the storyline regarding NETPs:

- Fast technological development, optimistic cost development, and co-operation between countries including open markets, availability of geological storage sites, pipeline transport, and biomass trade etc. are assumed.
- BECCS potential from energy crops is based on optimistic technological development, and moderate limitations for land use and planetary boundaries. Field and forest residues are used for BECCS, as well as bio-CCS from biogenic CO_2 point-sources.
- DACCS is assumed to be well developed and commercialized.
- Afforestation and reforestation may be implemented according to regional potentials based on land use availability.
- Optimistic assumption on biochar potential from “calorie neutral approach” (Werner 2023), moderate management and optimized performance and yield increases assumed. (Residues not used for biochar but for BECCS to avoid double counting.)
- Moderate soil carbon sequestration potential is assumed due to wider land-use for other NETPs.
- Use of enhanced weathering is included, based on deployment within existing croplands.
- Ocean alkalinisation is included.

- CO_2 storage potentials can be fully utilized – no political barriers (i.e. also onshore storage included).

➔ Storyline comparable with the IPCC AR6 1.5 scenarios with an overshoot.

2.3.2 Nature conservation and biodiversity (1.5C-Env)

The nature conservation and biodiversity storyline (1.5C-Env) describes a world, where no further pressure on overshooting planetary boundaries is accepted. Thus, it assumes highly increased environmental consciousness, which would impact on the resource use. The storyline assumes increased global co-operation to increase resource efficiency and to move towards circular economy. Consumption of material and energy would be reduced and become more efficient also because of more moderate GDP growth compared with the 1.5C-Tec scenario. The energy system is evolving towards very high share of renewables. Reduced consumption and strict limitation for use of resources would lead to slow economic growth.

In this storyline, NETPs are viewed more problematic due to the concerns of potential environmental impacts attached. NETPs should not further increase the pressure on the planetary boundaries, such as biosphere integrity, fresh water, and nutrients (D3.2, D3.3), even though it is recognised that they will be needed to achieve the climate targets of the Paris Agreement. As the use of NETPs is limited, deployment of rapid and stringent emission reductions is needed.

There would be no further land use expansion for NETPs, as biomass-based NETPs would be applied only within current bounds of arable land so that no further pressure was created on planetary boundaries (land use, water, nutrients, biosphere integrity). Monetary value would be given not only to carbon storage but also to other benefits, such as for biodiversity and ecosystem services. Due to land use limitations for other NETPs, DACCS would be needed more rapidly and in large scale, in order to reach the 1.5 °C target.

Dietary changes would take place due to progress towards planetary health diets (e.g. EAT-Lancet Planetary Health Diet), which would release former pasture land for NETPs. The released land area would be used for large-scale reforestation as it would jointly address international targets regarding both climate change mitigation and nature restoration (D3.7). In addition, soil carbon sequestration (SCS) would be prioritized due to co-benefits for soil quality (D1.1). Moreover, there is support for indigenous and local communities to discourage deforestation.

This storyline illustrates a world, where the current views of NGOs on favour of nature based NETPs would become predominant (D5.3). Environmental concerns and lack of social acceptance would constrain the CO_2 storage potential. For non-permanent GHG emission storages, dynamic risk, and liability mechanisms, such as buffer accounts, would be developed to facilitate the liability of stored carbon and lower risk storage over time (D2.4).

Main characteristics of the storyline regarding NETPs:

- No further pressure on planetary boundaries is accepted.
- Significant dietary changes are expected due to progress towards planetary health diets (50% global shift to EAT-Lancet Planetary Health Diet by 2050 and 100% shift by 2100): released pastureland is used for reforestation as this provides best co-benefits with nature restoration targets (D3.7).

- Biomass potential for BECCS is constrained to avoid further pressure on planetary boundaries. However, current use of bioenergy is included, and efficiency improvements are expected as traditional bioenergy use shifts to modern bioenergy use. In addition, field and forest residues are used for BECCS, as well as bio-CCS from biogenic CO_2 point-sources.
- Due to limitations on other NETPs, large-scale DACCS implementation would be needed more rapidly.
- Limited assumption on biochar potential from "calorie neutral approach" (Werner 2023), marginal management and current performance and lower yield increases assumed. (Residues not used for biochar but for BECCS to avoid double counting.)
- High soil carbon sequestration potential is assumed due to reduced land-use for other NETPs.
- Use of EW is constrained due to potential eco-toxicity risks illustrated in NEGEM LCA result (D1.5.)
- Ocean based NETPs are forbidden due to concerns of environmental risks (D3.5 and D3.8).
- CO_2 storage potentials are constrained due to lack of social acceptance (on-shore storage potential would not be used).

➔ A critical assessment of NETPs based on planetary boundaries and assumptions on potential environmental risks.

2.3.3 Security and self-sufficiency (1.5C-Sec)

In the "Security and self-sufficiency" storyline, the global development follows the current trajectory of multi-crisis mode with geopolitical situation, climate crisis and energy crisis. Nations and regions turn more to themselves, meaning local energy sources, production chains and food supply take on more significance. The world operates more in clusters through regional development rather than global, market-based co-operation. Co-operation and exchange are seen within clusters, with the European level underlined as important for the targets of NEGEM. Isolation, lack of co-operation and high prices would lead to slower economic growth than in the 1.5C-Tec scenario.

In this set-up, the priority of Paris agreement, and if the 1.5 C target can be achieved globally is questionable. Technological development in general is seen as challenging, and maybe even more so with NETPs due to significant time, R&D and international policy requirements for their large-scale introduction and deployment.

With limited international cooperation and mobility of resources, NETPs development would materialise within the boundaries of land and clean energy availability and resource independency. Energy independence would be essential to ensure self-sufficiency as NETPs, such as DACCS, require a lot of energy. DACCS would be limited by local renewable energy supply. Solutions with side benefits and implementable within local circumstances would be emphasized.

Dietary changes would be needed to reduce pressure on land use, energy, and food security. Dietary changes might be also forced due to use of local products and high food prices due to less functioning markets. There could be consequent revolutionary agricultural processes, with less energy and water requirements. As a positive opportunity from a European perspective, energy independence can be increased, and exportable technological solutions could be implemented from the locally developed NETPs applications.

Trust to build CO_2 pipelines between regions and countries would be insufficient, which would have consequences for the portfolio and volume of NETPs foreseen. Lack of international co-operation and heightened security concerns would reduce the CO_2 storage potential. In addition, ocean alkalinisation is not feasible due to lack of international co-operation on its policy and regulation.

Main characteristics of the storyline regarding NETPs:

- Slower technological development due to lack of co-operation and/or global open markets. Constraints for pipeline infrastructures (Russian gas, CO_2 pipelines, etc.). Imports of oil, gas and electricity from Russia remain fully terminated through the whole scenario period (i.e. up to 2100).
- BECCS potential from energy crops is based on assumption of land release due to significant diet changes (25% global shift to EAT-Lancet Planetary Health Diet, D3.7). The diet changes may occur partly due to higher food prices and increased use of local options in an isolated world. Field and forest residues are used for BECCS, as well as bio-CCS from biogenic CO_2 point-sources.
- DACCS technology is assumed to remain rather expensive due to slower technological developments in an isolated world (pessimistic estimate for price development from D5.4 used)
- Afforestation and reforestation are deployed, as they are considered local solutions.
- Moderate assumption on biochar potential from "calorie neutral approach" (Werner 2023), marginal management and optimized performance and with small yield increases assumed. (Residues not used for biochar but for BECCS to avoid double counting.)
- Moderate soil carbon sequestration potential is assumed due to increased land-use for other NETPs.
- Use of enhanced weathering is deployed, as considered a local solution.
- Ocean alkalinisation is not seen as an option due to lack of international co-operation on policy and regulation.
- Constraints for CO_2 storage potential take place due to lack of international co-operation and security concerns. Onshore CO_2 storage in Europe is very small, and low CO_2 storage potentials are applied globally.

➔ A critical assessment based on more conservative technology development, acceptance and potential risks related CO_2 transport and storage.

3 Modelling the alternative scenarios with TIMES-VTT IAM and with Pan-European TIMES

3.1 Description of the TIMES-VTT model

The TIMES-VTT model is a global multi-region model based on the ETSAP TIMES modelling framework. The model itself is a derivative of the global ETSAP TIAM model (TIMES Integrated Assessment Model, see Loulou 2016, Loulou 2008, Loulou & Labriet 2008). The methodology can be characterized as bottom-up, technology rich partial equilibrium modelling, and the model is usually run in a perfect foresight mode. The model covers all sectors, focusing on energy and emissions, with all Kyoto gases included (Figure 4).

With respect to regional structure, the global energy system is divided into 19 regions in the model. Within each region, the model describes the entire energy system including all essential current and future energy technologies over the full energy chains from primary energy supply to the useful energy services in the end-use sectors. Each region can also trade in various commodities (e.g. fuels, electricity, CO_2) with other regions, subject to resource availability and costs, and transportation infrastructure.

The model is driven by a set of demands for useful energy services in all sectors: agriculture, residential, commercial, industry and transport. The construction of the exogenous demands for energy services may be done by using the results from general equilibrium models, which can provide a set of coherent drivers for each region and for the world as a whole, such as population, household formation, GDP, and sectoral outputs.

The decoupling factors between the drivers and the demands for useful energy services account for phenomena such as saturation and suppressed markets and are in part empirically based. Most of these final demands have economic growth as their key driver. However, the demands for all other commodities (e.g. electricity, heat, various fuel commodities, emission allowances, CO_2 geological storage services) in the system are endogenously determined by the model according to their supply-demand equilibrium, which must always satisfy various resource and sustainability constraints.

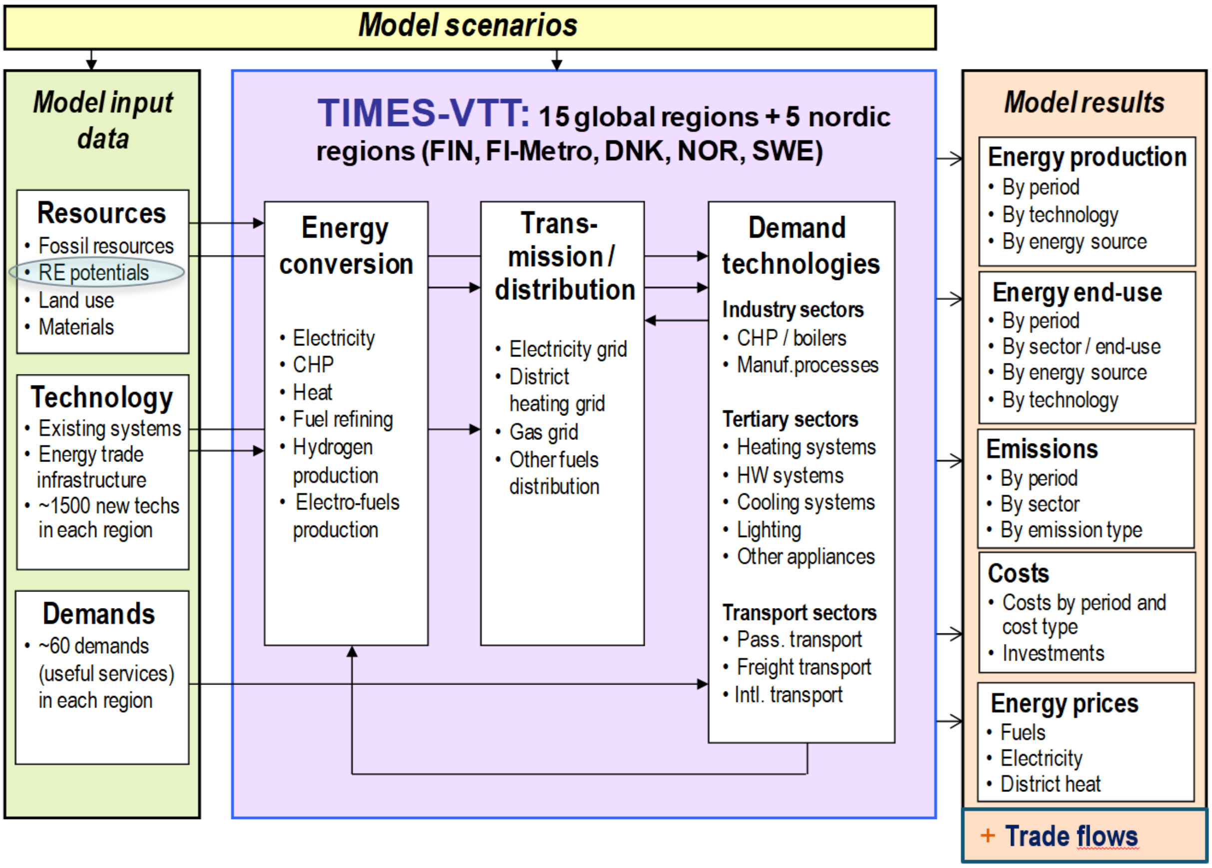

Figure 4. Components of the TIMES-VTT energy system model and simplified flowchart for one region.

Apart from the Baseline demand projections, the exogenous inputs of the model include numerous techno-economic parameters of the technologies, processes, and commodities. The outputs of the model (endogenous variables) include energy carrier variables (energy flows) between the different steps of the energy system, emissions and waste variables, capacity planning of the different technologies, and different economic variables, including energy prices, costs, profits, etc. In addition, the energy losses associated with the different processes are also endogenous to the model.

For supporting global integrated assessment modelling of climate change, the TIMES framework also incorporates an integrated climate module, with a three-reservoir carbon cycle for carbon dioxide (CO_2) concentrations and single-box decay models for the atmospheric methane (CH_4) and nitrous oxide (N_2O) concentrations, and the corresponding functions for radiative forcing. The forcing functions for CO_2, CH_4 and N_2O follow the non-linear formulations presented in the IPCC Fifth Assessment Report (Myhre et al. 2013) but are linearized around user-defined points. If necessary, by using an iterative approach the accuracy of the linearization can be improved to an arbitrary level. Additional forcing induced by other natural and anthropogenic causes is taken into account by means of exogenous projections. The changes in the global mean temperature are simulated for two layers, surface, and deep ocean (Loulou et al. 2016). When modelled, the emissions of fluorinated gases (F-gases), including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF6), can also be taken into account in the climate model by converting them into GWP-equivalent CO_2 emissions. Although both the carbon cycle and the concentrations of CH_4 and N_2O are represented by quite simple models, the radiative forcing from anthropogenic GHG emissions is reasonably well approximated by the TIMES climate module and is calibrated to reproduce historical levels.

The model has been used earlier to study global, regional, and national mitigation pathways to reach 1.5-2°C mitigation targets and also for impact assessments of national, Nordic and EU level climate and energy policies (Lehtilä & Koljonen 2018). TIMES-VTT model has been the core tool in formulating and analysing the impacts of Finland's climate and energy strategies and policies, including climate neutrality target by 2035 (Koljonen et al. 2021a, Koljonen et al. 2022). Recently, TIMES-VTT was also used to support the Finnish Government's decisions in updating national Climate Law (Koljonen et al. 2021b) and to update Finland's bioeconomy strategy (Koljonen et al. 2021c). A detailed description of the TIMES methodology can be found in the documentation (Loulou et al. 2016).

For the scenarios of the NEGEM project, we formulate long-term scenarios until 2100, using some of the key characteristics of mitigation pathways reported in the IPCC AR6 WG3 (2022). The pathways follow the current UNFCCC NDCs until 2030 and immediate action towards limiting warming to 1.5–2°C.

3.2 Description of PAN-European TIMES

PAN-European TIMES is a linear optimisation bottom-up technology model generated with the TIMES model generator. JRC-EU-TIMES model was developed as an evolution of the PAN-European TIMES in several European research projects[1] by JRC IPTS and IET institutes. The model is designed for analysing the role of energy technologies for meeting Europe's energy and climate change related policy objectives. The model represents the energy system of the whole Europe (EU-28 + EFTA + the Balkans) from 2010 to 2060, each country being their own region. The equilibrium is driven by the maximisation of the discounted present value of total surplus (i.e., minimising the total system cost) which is subject to many constraints such as supply bounds for primary resources, technical constraints of each technology, balance constraints for all energy forms and emissions and the satisfaction of a set of demands for energy services in all sectors (primary energy supply, electricity generation, industry, residential, commercial, agriculture and transport).

The model requires exogenous inputs of end-use energy services and materials demand, characteristics of the existing and future energy-related technologies, present and future sources of primary energy supply and their potentials, and policy constraints and assumptions.

The characterization of energy supply and demand technologies relies on data from Eurostat, supplemented by inputs from national sources to ensure alignment with official energy statistics. A meticulous bottom-up approach fine-tunes technology specifications, particularly for sectors with less comprehensive data, such as residential and commercial sectors. An extensive model database compiles detailed technical and economic information regarding new energy technologies. The original database is based largely on the Energy Technology Database by JRC-IET (for electricity generation) and on JRC-EU report "Best available technologies for the heat and cooling market in the European Union" (Pardo et al., 2012).

In terms of economic projections, GEM-E3 provides valuable insights by generating growth scenarios for the European Union (EU), amalgamating factors like population growth, energy prices, technological advancements, and labor productivity. These projections subsequently shape national macroeconomic drivers, including GDP growth, private consumption, and the growth of different sectors.

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[1] RES2020, REALISEGRID and REACCESS European research projects.

For information regarding primary energy sources, their potentials, and costs, the model relies on various sources including GREEN-X, POLES, RES2020, and the updates from the REALISEGRID project.

The model also provides flexibility by allowing users to define policy constraints, such as carbon emission limits, taxation policies, subsidies, and emissions trading. This enables customization to address specific policy questions. In summary, this model seamlessly integrates data from a wide range of sources to project energy and materials demand while considering economic, technological, and policy variables across diverse countries. More detailed model description is found in JRC (2013).

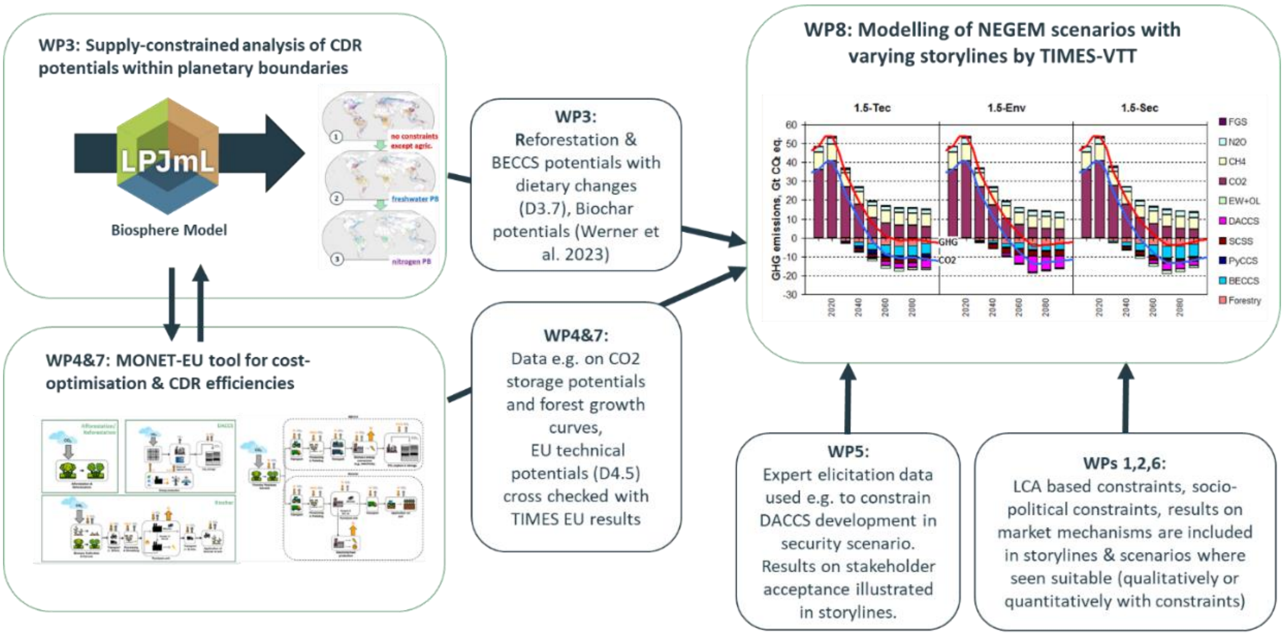
Within the NEGEM project, the database of the PAN-European TIMES model has been updated, in particular with respect to the negative emission technologies, but also to some extent in various other details, such as the demand drivers (partly only), EU member state emission targets, offshore wind power potentials, CO_2 storage potential, and hydrogen, e-fuel, and energy storage technologies. Existing power generation capacities up to 2021 have also been updated with recent statistical data (EIA 2023, IRENA 2023, BP 2022). In addition, the impacts of the Russian war against Ukraine have been considered in the projected energy trade potentials between Europe and Russia, either directly or via Belarus or Ukraine. The trading possibilities for natural gas and electricity have been largely reduced to zero for the whole model horizon, however, somewhat depending on scenario, such that in the Security scenario the trade links have been assumed to be most extensively closed.

3.3 Data and scenarios assumptions from earlier NEGEM work

The scenarios modelled here are inspired by the work done in other NEGEM work packages (WPs) both qualitatively and quantitatively (Table 1). The workshops and numerous discussions between the project partners have shaped the starting point for the storylines and scenarios (as described above). For the scenario analysis, especially the results from WP1 life cycle analysis (LCA) and WP3 land use modelling by LPJmL-NEGEM model have been used to set the potentials and constraints used in the Environment scenario. These constraints aim to reduce pressure caused by NETP deployment on planetary boundaries and on some environmental impact categories studied by LCA.

A big effort has been made to illustrate the impact of dietary changes on the reforestation potential in 1.5C-Env scenario and on the BECCS potential in 1.5C-Sec scenario based on D3.7 (Werner 2023). In addition, data on biochar potentials for all scenarios comes from WP3, being thus compatible with BECCS and reforestation potentials (Werner 2023b). The assumptions on these were described with the storyline descriptions above. For example, here no residues are used for biochar production so there is no risk with double counting with BECCS from residues. Several discussions between WP3 and WP8 took place on how to apply data from LPJmL-NEGEM modelling to the TIMES model.

Data from WP4 and WP7 were used for some CO_2 storage potentials (biophysics database D4.2, Sunny 2022), and for defining the forest growth curves (Chiquier 2022). Discussions with WP5 took place to enable the use of their results in the scenario modelling. Data from WP5 expert elicitations were used to constraint the price development of DACCS in the Security scenario, and results of stakeholder perceptions were qualitatively used in the storylines (D5.4, Reiner et al. 2023). Also, the results of WP2 and WP6 qualitatively inspired the formulation of the storylines. Figure 5 illustrates the data and information flows to the scenario modelling.



WP3:
Reforestation & BECCS potentials with dietary changes (D3.7), Biochar potentials (Werner et al. 2023)

WP4&7:
Data e.g. on CO2 storage potentials and forest growth curves,
EU technical potentials (D4.5) cross checked with TIMES EU results

WP5:
Expert elicitation data used e.g. to constrain DACCS development in security scenario.
Results on stakeholder acceptance illustrated in storylines.

WPs 1,2,6:
LCA based constraints, socio-political constraints, results on market mechanisms are included in storylines & scenarios where seen suitable (qualitatively or quantitatively with constraints)

Figure 5 Data and information flows from NEGEM WPs to the scenario modelling

Table 1. Description on use of WP results in NEGEM storylines and scenarios

WP results used	Quantitative / Qualitative input	How the result have been used / inspired the storylines and scenarios
WP1: LCA results for NETPs (D1.1, 1.4, 1.5,3.9)	Qualitative	Selection of NETPs studied is based on D1.1. Performance of NETPs according to LCA studies has inspired the storylines: e.g. DACCS considered promising, nature based methods promising, BECCS from residuals materials promising, EW promising but with a risk of eco-toxicity and thus constraint in the 1.5C-Env scenario.
WP2: Results on commercialization methods, discussion on storage permanence (D2.1, 2.2)	Qualitative	Storylines are inspired by the analysis on commercialization methods, which currently consider mostly afforestation and SCS. Afforestation has been included in 1.5-Tech and 1.5Sec, and SCCS in all scenarios.
WP3: Results on biomass and af-/reforestation potentials with dietary changes (D3.3, 3.7), results on land and calorie neutral biochar potentials (Werner et al. 2023b)	Quantitative	Data on reforestation potential in 1.5C-Env scenario and on the BECCS potential in 1.5C-Sec scenario are based on D3.7 and estimations on significant global dietary changes. Data on biochar potentials for all scenarios from (Werner 2023b), being thus compatible with BECCS and reforestation potentials. Constrain for afforestation in 1.5C-Env (D3.3).
WP4&7: Results on storage potentials, forest growth curves and EU and member state NETPs portfolios (D4.2, 4.5, Chiquier et al. 2022)	Quantitative	Data used for some CO_2 storage potentials from biophysics database (D4.2). Definition of the forest growth curves from Chiquier et al. (2022) to enable use of D3.7 data for reforestation potentials. Results of this deliverable cross-checked with D4.5 on Member State potentials, and discussion provided.
WP5: Expert elicitation data, results on stakeholder views (D5.2, 5.3)	Quantitative / Qualitative	Data from expert elicitations (D5.4) is used to constraint the price development of DACCS in the Security scenario. Results of stakeholder perceptions qualitatively used in the storylines,

		illustrating the acceptance of NETPs by different stakeholder groups.
WP6: Results and discussions on policy frameworks (e.g. D6.1, 6.3)	Qualitative	Learnings from WP6 deliverables and discussions have been used to inspire the storylines. 1.5-Tech would represent development with strong international co-operation also on NETPs regulation, whereas this co-operation would lack in 1.5C-Sec. In 1.5C-Env emphasis would be on policy framework respecting planetary boundaries.

3.4 Description of the alternative scenarios

3.4.1 Overview of the final global scenarios

For the final NEGEM scenario analysis four global scenarios are studied; a reference scenario with NDCs emission trajectories and three global climate policy scenarios based on the NEGEM storylines and 1.5°C target for the maximum global temperature change with an allowed interim overshoot. In the reference scenario, the climate policies imposed consist only of the updated NDCs under the Paris Agreement, which were published at the COP26 in October 2021 (United Nations 2021). The policies considered in the scenarios are mainly implicit through the economic, energy and technology diffusion data. An exception is the explicit NDCs, which are modelled in the reference scenario separately for Europe, USA, China, India, and Africa, as well as for the world as a whole. The exploitation of limited renewable energy resources such as hydro and biomass are constrained in all model regions to avoid overly large expansions that could be environmentally and politically sensitive.

In the interim NDC registry[2] as of 12 October 2021, the NDCs covered 94.1% of the total global emissions in 2019, which are estimated at 52.4 Gt CO_2 eq. without LULUCF. Since the COP27, there have been minor updates in the NDCs, which are not considered in our reference scenario. However, the NDCs are not comparable between each other as they vary in content, background assumptions, scope and coverage, etc. In addition, they do not include all the information, which would be needed for scenario modelling. As an example, the NDCs typically include gross GHG or CO_2 emission reduction targets for 2030 as well as net carbon neutrality target by 2050 or some other specified year (e.g., including LULUCF) but no complete information on either gross or net GHG targets by 2030 and beyond. In the IPCC AR6 report (2022), NDCs were analysed and mitigation pathways with NDCs until 2030 and below 2°C thereafter were reported. As the IPCC report did not include a complete scenario data on NDCs, we have used one scenario dataset published in the IIASA AR6 database as a reference for and the benchmark scenario (see below).

The NEGEM scenarios modelled are long-term scenarios for the global energy system until 2100. For the scenario formulation, we have used the key characteristics of mitigation pathways reported in the IPCC AR6 WG3 (2022). The pathways follow the NDCs until 2030 and immediate action towards limiting warming to 1.5-2 °C, as follows:

- **NDC (Reference scenario):** The global and European GHG emissions reductions trajectory is taken from the EN_INDCi2030_1400f scenario results of the REMIND-MAgPIE 2.1-4.2 model in the IIASA database (IIASA 2022). This scenario describes the impact of Nationally Determined Contributions on the annual GHG emission trajectories, on the global scale and by region, which lead to a temperature increase of about 2°C by 2100.
- **1.5C-Tec:** The scenario assumptions correspond to the "Advanced technology and global markets" storyline. The global temperature change is limited to 1.5°C by 2100, but the minimum

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[2] United Nations NDC registry can be found in https://unfccc.int/NDCREG

regional GHG emissions reduction trajectories are as in the NDC scenario. Interim overshoot is allowed. World population growth is stably slowing down, reaching about 9.8 billion by 2100. Economic growth drivers are modelled according to SSP2 storyline from IPCC AR6 report.

- **1.5C-Env:** The scenario assumptions correspond to the "Nature conservation and biodiversity" storyline. The global temperature change is limited to 1.5°C by 2100, but the minimum regional GHG emissions reduction trajectories are as in the NDC scenario. Interim overshoot is allowed. World population growth is stably slowing down until 2100. Economic growth drivers are modelled according to SSP4 storyline from IPCC AR6 report, assuming slowdown of global economic growth, reflecting enhanced environmental awareness and circular economy. For Europe, CO_2 price is assumed to develop according to the recommendations by the European Commission for a WAM scenario (EC 2022), and the 2030 targets for burden sharing sector are set by region, in accordance with EU Regulation (2023/857). The methane emission reduction due to the assumed dietary changes is taken into consideration in the modelled emissions associated to livestock (46% emission reduction in CH_4 emissions according to D3.7).
- **1.5C-Sec:** The scenario assumptions correspond to the “Security and self-sufficiency” storyline. The global temperature change is limited to 1.5°C by 2100, but the minimum regional GHG emissions reduction trajectories are as in the NDC scenario. Interim overshoot is allowed. World population growth is stably slowing down until 2100. Economic growth drivers are modelled according to SSP4 storyline from IPCC AR6 report, assuming slowdown of global economic growth, reflecting the impacts of deglobalization and polarization. For Europe, the CO_2 price is assumed to develop according to the recommendations by the European Commission for a WAM scenario (EC 2022), and the 2030 targets for burden sharing sector are set by region, in accordance with EU Regulation (2023/857). The methane emission reduction due to the assumed dietary changes is taken into consideration according to D3.7.

In the NDC scenario, the total global net GHG emissions with removals are about 25 Gt(CO_2 eq.) in 2050 and about 11 Gt(CO_2 eq.) in 2100. The scenario is characterized as a category C4 scenario in the IPCC AR6 WG3, which limits warming to 2°C (with a probability of 50% or greater). Overshooting the temperature targets before 2100 is allowed in our three global climate change mitigation scenarios, but with a high penalty cost simulating the associated damage (about 10% of global GDP per degree). Consequently, in the scenario modelling results the overshooting will be quite small due to the damage exceeding the compliance cost.

According to the model results, the EN_INDCi2030_1400f scenario does indeed lead to a 2.0°C temperature increase by 2100, and according to the IPCC AR6 scenario documentation that should be reached with a probability higher than 50%. Therefore, we may assume that the three 1.5°C scenarios may also be categorized as reaching their temperature targets with the same level of probability. The assumed climate sensitivity (3.0) also corresponds well to a central estimate. As an additional back-end temperature constraint, in the scenarios we also required that by 2150 the global temperature increase must be further reduced to at most 1.3°C, assuming that GHG emissions remain constant at the 2100 levels during 2100–2150.

3.4.2 Main assumptions related to NETPs in the Global scenarios

In all four scenarios, an expanded portfolio of NETs is modelled for carbon dioxide removal. These technologies and practices include afforestation and reforestation schemes, various BECCS technologies in the energy conversion sector, pyrolysis process for soil amendment with biochar, a few DACCS technology variants, enhanced weathering (EW), soil carbon sequestration (SCS), and ocean alkalinisation (OL). The assumptions related to all NETs have been updated based on NEGEM data and newly published literature sources. In accordance with the scenarios and their background storylines presented in section 2.2, the main differences in the modelling assumptions concerning NETPs are summarized in Table 2.

BECCS technologies modelled include several power plant technologies, combined heat and power production (CHP), many fuel refining technologies, hydrogen production, and carbon capture in biogenic point-sources e.g. in pulp and paper industry. The technology data for BECCS is based on numerous studies, but for basic biomass-fuelled power plant technologies the EU Reference Scenario 2020 technology assumptions and JRC data have been used (EC 2021, Tsiropoulos et al. 2018). For all scenarios, use of field and forest residues for BECCS is considered, as well as bio-CCS from biogenic CO_2 point-sources. The assumption for the global bioenergy crop potential is between 14 and 55 EJ in 2050, and somewhat higher by 2080 (along with stagnating population and increasing productivity). For Europe, the assumed potentials are 1.6–3.8 EJ in 2050, of which the lower end range is well in line with the low and mid estimates of the sustainable potential by the JRC (Ruiz et al 2019) and those published by Vera et al (2021) using the EU REDII sustainability criteria. In the 1.5C-Tec scenario, potential for energy crops is based on optimistic development, and less strict limitations for land use and planetary boundaries related to land-system change, biosphere integrity, freshwater use and nitrogen (N) cycling. In the 1.5C-Env scenario the potential of biomass feedstock from energy crops is limited relatively close to the current use levels by 2050, to avoid further pressure on planetary boundaries. In the 1.5C-Sec scenario, the energy crops potential is based on assuming land being released due to significant diet changes (25% global shift to EAT-Lancet Planetary Health Diet, D3.7), leading to the largest energy crops potentials compared to other scenarios (Table 2).

For biochar from pyrolysis process, the latest results from the “land and calorie neutral approach” by Werner et al. (2023b) are used, with varying assumptions on crop management, conversion performance, and yield improvements due to biochar application. The resulting biochar-mediated yield increases on cropland (up to 15%–30%, Werner et al. 2023b) are assumed to compensate the land requirements for producing the biochar biomass feedstock and would thus make biochar as a land-use neutral NET option. In the 1.5C-Tec scenario the assumptions are the most optimistic, as technology development is considered to progress favourably in that storyline. For 1.5C-Env the assumptions are the most pessimistic, as the process is considered to realise with less intensive land management and less optimistic technology development. For the 1.5C-Sec scenario moderate assumptions are made. Here residues are not used for biochar but may be used for BECCS, to avoid double counting.

As a side-benefit, using the biochar as a soil improvement is assumed to increase soil fertility and thus bring about considerable reductions also in the N_2O emissions from agricultural lands. Although most papers on the subject seem to agree on a potential emissions reduction, good numerical estimates appear to be scarce in the literature, and the modelling assumptions thus include high uncertainties. We assume N_2O emission reductions adding 25% on top of the negative emissions obtained by the permanent carbon stored in soil, in terms of CO_2 equivalent emissions (Gaunt & Lehmann 2008).

Afforestation is not included in the 1.5C-Env scenario, because according to Braun et al. (2022), afforestation may be associated with non-native tree monocultures that have adverse effects on planetary boundaries. However, other studies define afforestation to include both afforestation and reforestation, both of which are defined by FAO’s Forest Resource Assessment (FAO 2018) as the establishment of forest through planting and/or deliberate seeding. It has also been argued that afforestation implemented as planted forests without active management after establishment reduce the adverse effects on nutrient and hydrological cycles and biodiversity (Doelman et al. 2020). Thus, afforestation is included in the other scenarios together with reforestation. For 1.5C-Env, the reforestation potential is driven by significant dietary changes due to progress towards planetary health diets (50% global shift to EAT-Lancet Planetary Health Diet by 2050 and 100% shift by 2100). The released pastureland is in total used for reforestation as this provides best co-benefits with nature restoration targets (D3.7). Forest growth curves from Chiquier et al. 2022 were used to estimate the growth over the modelling period (as WP3 results were modelled only for 30 years' time horizon).

Soil carbon sequestration (SCS) potentials are taken from a comprehensive external study (Roe et al. 2021), using cost-effective potentials only. For 1.5C-Tec and 1.5C-Sec the potentials are constrained in comparison to 1.5C-Env due to more intensive land use for bioenergy crops and afforestation. The potential of SCS as a negative emission practice has attracted attention in recent years because of its considerable potential, up to 9 Gt CO_2 eq./a according to IPCC (2019). Compared to such high-end estimates, the assumptions adopted for our scenarios (Table 2) can be considered sufficiently conservative, in line of the NEGEM objectives of realistic sustainable potentials.

EW potentials and the associated grinding energy requirements are based on Beerling et al. (2020). In the 1.5C-Env scenario the potentials were reduced from those due to toxicity risks according to NEGEM LCA studies. For Europe, however, the EW potentials were spread over a wider range of EU member states, including the UK, Portugal, Austria, Czech, Slovakia and Hungary in addition to the five countries (Germany, France, Spain, Italy and Poland) that were only considered by Beerling et al., using rough estimates on the availability of rock and arable land. Among these additional countries, the potential in the UK was assumed to be the highest, 15–20 Mt(CO_2)/a, based on Royal Society (2018) and Kantzas et al. (2022). The original potentials in the five EU member states were thereby somewhat levelled down.

Additionally, one should note that the potentials for land use based NETPs, afforestation, reforestation, bioenergy crops, biochar, SCS, and EW may all be based on using similar types of land or biomass, and therefore the potentials should be verified not to include double counting, or the competing land use potentials should be endogenously modelled. For the NEGEM scenarios risk of double counting is minimised by using data from WP3 land use modelling where possible, that data being compatible for BECCS, reforestation and biochar. Also, here the residues are used only for BECCS, and not for biochar. However, also assumptions on SCS from literature may be based on a certain level of residues left on the fields, which can create a risk of double counting. In addition, EW application requires vast land areas. It is unclear if several NETPs can be simultaneously applied on the same land area, e.g. if soil carbon sequestration and enhanced weathering can be done simultaneously. Thus, the possibility of double counting cannot be completely removed. Nevertheless, based on the JRC Global Energy and Climate Outlook 2021 analysis, which employs the IIASA Globiom model for land-use balances, we think that the assumed afforestation and energy crop potentials can be considered reasonably well mutually consistent also in the 1.5C-Tec scenario (Keramidas et al 2021).

The DACCS option is modelled based on a few technology variants described in the literature (e.g. Keith et al. 2018, Liu et al. 2020, DEA 2021), including full process energy balances and cost estimates for plant investments and operation. However, some further refinement may be needed concerning the assumed amounts of the make-up chemicals needed to account for the regeneration losses within the process (see e.g. Realmonte et al. 2019). In the cost projections, we have avoided using the most optimistic estimates in the literature, which may often employ rather rudimentary learning rate approaches without detailed process analysis. Moreover, in the modelling we have now included only technology concepts based on the reasonably well-proven liquid sorbent processes. In several studies, processes based on solid sorbents have been assessed potentially more promising in terms of energy requirements and total removal costs, but these processes involve still considerably higher uncertainties in terms of their techno-economic performance, and therefore to avoid too high uncertainties about the role of DACCS, confining to the more proven concepts was considered reasonable for the NEGEM scenarios.

We also included an ocean alkalinisation option, based on ocean liming, in 1.5C-Tec scenario. In 1.5C-Env and 1.5C-Sec, ocean liming is not allowed according to the storylines. While the required lime production by itself inevitable causes some fossil emissions from the limestone feedstock and energy inputs, that sub-process can be equipped with carbon capture and subsequent storage. These are endogenously modelled subsystems downstream of the ocean liming technology option, which also assumes considerable investments into the ship fleet and port facilities needed. The feasible global potential for negative emissions has been estimated to be up to 3 Gt(CO_2)/a in the parallel OceanNETs Horizon 2020 project (van Kooten et al. 2022). The energy and material balances as well as the costs for the ocean liming option are also based on the OceanNETs data, except for the lime production sub-systems, for which data from a comprehensive Swedish study have been adopted (Sandberg 2022).

For the BECCS and DACCS, permanent geological storage is needed for the CO_2 captured in order to achieve negative emissions. The CO_2 storage potentials assumed in the scenarios are higher in the NDC and 1.5C-Tec scenarios, and limited according to the storylines in 1.5C-Env and 1.5C-Sec scenarios, due to social acceptability and security concerns. The potentials in Europe are based on the NEGEM project data (D4.2, Sunny et al. 2022) and the global potentials are primarily based on the lower estimates of Kearns et al (2017, for saline aquifers) but partly also on the TIAM datasets (Loulou & Labriet 2008, Selosse & Ricci 2019). Trade in the storage services is also allowed within the European regions that could utilize the large offshore storage potential around the North Sea area, and the CO_2 transportation costs are in the global model based on those estimated for shipping. In the European model, trade in the storage services is likewise extensively modelled (based on the original JRC-EU-TIMES model, see JRC 2013).

Table 2. Summary of the modelling assumptions concerning NETPs in the global NEGEM scenarios (G = Global, E=Europe).

NETP assumption	NDC	1.5C-Tec	1.5C-Env	1.5C-Sec	References
Energy crop feedstock potential	G-2050: 45 EJ/a G-2080: 60 EJ/a E-2050: 2.4 EJ/a	G-2050: 45 EJ/a G-2080: 60 EJ/a E-2050: 2.4 EJ/a	G-2050: 14 EJ/a G-2080: 20 EJ/a E-2050: 1.5 EJ/a	G-2050: 55 EJ/a G-2080: 70 EJ/a E-2050: 3.8 EJ/a	Ruiz et al (2019) Vera et al (2021) Frank et al (2021)
BECCS potential	Driven by feedstock supply potentials	Driven by feedstock supply potentials	Driven by feedstock supply potentials	Driven by feedstock supply potentials	Fuss et al (2018)
DACCS potential	G-2050: 5 Gt(CO2)/a G-2080: 30 Gt(CO2)/a	G-2050: 5 Gt(CO2)/a G-2080: 30 Gt(CO2)/a	G-2050: 5 Gt(CO2)/a G-2080: 20 Gt(CO2)/a	G-2050: 5 Gt(CO2)/a G-2080: 20 Gt(CO2)/a	Fuss et al (2018) Realmonte et al 2019
Biochar (PyCCS) potential	G-2050: 1.9 Gt(CO2)/a G-2100: 2.3 Gt(CO2)/a G-2025–2100: 140 Gt(cum.)	G-2050: 1.9 Gt(CO2)/a G-2100: 2.3 Gt(CO2)/a G-2025–2100: 140 Gt(cum.)	G-2050: 0.2 Gt(CO2)/a G-2100: 0.3 Gt(CO2)/a G-2025–2100: 15 Gt(cum.)	G-2050: 0.4 Gt(CO2)/a G-2100: 0.7 Gt(CO2)/a G-2025–2100: 30 Gt(cum.)	Werner et al (2023b)
SCS potential	Not considered	G-2050: 2.0 Gt(CO2)/a	G-2050: 2.9 Gt(CO2)/a	G-2050: 2.0 Gt(CO2)/a	Roe et al (2021)
Afforestation potential	G-2050: 3.0 Gt(CO2)/a G-2100: 5.0 Gt(CO2)/a G-2025–2100: 230 Gt(cum.)	G-2050: 3.0 Gt(CO2)/a G-2100: 5.0 Gt(CO2)/a G-2025–2100: 230 Gt(cum.)	Not allowed	G-2050: 3.0 Gt(CO2)/a G-2100: 5.0 Gt(CO2)/a G-2025–2100: 240 Gt(cum.)	Doelman et al (2020) Frank et al (2021) Braun et al (2022)
Reforestation potential	Not considered (included elsewhere)	Not considered (included elsewhere)	G-2050: 2.9 Gt(CO2)/a G-2100: 200 Gt(CO2) (cumul. by 2100)	Not considered (included elsewhere)	Braun et al (2022) Werner et al (2023a)
Ocean alkalinisation	G-2050: 2.2 Gt(CO2)/a G-2080: 3.0 Gt(CO2)/a	G-2050: 2.2 Gt(CO2)/a G-2080: 3.0 Gt(CO2)/a	Not allowed	Not allowed	Fuss et al (2018) Van Kooten (2022)
Enhanced weathering	Not considered	G-2050: 2.0 Gt(CO2)/a	G-2050: 1.1 Gt(CO2)/a	G-2050: 2.0 Gt(CO2)/a	Fuss et al (2018) Beerling et al (2020)
Geological CO2 storage potential	G: 6700 Gt(CO2) E: 175 Gt(CO2)	G: 6700 Gt(CO2) E: 175 Gt(CO2)	G: 3200 Gt(CO2) E: 110 Gt(CO2)	G: 2700 Gt(CO2) E: 80 Gt(CO2)	Kearns et al. (2017) Selosse & Ricci (2017) Sunny et al (2022)

3.4.3 Overview of the final European scenarios

In the Pan-European TIMES model, the 1.5C-Tec, 1.5C-Env, and 1.5C-Sec scenarios are modelled up to 2060. One should note that the European model includes only CO_2 emissions and excludes current and projected Baseline emissions from the AFOLU/LULUCF sector. Total EU-wide ETS sector emission targets and member state specific emission reduction targets for the effort sharing sectors were defined up to 2030 closely in accordance with the so-called Fit for 55 package, thereby imposing a minimum of 67% reduction in total ETS emissions (from 1990) and a minimum of 40% reduction in the total ESR emissions (from 2005) in EU-28 by 2030, from 2005. The country-specific targets defined for the effort sharing sector are thus also complying with the EU effort sharing regulation (EU 2023/857). Beyond 2030, the total CO_2 emission target for the year 2050 assumes a net zero target for the total CO_2 emissions on the aggregate EU-31 level, in accordance with the European climate neutrality target (EU 2021/1119), and by 2060 a net negative target of 6.5% in proportion to the total 2005 CO_2 emissions. The total net targets include negative emissions achieved by any of the NETPs taken into account in the modelling, including afforestation and reforestation, which would thus fall into the LULUCF emissions category. Moreover, the net targets apply to total CO_2 emissions, including also aviation and marine bunkers.

In contrast to the global scenarios, national macroeconomic drivers including GDP growth, private consumption and sector production growth were not varied in the European scenarios. Updating the macroeconomic drivers of all 31 countries was seen out of scope of this work, since it would have required an extensive search of reliable data for each country. Hence, the reduced consumption of material and energy does not appear in the European 1.5C-Env scenario, nor the slower economic growths in the 1.5C-Env and 1.5C-Sec scenarios. This has potential implications for the European results, which should be kept in mind when making final conclusions.

3.4.4 Main assumptions related to NETPs in the European scenarios

The European scenarios were calculated with the Pan-European TIMES model, which is based on the well-known JRC-EU-TIMES model. Only the three 1.5°C scenarios were modelled, because the NDC and LTS emission targets within the EEA countries are already very close to more ambitious policies based on the 1.5°C temperature target. Like for the global scenarios, a wide portfolio of NETs is again modelled for carbon dioxide removal, including afforestation and reforestation schemes, various BECCS technologies (including also biomass *waste streams* from chemical pulping), PyCCS process for soil amendment with biochar, high temperature DACCS technologies, enhanced weathering (EW), and soil carbon sequestration (SCS). Ocean liming is left out of consideration for Europe. The main assumptions for the European scenarios follow closely the corresponding assumptions of the global scenario and are described Table 3.

The key assumptions can be summarized as follows:

- **1.5°C Tec Scenario** ("Advanced technology and global markets" storyline)
  - CO_2 storage potentials can be fully utilized – no political barriers
  - DACCS technology assumed to become well developed and commercialized
  - Bioenergy crop potentials are according to the JRC medium estimates (≤ 2.6 EJ/a in EU31 by 2050, Ruiz et al 2019)
  - Optimistic potentials assumed for land-neutral biochar production (Werner et al 2023b)
  - Less soil carbon sequestration potential, due to wider land-use for NETPs

- **1.5°C Env Scenario** ("Nature conservation and biodiversity" storyline)
    - Carbon dioxide price assumed to follow the EC recommendation for WAM scenarios (EC 2022)
    - Forestation potentials remain first somewhat smaller (afforestation being restricted) but then gradually enlarged due to dietary changes relaxing the pressure on land-use
    - Bioenergy crop potentials reduced below the JRC low estimates (≤ 1.6 EJ/a in EU31 by 2050)
    - Conservative potentials assumed about land-neutral biochar production for PyCCS, to avoid any double counting concerning land-use (Werner et al 2023b)
    - Smaller enhanced weathering potential due to environmental concerns
    - The EU-ETS carbon price has been set according to EC recommendations (EC 2022)
    - CO_2 storage potentials cannot be fully utilized due to environmental concerns and lower acceptance due to social and environmental concerns
- **1.5°C Sec Scenario** ("Security and self-sufficiency" storyline)
    - Carbon dioxide price assumed to follow the EC recommendation for WAM scenarios (EC 2022)
    - DACCS technology assumed to remain rather expensive (NEGEM WP5 expert elicitation)
    - Higher bioenergy crop potentials (≤ 3.8 EJ/a in EU31), due to diet change (D3.7, Werner et al 2023)
    - Medium assumptions about land-neutral biochar production for PyCCS (Werner et al 2023b)
    - Less soil carbon sequestration potential, due to wider land-use for NETPs
    - Trade in bioenergy from/to outside of Europe limited to very small levels
    - Imports of gas and electricity from Russia & Ukraine remain fully terminated
    - The EU-ETS carbon price has been set according to EC recommendations (EC 2022)
    - CO_2 storage potentials cannot be fully utilized due to security concerns

Table 3. Summary of the modelling assumptions concerning NETPs in the European NEGEM scenarios (G = Global, E=Europe).

NETP potential assumption	1.5C-Tec	1.5C-Env	1.5C-Sec	References
Energy crop feedstock potential	E-2030: 1.9 EJ/a E-2050: 2.6 EJ/a	E-2030: 1.4 EJ/a E-2050: 1.6 EJ/a	E-2030: 2.3 EJ/a E-2050: 3.8 EJ/a	Ruiz et al (2019) Vera et al (2021) Werner et al (2023) Frank et al (2021)
BECCS potential	Driven by biomass feedstock supply potentials	Driven by biomass feedstock supply potentials	Driven by biomass feedstock supply potentials	Fuss et al (2018)
DACCS potential	E-2030: 1 Gt(CO2)/a E-2050: 2 Gt(CO2)/a Moderate learning	E-2030: 1 Gt(CO2)/a E-2050: 2 Gt(CO2)/a Moderate learning	E-2030: 1 Gt(CO2)/a E-2050: 2 Gt(CO2)/a Slow learning	Fuss et al (2018)
Biochar (PyCCS) potential	E-2030: 40 Mt(CO2)/a E-2050: 70 Mt(CO2)/a E-2025–2100: 5.1 Gt(CO2,cum.)	E-2030: 1.1 Mt(CO2)/a E-2050: 1.8 Mt(CO2)/a E-2025–2100: 0.1 Gt(CO2,cum.)	E-2030: 13 Mt(CO2)/a E-2050: 22 Mt(CO2)/a E-2025–2100: 1.6 Gt(CO2,cum.)	Schmid et al (2019) Werner et al (2023b)
SCS potential	E-2030: 60 Mt(CO2)/a E-2050: 138 Mt(CO2)/a	E-2030: 75 Mt(CO2)/a E-2050: 185 Mt(CO2)/a	E-2030: 60 Mt(CO2)/a E-2050: 138 Mt(CO2)/a	Roe et al (2021) Doelman et al (2020)
Afforestation potential	E-2030: 150 Mt(CO2)/a E-2050: 320 Mt(CO2)/a E-2025–2100: 11.6 Gt(CO2,cum.)	Not allowed	E-2030: 150 Mt(CO2)/a E-2050: 330 Mt(CO2)/a E-2025–2100: 12.0 Gt(CO2,cum.)	Frank et al (2021) Braun et al (2022)
Reforestation potential	Not considered (included above)	E-2030: 140 Mt(CO2)/a E-2050: 280 Mt(CO2)/a E-2025–2100: 10.1 Gt(CO2,cum.)	Not considered (included above)	Braun et al (2022) Werner et al (2023a)
Ocean alkalinisation	Not considered	Not allowed	Not considered	Fuss et al (2018) Van Kooten (2022)
Enhanced weathering	E-2030: 100 Mt(CO2)/a E-2050: 210 Mt(CO_2)/a	E-2030: 50 Mt(CO2)/a E-2050: 110 Mt(CO2)/a	E-2030: 100 Mt(CO2)/a E-2050: 210 Mt(CO_2)/a	Fuss et al (2018) Beerling et al (2020)
Geological CO_2 storage potential	G: 6780 Gt(CO2) E: 175 Gt(CO2)	G: 3200 Gt(CO2) E: 110 Gt(CO2)	G: 2700 Gt(CO2) E: 80 Gt(CO2)	Fuss et al (2018) Selosse & Ricci (2017) Sunny et al (2022)

4 Scenario results

4.1 Global NEGEM scenario results

4.1.1 Global primary energy supply

The global primary energy supply (TPES) has been increasing steadily throughout the 2000s, with an increase of over 40% between 2000 and 2019 (IEA 2021c). If similar growth rates prevailed in the future, the total energy supply would increase five to six-fold by 2100 from 2020. Such growth obviously cannot continue, but many studies have been projecting the total primary energy consumption may be roughly doubling from the present levels by 2100, although the range of different projections is quite large (e.g., IIASA 2022). While electrification and the expanding use of renewable electricity generation tend to reduce growth in primary energy (IRENA 2022, Murphy et al. 2020, Nadel 2019), the transition to post-fossil economy may also increase energy losses in some parts of the energy system, notably in storage systems, hydrogen and power-to-X conversion systems to produce synthetic fuels and other products, and due to application of CCS, biochar or DACCS for climate change mitigation. All these various effects are reflected in our modelling results. Figure 6 illustrated the development of global primary energy supply.

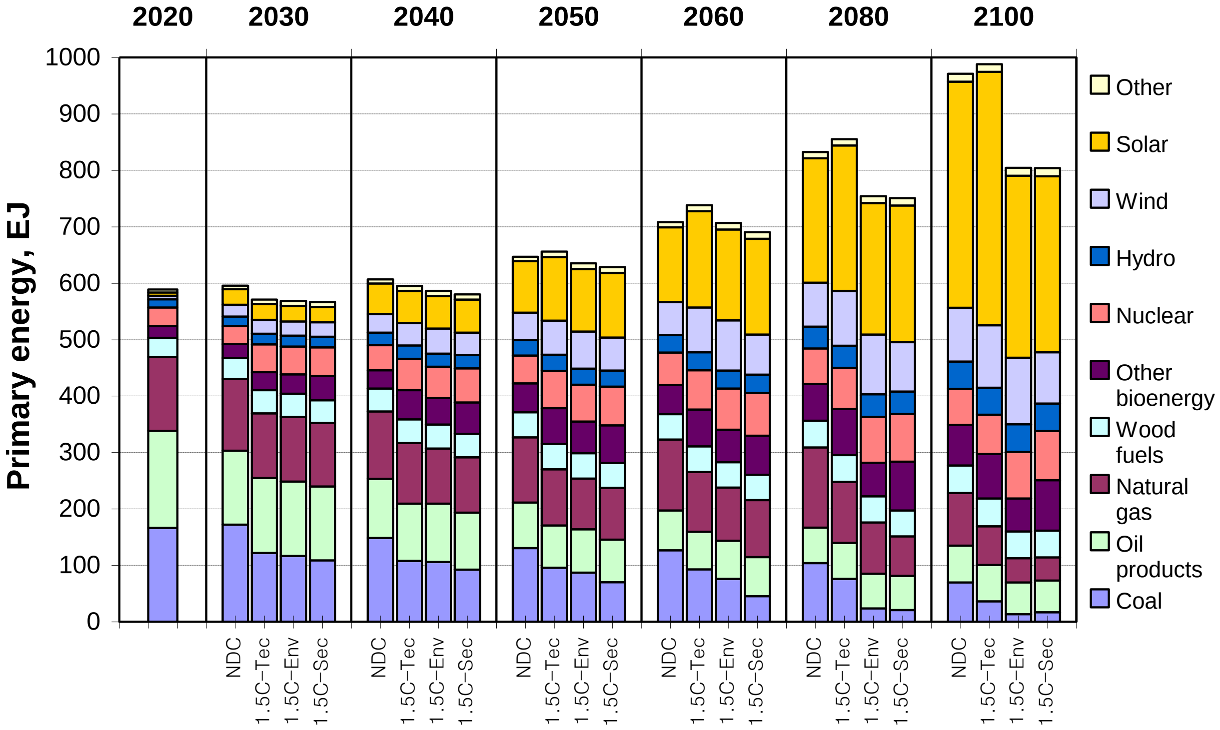

Figure 6. Development of global total primary energy supply (TPES) in the scenario variants, including non-energy uses.

In the current scenario experiment, the growth in total energy supply remains quite moderate until 2050 (about 10% from 2020), but the growth becomes higher in the latter half of the century, the TPES reaching about 970 EJ in 2100 in the NDC case (Figure 6). Some additional growth in the 1.5C-Tec scenario is consistent with the increasing efficiency losses due to decarbonizing the energy systems or by applying certain NETs (DACCS and ocean liming). However, to some extent we may be also underestimating the potential technology advances beyond 2050 (technology parameters are often estimated only up to 2050), as well as future changes in consumption patterns and driver elasticities for some energy service demands. Lower assumptions for economic growth in the 1.5C-Env and 1.5C-Sec scenarios is reflected in slower growth in global total primary energy supplies, reaching a considerably lower level of 800 EJ in 2100 in these scenarios, which corresponds to a 36% increase from 2020.

Among the most important energy sources, solar energy becomes the dominant source for primary energy in the latter half of the century, as one can expect. On the global scale, solar would leave wind behind already before 2040, even though wind power also continues to expand significantly. Larger scale deployment of offshore wind power could also be possible but would require heavy investments into infrastructure.

One major uncertainty related to future energy sources is the sustainable bioenergy supply potential in the longer term, having a direct link to the prospects for BECCS deployment. Like in IAM models in general, in the TIMES-VTT model the use of limited resources are exogenously constrained to sustainable potentials estimated from literature and from other NEGEM studies as described above. In particular, bioenergy supply is divided into a number of biomass categories (primary, secondary and tertiary biomass supply) with simplified supply-cost curves, and the sustainable potentials of primary biomass production by type have been estimated based on the data sources. In 2020, the global primary production of primary biomass for energy (excluding the biomass fraction of municipal waste) was about 60 EJ, of which about 35 EJ wood fuels, about 15 EJ agricultural residues and 7–10 EJ energy crops (not clearly reported in terms of biomass in the primary energy statistics but mostly in terms of liquid fuels). In the NEGEM 1.5°C mitigation scenarios, by 2050 the global primary solid biomass use for energy increases to about 97–98 EJ in the 1.5C-Tec and 1.5C-Sec scenarios, but only to about 86 EJ in the 1.5C-Env scenario. These figures may be compared with the IEA NZE scenario (IEA 2021a), where the production of modern bioenergy increases from about 38 EJ in 2020 to around 100 EJ in 2050, and "*all bioenergy in 2050 comes from sustainable sources and the figures for total bioenergy use are well below estimates of global sustainable bioenergy potential, thus avoiding the risk of negative impacts on biodiversity, freshwater systems, and food prices and availability*." In that respect, the level of bioenergy use in the NEGEM scenarios can also be considered to comply with these sustainability criteria. By 2100 the total biomass use increases to about 120 EJ in the 1.5C-Sec and 1.5C-Tec scenarios but remains around 90 EJ in the 1.5C-Env scenario.

On the global scale, the impacts of climate change on biomass yields are likely to be negative, even though CO_2 fertilization and soil improvements through biochar application might counter-balance some of those impacts. In addition, one can expect an increasing demand of biomass for material use and for various chemicals, and introduction of stricter sustainability criteria, all having adverse impacts on biomass energy use in the long term. Therefore, the 1.5C-Sec and 1.5C-Tec scenarios, where the reliance on bioenergy becomes higher, do include risks of failing to achieve the negative emissions by the relatively large-scale utilization of bioenergy, that may affect BECCS in particular, but to a much lesser extent biochar.

4.1.2 Global electricity supply

The electrification of the global energy systems, as well as the expanding hydrogen economy, electrofuels and decarbonised industrial systems, all increase electricity consumption, which may approach 180 PWh by 2100 according to the scenario results of 1.5C-Tec scenario (Figure 7). On the other hand, in the 1.5C-Env and 1.5C-Sec scenarios with lower economic growth assumptions, electricity consumption stabilizes to a lower level of 140 PWh by 2100. The cost reductions of solar PV systems that have already taken place, and the projected further technical developments, can make solar power highly competitive on a large scale within the next few decades. The modelling results indicate that by 2040, solar power may surpass wind power in the global electricity generation mix, and the trend would continue thereafter. Despite the additional flexibility required due to the variable nature of solar generation, the model results suggest that by 2100 60–70% of global electricity generation would be solar based, the highest contribution being reached in the technology-optimistic 1.5C-Tec scenario.

As expected, fossil fuel-based electricity generation will be phased out almost completely by 2100, with natural gas fired power remaining on a somewhat notable level until 2080 (Figure 7). Hence, much in line with the storylines, the role of renewable energy becomes very prominent. Bioenergy-based power generation will not gain significant overall market share but will nonetheless be important in some regions and globally with respect to the negative emissions achieved though BECCS power plants. In absolute terms, nuclear power also increases notably in the scenarios, most prominently in the 1.5C-Sec scenario but loses some share of total global generation in all scenarios. Despite its high capital costs, nuclear power has the benefit of providing stability in the *power* grids *under high variable power integration,* and particularly modular reactor technologies can improve their economy and become feasible in many countries.

Until 2050, the global electricity supply is in fact very well in line with that in the IEA NetZero by 2050 scenario (IEA 2021a). The total supply is around 70 PWh in all the scenario variants, while the figure in the IEA NZE scenario was 71 PWh in 2050. Beyond 2050, the growth in the supply may appear large, but is well explained by high electrification being the key factor behind the growth, which can be understood also by observing the moderate growth in the primary energy consumption shown in Figure 6. High scale of electrification id enabled by use of several types of energy storages in the model, such as batteries, power-to-x, hydro power, and pumped-storage hydropower. The additional electricity consumption of DACCS plants becomes very significant beyond 2050 in the 1.5C scenarios highly reliant on this technology. At their peak around 2070, they consume about 11% of global electricity in the 1.5C-Env case, and about 5% in the 1.5C-Tec and 1.5C-Sec cases. In the NDC scenario, the global electricity supply is about 60 PWh in 2050, well in line with the JRC GECO projection, 63 PWh gross (Keramidas et al. 2021).

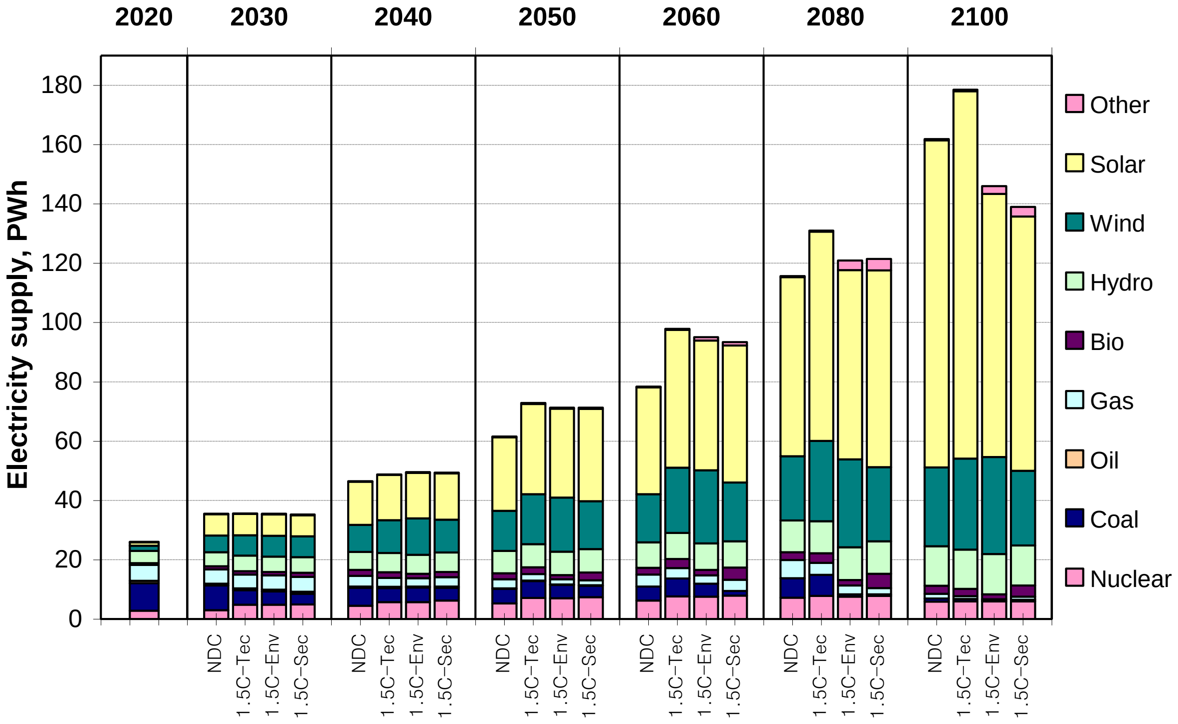

Figure 7. Development of global total net electricity supply in the scenario variants, excluding power plants own consumption.

4.1.3 Global greenhouse gas emissions

Figure 8 and Figure 9 illustrate the development of global GHG emissions in the reference scenario (NDC) and in the 1.5°C mitigation scenarios. In the NDC scenario, the total net emissions develop exactly according to the regional and global emission caps that were exogenously defined (Figure 8). In this case, the total CO_2 emissions approach zero only in 2100, and the total GHG emissions remain above 10 Gt(CO_2 eq.)/a until 2100. For Europe (excluding FSU−Baltics), total GHG emissions (excluding LULUCF) fall to around 1 Gt(CO_2) by 2050 and below 0.4 Gt(CO_2) in 2100 in the NDC scenario. The 1.5°C mitigation scenarios follow considerably more steeply decreasing emission paths, reaching the temperature target of 1.5 °C in 2100 after intermediate overshooting (Figure 8 and Figure 9). Even though the global net CO_2 emissions (including LULUCF) fall to zero around 2050, the temperature has risen to 1.6°C by that time and would keep rising, unless those substantial amounts of additional negative emissions would be produced during the latter half of the century for fully reaching the climate target of maximum 1.5°C by 2100.

The scenario results suggest that a transition away from fossil fuels may happen relatively slowly unless strict policies are implemented for accelerating that transition. Such policies were not assumed in the analysis, apart from the carbon price projections for Europe according to EC (2022). The overall targets were imposed on the total emissions or temperature limits, and thus the results are representing indicative least-cost trajectories under relatively conservative assumptions on technology development in certain sectors, especially within energy-intensive industries and beyond 2050 in general. That can be seen reflected in the considerable role of fossil CCS (FECCS) and negative emissions by NETPs in the results (Figure 8, Figure 9a).

The role of NETPs and FECCS in all the cases is already considerable, around 20–30 Gt/a during the last decades of the century. In Figure 8 and Figure 9a FECCS is illustrated together with the removals by NETPs, but also included as fossil CO_2 emissions. Fossil CCS cannot be considered as “carbon dioxide removal” as it only prevents CO_2 entering to the atmosphere. However, the information on the amount of fossil CO_2 captured is crucial in order to understand the use rate of geological storage potentials.

The results indicate that fossil energy technologies with carbon capture (FECCS, including capture of related process emissions) would be employed on a large scale within the power generation sector, energy-intensive process industry, and other energy transformation sector. In the short term, power plants would dominate the volume of FECCS applications but already by 2050, the captured amounts associated to industrial processes would exceed those in the electricity sector. The most important processes where CCS would be applied are within the basic metal, chemicals and non-metallic minerals manufacturing While in the energy sector the role of fossil-fuel based power plants would be soon decreasing, CCS would gain additional importance in the upstream fuel transformation sector, most notably in hydrogen production. In general, within fossil fuel-based energy transformation additional policies could be introduced to accelerate the transition to renewable energy, for example electrolysers in hydrogen production, to reduce the reliance on CO_2 capture and storage.

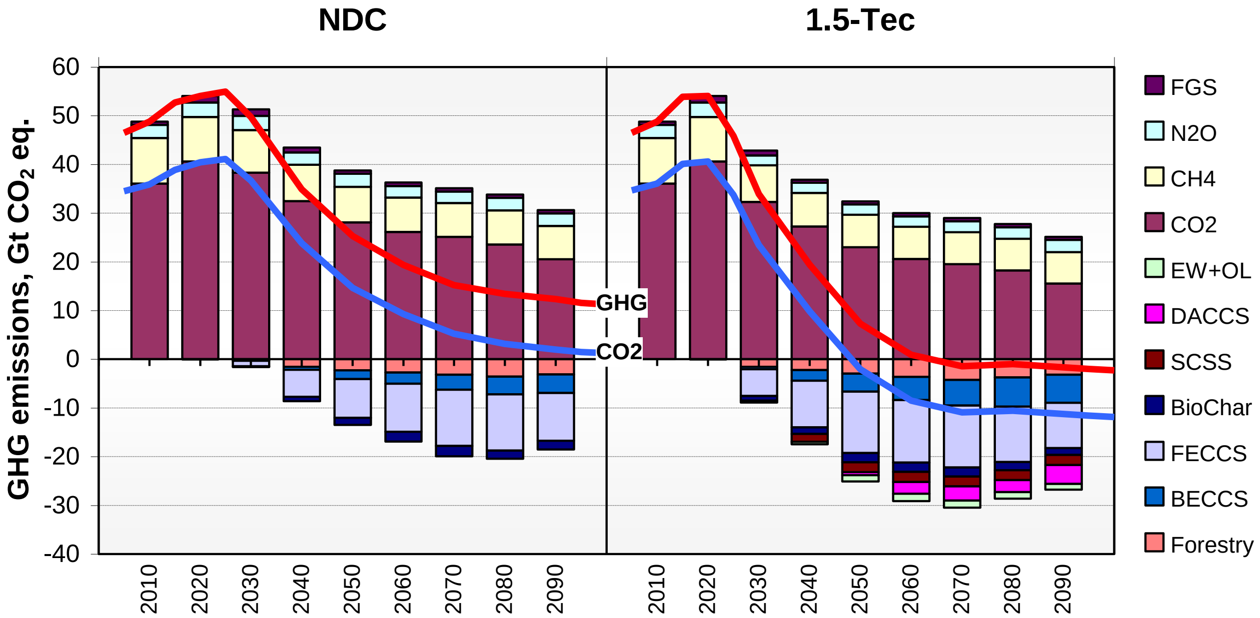

Figure 8. Development of greenhouse gas emissions (Kyoto gases) in the NDC and 1.5C-Tec scenario variants, including fossil energy with CCS, FECCS.

The 1.5C scenarios have different policy implications, as the total net emissions have to be reduced equally rapidly to keep the temperature rise below 1.5 °C in 2100, but with sustainable potential available for negative emission options differing between the cases. However, the economic growth assumed lower in 1.5C-Env and 1.5C-Sec cases makes the burden of mitigation slightly less challenging in these cases. In total, the role of NETPS grows in all the cases to the highest level during 2070–2080 around 16–18 Gt/a, but is reduced thereafter along with the temperature rise having turned to a decreasing trend towards the 1.5 °C target and beyond.

The results clearly indicate that moving from the 2°C target (achieved in the NDC case) to the 1.5°C target leads to much more rapid emissions reductions and much higher mitigation costs. In the NDC scenario the marginal emission price approaches 200 € (2020) per metric tonne (CO_2 eq.) only by 2100. The marginal costs in the 1.5C-Tec and 1.5C-Env scenarios are around 200 €/t in 2050 and then increase by 2080 to about 250 €/t. In the 1.5C-Sec scenario the costs are somewhat higher, about 230 €/t in 2050 and about 300 €/t by 2080. In 1.5C-Sec scenario the limited geological CO_2 storage and slower cost development for DACCS cause the higher marginal costs.

When looking at these marginal cost results, one should bear in mind the fact that in the scenarios no explicit policies were assumed to accelerate the deployment of new technologies that could replace fossil-based processes e.g., within energy-intensive industries, but the technology penetration was based on a cost-optimal solution. Therefore, substantial deployment of CCS remains the major economical option for achieving deeper emissions reductions, and on top of that, employing DACCS on a relatively large scale appears to become necessary. However, it is noteworthy that the projected costs of the DACCS options are so high that they would not become competitive before 2050 under any of these 1.5 °C scenarios, and in the NDC scenario the marginal emission price approaches 200 € (2020) per metric tonne (CO_2 eq.) only by 2100, which barely makes DACCS visible appear in the results for the last two decades. Unlike BECCS and biochar, DACCS does not have any co-benefits, like energy or fuel production, which reduces the cost-efficiency of DACCS. However, in future heat integration of DACCS could be possible, e.g. DACCS providing excess heat to district heating networks.

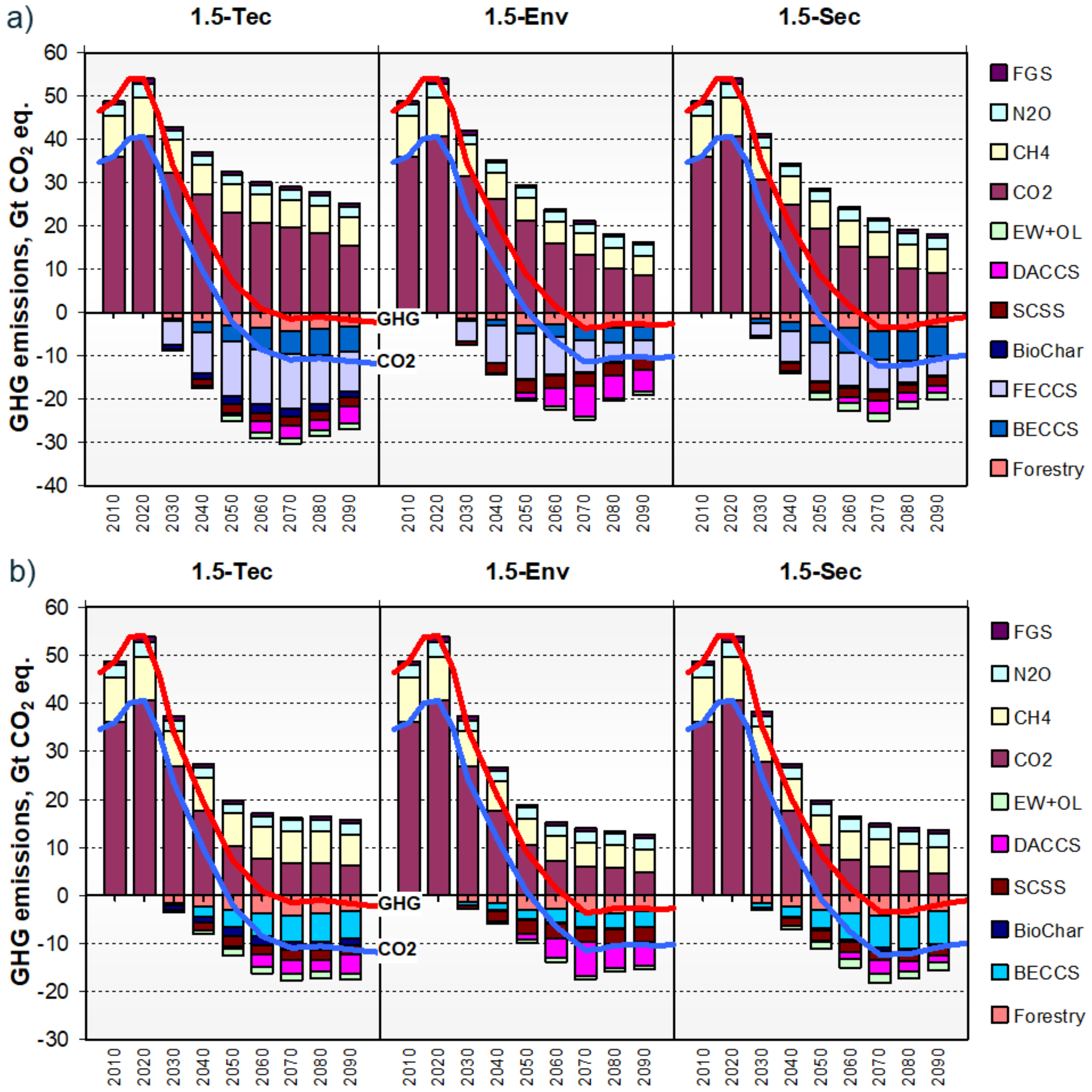

Figure 9. Development of greenhouse gas emissions (Kyoto gases) in the studied scenarios. The red and blue lines represent the total net emissions of GHGs and CO_2, respectively. In a) the vertical bars show the gross emissions (positive) and removals (negative) either from fossil flue gases or the atmosphere. Here fossil CO_2 emissions captured are illustrated also as emissions. b) only removals from atmosphere are shown, and FECCS is excluded. (BECCS = bioenergy with CCS, FECCS= fossil energy with CCS, forestry = afforestation and reforestation, SCSS = soil carbon sequestration, DACCS = direct air carbon capture and storage, EW+OL = enhanced weathering + ocean liming).

4.1.4 Role of NETPs

Among the NETPs, all the options modelled also appeared in the 1.5°C scenario results, but depending on the scenario, one may argue that according to the results DACCS or sustainably constrained BECCS appear to emerge as the most significant options. In total, all the NETs considered account for about 10 Gt(CO_2)

during 2080–2100 in the NDC scenario (Figure 8), but even up to over 18 Gt/a in the 1.5°C scenarios (Figure 10). In Figure 10, the amounts shown are the direct removal impact of the NETs, while their net impact is somewhat smaller for BECCS, DACCS, biochar, EW and Ocean alkalinisation due to energy consumption in the capture process and other upstream emissions. These upstream emissions are accounted for in the upper part of Figure 9.

The biomass-based technology options BECCS and biochar both become competitive in all three 1.5°C scenarios (more on BECCS in section 4.1.5). Obviously, biochar also has improved comparative advantage when the competing uses of biomass remain at lower levels because of the yield increases achieved by using the biochar for soil improvement. Overall, biochar is deployed roughly at the maximum scales assumed realistic after 2050, specifically; 2.3 Gt(CO_2)/a in the 1.5C-Tec case, and 0.2-0.7 Gt in the other scenarios. As a side-benefit, according to the modelling assumptions, biochar deployment enables a significant reduction in the N_2O emissions from agricultural lands.

As mentioned above, due to its relatively high costs, DACCS appears only in the 1.5°C cases after 2050s, as it reaches deployment levels of 1.5–7 Gt/a during 2060–2100. At this point, costs of DACCS start to be feasible compared to other available options for emission reductions. It turns out that the need for DACCS would in fact be the highest in the 1.5C-Env scenario, due to the strict sustainability constraints imposed on other NETP options. However, the DACCS levels of 1.5C-Tec scenario reach practically similar levels in 2100. Compared to the preliminary NEGEM scenarios (D8.6), the DACCS results reach considerably more conservative levels. Also, in comparison with some other studies with the 1.5°C target (e.g. Realmonte et al. 2019), the maximum DACCs capture rate assessed here is lower. This is e.g. due to the expanded NETPs portfolio included in the modelling.

While the nature-based solutions of af-/reforestation, and soil carbon sequestration can both be quite competitive and sustainable, under the assumed storylines their combined potential still seems far from sufficient for stabilizing the climate by keeping the temperature change within the imposed limits, while avoiding further transgressions of other planetary boundaries. The nature-based solutions provide around half of the global removals needed by 2050, and around one third by 2100.

As a newly added option in the updated scenario, the removal potentials modelled for SCS were based on the sustainable and cost-effective estimates of Roe et al. (2021). Because the unit costs have been estimated under 100 €/t(CO_2) for a range of SCS deployment (consistent with even larger potentials in D1.2) basically the full SCS potentials assumed would indeed be cost-effective under the 1.5C scenarios. As another newly added option in the updated scenarios, EW seems to have prominent potentials according to Beerling et al. (2020). However, in our scenarios the EW potentials have been constrained in order to produce responsible estimates of their potential role, e.g. considering the toxicity risks according to the NEGEM LCA studies, and therefore reaching quite modest levels in the results.

Compared to the preliminary scenario results (D8.6), modelling with an expanded portfolio of NETPs shows that the cost-efficiency of ocean liming seems to be weak, and it only appears in minor quantity of 0.1 Gt/a at 2060 in 1.5C-Tech scenario (Figure 10).

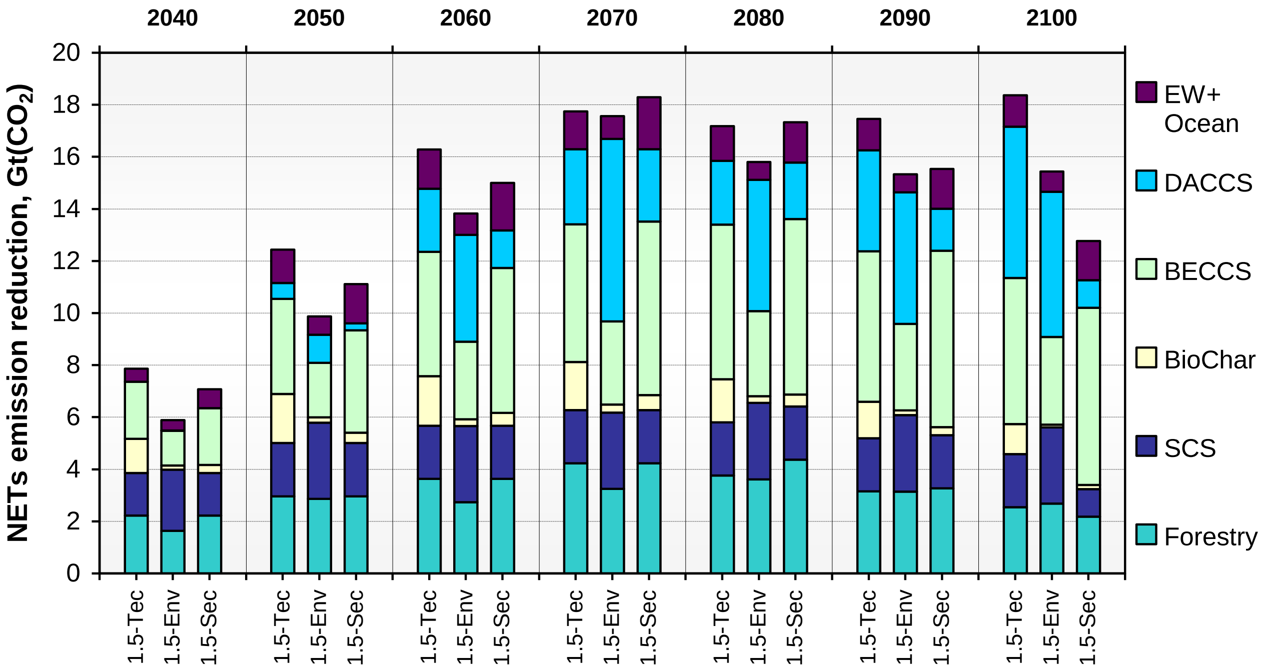

Figure 10. Contribution of NETs to the emission reductions in the experimental climate policy scenarios. Note that the amounts shown are the direct impact of the NETs, while their net impact is somewhat smaller for BECCS, DACCS, biochar, EW, and Ocean liming. EW+Ocean class consists mostly of enhanced weathering, with only marginal share of ocean liming in 1.5-Tec scenario (less than 0.1 Gt in 2060). Forestry includes afforestation and reforestation in 1.5-Tec and 1.5-Sec, and only reforestation in 1.5-Env.

4.1.5 BECCS and energy crops

Concerning BECCS applications, by 2050 the total negative emissions amount to at most about 4 Gt/a in the 1.5C-Tec and 1.5C-Sec scenarios, and a more conservative volume of 2 Gt/a in the 1.5C-Env scenario. According to the more detailed technology results (Figure 11), power plants (including CHP) become cost-competitive after bioliquids and biogas applications entering the markets in 2030s. In 1.5C-Tec and 1.5C-Sec scenarios with most extensive potential for BECCS, the power plant applications around would mostly account for about 50%-70% of the captured amount globally after 2050's, while other energy conversion technologies cover the rest. In all the 1.5°C cases, the power plant share of BECCS applications is at its lowest before 2050, and then increases over time.

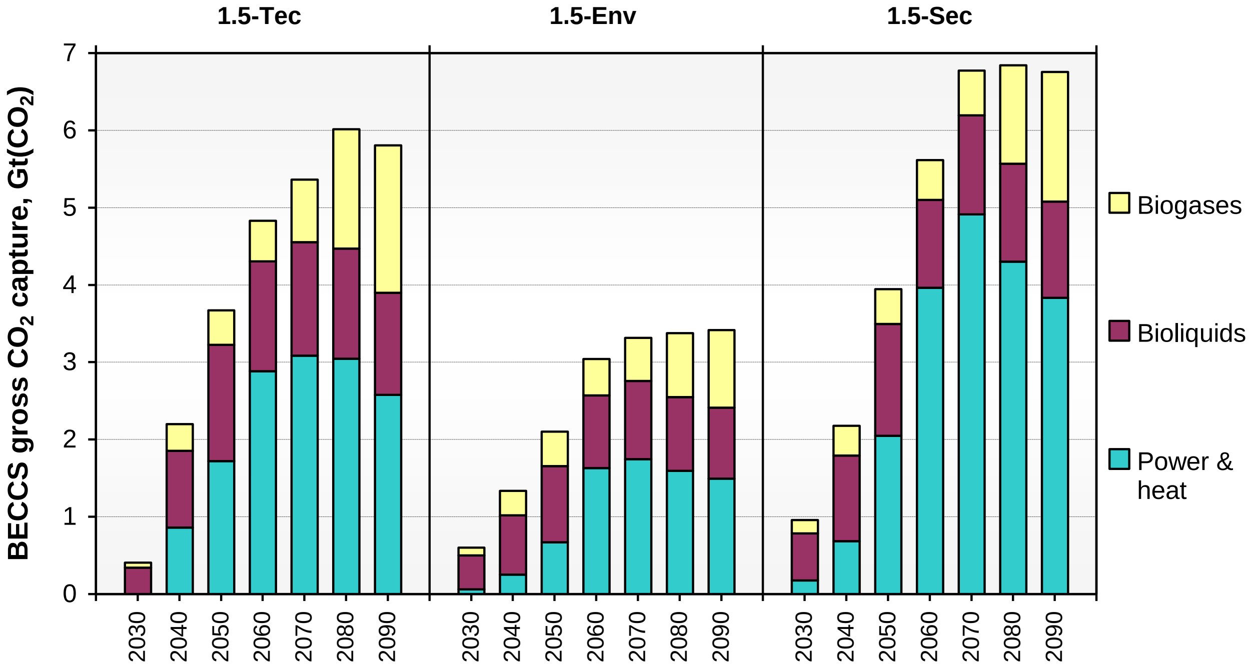

Figure 11. Contribution of BECCS by application (gross capture).

As the sustainable potential for producing bioenergy crop feedstock appears to be one of the most critical issues for the large scale deployment of BECCS, which is one of the most discussed NET options, the development of the total energy crops and biochar crops production in the results of the preliminary NEGEM scenarios is illustrated below in Figure 12. According to available international energy statistics, the 2020 level of global bioenergy crop production can be estimated to at 7–10 EJ. As mentioned above, the projections for the sustainable potential have a wide range, from about 10 EJ to well over 100 EJ by 2050, while our assumptions were between 14 and 55 EJ. The results indicate that the assumed potentials would become mostly utilized in each scenario, reaching 40 EJ in the 1.5C-Sec case, 35 EJ in the 1.5C-Tec case and 14 EJ in the 1.5C-Env case by 2050, and further up to over 60 EJ in the 1.5C-Sec case, over 50 EJ in the 1.5C-Tec case and nearly 20 EJ in the 1.5C-Env case by 2080. For comparison, the biomass crop feedstock amount required for the biochar deployment are also shown in the Figure 12. However, as discussed above, in accordance with the analysis by Werner et al. (2023b), we assumed the biochar concept to be a land-and calorie neutral NET option when deployed within the global potential constraints assumed in the scenarios.

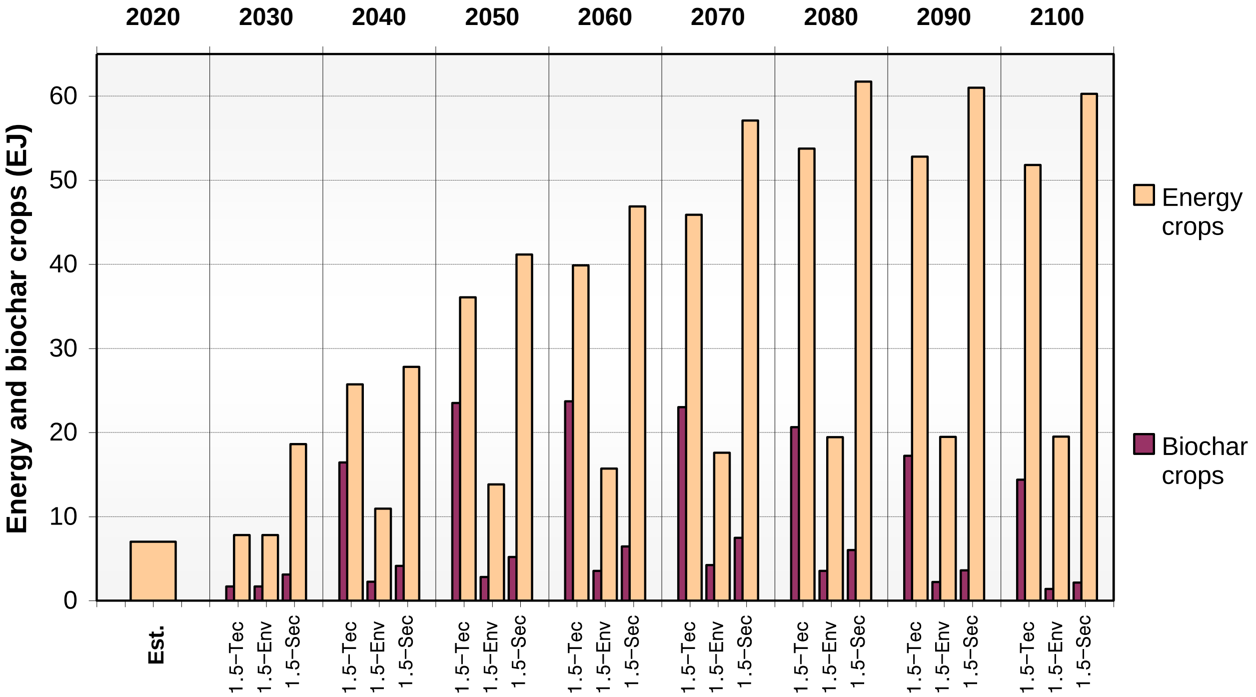

Figure 12. Global production of energy crops and biochar feedstock for soil improvement, all in energy equivalents.

4.1.6 Cumulative removals

Figure 13 shows the global cumulative carbon dioxide removals created by NETPs in each scenario. The cumulative removals vary from around 900 $GtCO_2$ in 1.5C-Env scenario to 1000 $GtCO_2$ in 1.5C-Tec scenario. The highest cumulative share of removals is by BECCS in 1.5C-Tec and 1.5C-Sec scenarios, and by DACCS in 1.5C-Env scenario (Figure 14). In the IPCC AR6 WG3 1.5°C scenarios the cumulative removals by BECCS vary between 30-780 $GtCO_2$ and by DACCS 0-310 $GtCO_2$ by 2100. The cumulative removals by BECCS in the NEGEM scenarios are around 200-380 $GtCO_2$ representing moderate levels compared to the highest IPCC scenarios. Removals by DACCS vary form around 50 to 220 $GtCO_2$. Removals by re-/afforestation (forestry) show constant levels in each scenario. In the 1.5C-Env scenario significant land release for forestry is assumed due to dietary changes. However, afforestation is excluded according to storyline. In the 1.5C-Tec and 1.5C-Sec scenarios afforestation is allowed, thus showing a little higher total removals by forestation.

In comparison to many earlier IAM scenarios (e.g. IPCC AR6 WG3), removals by SCS, EW, and biochar are also included here in 1.5°C scenarios. The results shows that these additional NETPs are interesting from the point of view of cost-optimisation, as they provide additional removal potential with resonable costs, and thus decrease the pressure to gain removals e.g. by BECCS and DACCS.

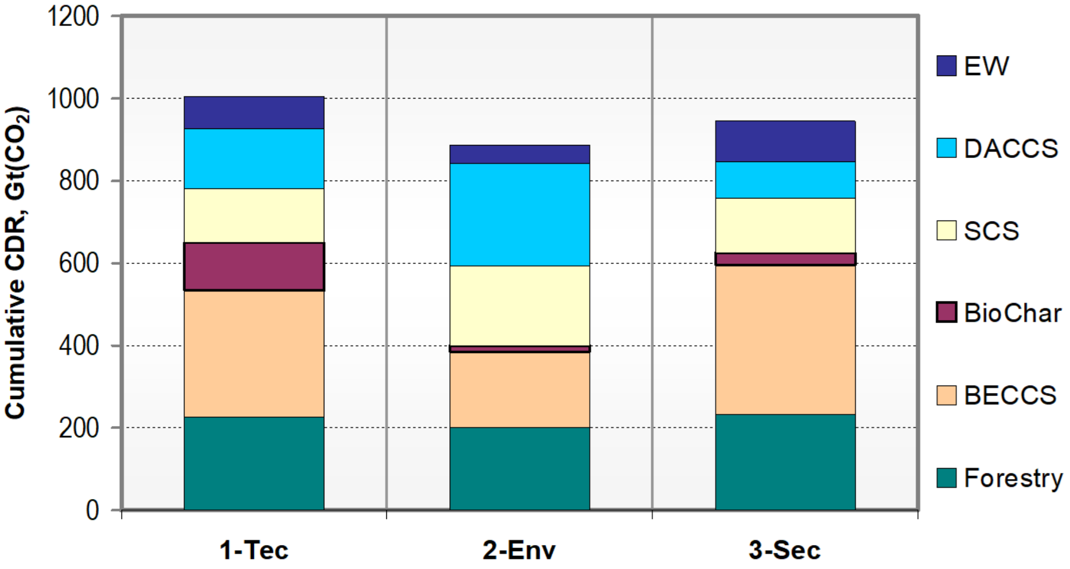

Figure 13. Cumulative global carbon dioxide removals by NETPs, 2025-2100 in the three scenarios studied.

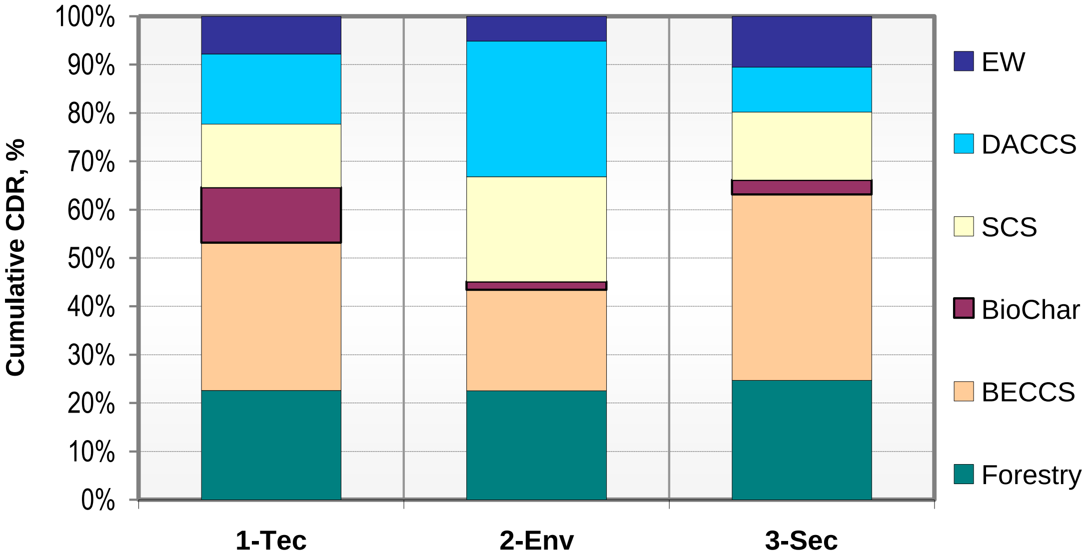

Figure 14. Shares of cumulative global carbon dioxide removals by NETPs, 2025-2100 in the three scenarios studied.

4.2 European NEGEM scenario results

Because the more detailed modelling for the European scenarios was based on a different model, the Pan-European TIMES model, the results are inevitably to some extent different from the global model in general, and of course for Europe in particular. As the Pan-European TIMES model describes the energy systems of each member state and country, the more detailed results obtained with this model may be considered also more reliable for Europe.

The differences in the model and the more detailed regional resolution are also reflected in the marginal costs, which are notably higher in the European model than in the global model. This can be to a large part explained by the optimization, which in the global model allows the model to allocate the highest-cost mitigation measures to regions where the marginal costs are the lowest. In the European scenarios, the marginal carbon price is in 2050 about 280 €(2020)/t in the 1.5C-Tec scenario, about 400 €/t in the 1.5C-Env scenario and about 410 €/t in the 1.5C-Sec scenario. However, by 2060, the marginal costs converge in all three scenarios to levels between 310 and 340 €/t, meaning that in the 1.5C-Env and 1.5C-Sec scenarios the peak marginal costs occur around 2050. The levelling of the peak in the marginal costs can be explained by the inertia in the adaptation of the energy systems, and by the dynamic constraints on the expansion of NETP deployment, in particular with respect to DACCS. According to results of the scenarios on Europe, BECCS and DACCS demonstrated the highest potentials for CO_2 removal across all scenarios, while Biochar, SCS, and EW showed lower capacities (Figure 15 and Figure 16).

Despite the intention to maximize variability of NETs for CDR, the European scenarios relied on similar technologies, mainly BECCS and DACCS, for achieving the required cost-efficient CO_2 reductions to reach net zero on EU-level by 2050. The somewhat higher marginal costs in the European scenarios, as compared to the global scenarios, clearly has an accelerating impact on the penetration of the DACCS technology, which now appears in the results on a small scale already in 2040 and becomes important even in the 1.5C-Sec scenario, despite the assumptions leading to about 50% higher investment costs in that scenario.

Soil Carbon Sequestration (SCS) emerged as the most utilized nature-based approach in the 1.5C-Env scenario, aligning with its focus on environmental sustainability and adherence to planetary boundaries. One should also note that due to the SCS potential estimates being reasonably conservative (Roe et al 2021), the levelized costs of this option were assumed to remain at 200 €/t or below, and therefore the assumed potentials were basically fully taken into use in all European countries after 2035.

Afforestation and reforestation exhibited similar cumulative CO_2 reduction capacities across all scenarios, indicating their consistent contribution to CDR. EW was notably more prevalent in the 1.5C-Sec scenario, due to its applicability at regional levels. Conversely, the limited potential of biochar was detected in all scenarios, with nearly zero potential in the 1.5C-Env scenario.

One can also see from Figure 15 the optimized distribution of net emission reductions between direct emissions abatement and the deployment of NETPs. The lowest levels for direct emissions (including the CO_2 from bunker fuels) are reached in the 1.5C-Env scenario, where those emissions are reduced by about 76% from the 1990 level. The rest of the reductions in total net emissions, 24%, would be covered by the NETPs. These results, based on the detailed Pan-European model, thus indicate that the marginal costs of direct emissions reductions will exceed those of NETPs when going beyond this level of direct emissions reduction. In the global model results, the global direct emission reductions compared to the 2010 total emissions levels were roughly on the same level as for Europe. However, the global model did project net negative CO_2 emissions for Europe a bit earlier, already in 2050, and thereby also indicated somewhat lower marginal costs for the direct emissions reductions.

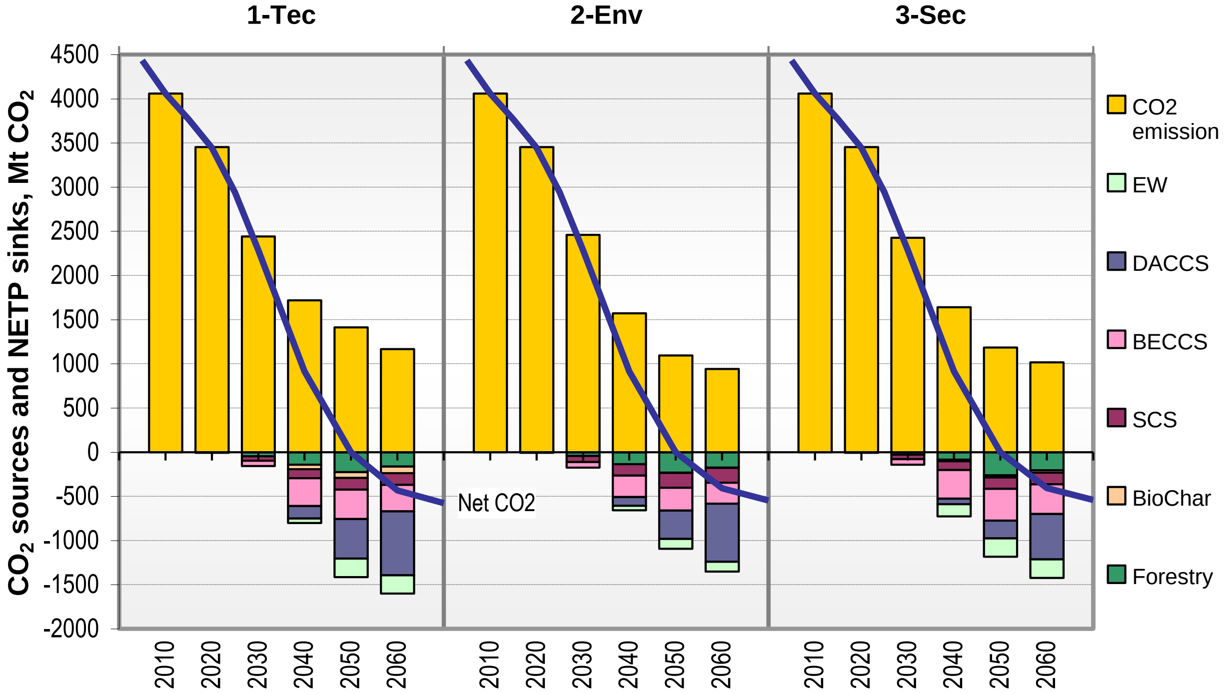

Figure 15. EU-31 NEGEM scenarios: Carbondioxide Balance in 2010–2060.

However, one should additionally bear in mind that we also included the recommended carbon price trajectory for the direct emissions in 1.5C-Env and 1.5C-Sec scenarios (reaching the level of 410 €(2020)/t in 2050). As this price trajectory is imposed on the direct emissions, and not on the NETPs, the exogenous price is, in fact, acting as an incentive specifically for the direct emission reductions, and not for the NETPs, which are driven by the overall net emission target of reaching zero in 2050.

As depicted in Figure 16, the scenario results suggest an overall level of NETPs application for Europe around 1.1–1.4 $GtCO_2$ in 2050. Because of the imposed exogenous carbon price trajectory in the 1.5C-Env and 1.5C-Sec scenarios, the reduction paths for the direct emissions become steeper, having a visible impact in 2050 compared to 1.5C-Tec scenario, on the projected need for NETPs. On the basis of the results, nature-based solutions would be highly important for reducing the need for options relying on geological CO_2 storage. Among these reforestation and afforestation, which would actually fall into the LULUCF category clearly, appear to have the most significant potential and would also support achieving other important SDGs.

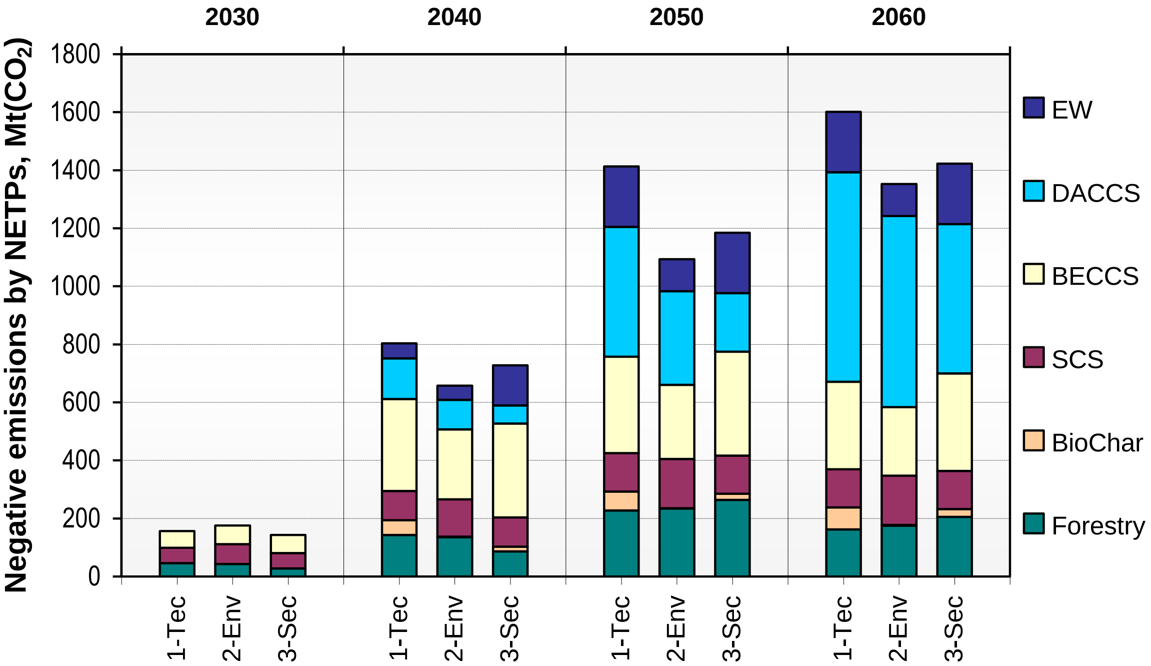

Figure 16. EU-31 NEGEM scenarios: NETPs contribution

Overall, our results indicate that in Europe the cost-optimal portfolio of NETPs, when expressed in terms of their cumulative contribution by 2065 averaged over the three scenarios (in Figure 17), is comprised of DACCS (10 Gt CO_2), BECCS (10 Gt CO_2), afforestation (6 Gt CO2), enhanced weathering (4 Gt CO_2), soil carbon sequestering (4 Gt CO_2) and biochar (1 Gt CO_2). In total, the cumulative removal by NETPs would be, on average, about 35 Gt CO_2. This average overall amount is in good agreement with the NEGEM WP4 results on EU-28 member state portfolios of NETPs (D4.5), however, according to our results the role of BECCS deployment is significantly smaller, due to our estimates of sustainable biomass resources in Europe being much more limited. Conversely, the role of DACCS is much more important in our results.

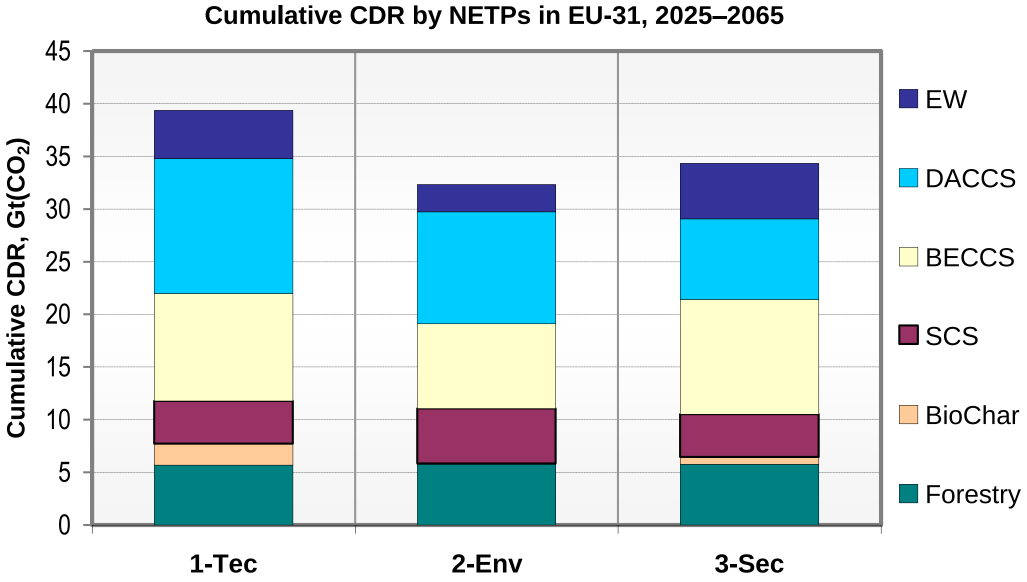

Figure 17. EU-31 NEGEM scenarios: Cumulative CDR amounts over the years 2020–2065.

The total negative emissions from BECCS applications in Europe amount to 330–360 Mt/a in the 1.5C-Tec and 1.5C-Sec scenarios, and to a more conservative volume of 250 Mt/a in the 1.5C-Env scenario by 2050. According to the more detailed technology results (Figure 18), power plants (including CHP) become cost-competitive after bioliquids applications entering the markets in 2030s, and biogases (including hydrogen from biomass gasification) significantly in the 2050s, respectively. Despite the assumed favourable development of electrolysis technologies, hydrogen production from biomass appears also to become competitive in some European countries (e.g. Norway and Spain), due to the economics being boosted by the high carbon prices. Nonetheless, according to the results it would have a proportionally smaller role in Europe than globally, because of the rather limited sustainable biomass resources in Europe.

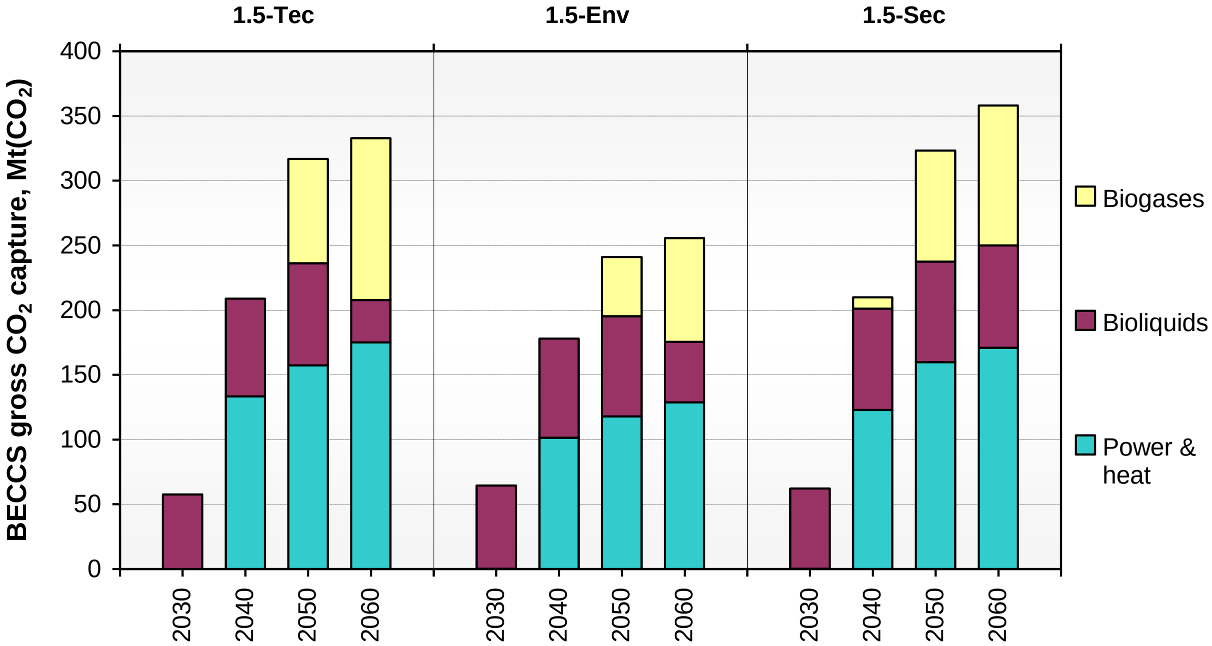

Figure 18. EU-31 NEGEM scenarios: Deployment of BECCS by application (gross capture).

Biochar, SCS and enhanced weathering are all NETPs based mainly on deployment on arable lands, croplands or grasslands. Studies on EW have assumed even high proportions of cropland to be used for EW deployment (Beerling et al 2020, Baek et al 2023). Therefore, it may be dubious to assume that all these potentials could indeed be realized on those same land areas. We have tried to eliminate double counting between the SCS and biochar deployment potentials in the scenarios, but the coupling effects with the EW potentials remain less clear. Nonetheless, for Europe the assumed EW potentials in the scenarios were reasonably small (max. 200 Mt/a), e.g. in comparison with the estimates of Baek et al. (2023), and likewise, the combined SCS and biochar potentials (max 250 Mt/a) can also be considered sufficiently conservative. Therefore, according to our judgement, the scenario results based on these assumptions comply reasonably well with the NEGEM objectives about realistic scenarios. However, among the scenarios, the 1.5C-Env results are clearly the most conservative in this respect.

Concerning country-specific results for Europe, **Appendix 1** presents the distribution of the deployment of NETPs over the European countries included in the scenarios (a few Balkan countries being excluded). The results suggest that DACCS would be deployed most significantly in the UK, Italy, and Spain, while BECCS would be deployed in largest scales in France, Germany, Italy and Spain. The allocation is driven by the cost optimization, taking into account e.g. energy resources and energy system development, CO_2

storage capacities, trade in biomass, and CO_2 transportation. Afforestation and reforestation would be distributed somewhat more evenly, the most significant deployments occurring in Spain, in the UK, France and Romania, rather closely in line with the potential estimates. Detailed country level analysis is out of the scope of this deliverable and will be further developed in the following WP8 deliverables D8.3 on NEGEM vision and D8.4 on final recommendations.

4.3 Comparison to earlier NEGEM results

At the time of finalizing this deliverable, the NEGEM project has been running for nearly three and a half years. This deliverable has a core aim at utilizing the NEGEM results widely to come up with realistic NETPs potentials. Importantly, in distinction to earlier scenario exercises, the main NEGEM results from the different WPs were largely available for the work. Hence, in this section, the results of this deliverable briefly reflect on some earlier key results to paint a picture of the process as a whole. Furthermore, such comparison highlights the novel aspects concluded in this deliverable and accompanying work.

Deliverable 8.6

In comparison to *D8.6: Quantitative assessments of NEGEM scenarios with TIMES-VTT, preliminary results*, released in November 2022, an additional scenario variant corresponding to the storyline of *Security and self-sufficiency (1.5C-Sec)* is included in the current modelling experiment. Following the plan of D8.6 and reflecting the results of the joint workshop on storylines, this was done to capture the space of possible futures more widely. Furthermore, a significant effort was made to extend the portfolio of NETPs, and also to scrutinize the potentials more critically reflecting the latest NEGEM results and external literature. Importantly, the portfolio of NETPs included in the modelling is supplemented with enhanced weathering and soil carbon sequestration, as well as updates on BECCS and biochar (PyCCS) potentials, DACCS costs and geological storage options. The updates also reflect the differences in qualitative storylines and/or quantitative results to extensively capture the results and conclusions of other NEGEM WPs (see closer in section 2.3)

In the preliminary scenarios (D8.6), the results suggest roughly similar global primary energy supply in all the scenarios in 2050 and in 2100. Reflecting the storylines, the updated set including 3 + 1 variants (section 2.3) portrays smaller consumption in *1.5C-Env* and *1.5C-Sec* scenarios. Most visibly, this is seen in the total energy supply varying from 800 to over 970 EJ in 2100 according to current scenario results. Whereas the preliminary scenarios with less NETPs options suggest a total volume of around 8–10 Gt/a in 2050 and 15–18 Gt/a in 2100 and peaking at 22 Gt, the updated scenarios with *expanded* portfolios reach 10–12 Gt/a in 2050 and 13–18 Gt/a in 2100, respectively. Of the single NETP options, the preliminary scenarios suggested volume of DACCS applied globally 2.7-14.5 Gt during 2060-100, whereas the updated figures suggest a more conservative range of 1.5–7 Gt/a in the studied period. For BECCS, the updated scenario results vary from 2–4 Gt/a in 2050 to roughly 7 Gt/a for BECCS in 2100 in the newly added *1.5C-Sec* scenario. In the preliminary scenarios a range of 2.5-4.6 Gt/a in 2050 to over 5 Gt/a in 2100 was estimated. The increased potentials in 1.5-Sec scenario here are due to the assumption of significant land release to energy crops cultivation from dietary changes. Hence, on one hand, the observed differences are due to an enhanced portfolio of NETPs and, on the other hand, due to more critically assessed potentials and conservative cost developments based on NEGEM results incorporated in the assessments.

PyCCS results have changed from the D8.6 due to updated data from PIK (Werner et al. 2023b). In addition, the amount of ocean liming significantly decreased compared to the initial scenario results (D8.6) when soil carbon sequestration and enhanced weathering were added to the NETPs portfolio.

Deliverable 8.1

In *D8.1: Stocktaking of scenarios with negative emission technologies and practises. Documentation of the vision making process and initial NEGEM vision,* a review of scenarios prepared in other studies and organizations, was conducted in late 2020 - January 2021. Noteworthy, it was concluded that the median estimates in the IAMC 1.5 C Scenarios Database for all NETPs combined gave a total estimate of almost 12 $GtCO_2$/year negative emissions in 2050 and 30 $GtCO_2$/year in 2100 respectively. Based on 266 scenarios, the corresponding median value for BECCS was above 3 $GtCO_2$/year in 2050 and nearby 11 $GtCO_2$/year in 2100. Of only 8 scenarios with DACCS assessed, the median value for 2050 was 0.05 Gt/year and 6.4 Gt/year for 2100. In comparison, our updated set of NEGEM scenarios demonstrates a total utilization of NETPs about 8–10 Gt/a in 2050, and 13–18 Gt/a in 2100. Hence, reflecting to these figures, the impact of conservative estimates prepared for the NEGEM scenarios is increasingly visible towards the end of the studied period. While downgrading the potentials with the results of NEGEM is most obvious with BECCS, the suggested DACCS figures seem to counterbalance the total volume of NETPs to an extent. Furthermore, based on D8.1, it is worth noticing that very few scenarios can include a portfolio of NETPs as diversified as the scenarios modelled for this deliverable.

The assessed total NETPs contribution for EU-31 of 1100–1400 Mt in 2050 in the NEGEM scenarios suggests larger volumes for NETPs than some of the earlier EC work, e.g. 50–250 Mt or 500 Mt referred in D8.1. Furthermore, a novel set of country portfolios of NETPs in single European countries was created for this deliverable (Appendix 1). A detailed review of country portfolios is beyond the scope of this deliverable and left to subsequent studies. Yet, the development of the country-specific tool for future assessments is worth noticing.

Deliverable 4.5

The European NETs portfolios have been studied also in NEGEM deliverable 4.5 with MONET model. The scenario results presented here differ somewhat compared to D4.5, as D4.5 focuses on technical potentials and this deliverable on the scenarios on realistic BECCS according to the defined storylines. In addition, in D4.5 the cumulative results for Europe (in Figure 10) are based on deterministic optimisation, aiming for a certain level of NETPs utilisation by 2100 according to defined effort sharing principles.

In D4.5 BECCS is seen as the most significant (73%) cost-optimal NETP-based solution for EU-27 and the UK cumulatively up to year 2100. Afforestation is in turn the second largest (20%), with small shares for biochar (5%) and EW (2%). DACCS is not applied at all, due to its high costs. This differs significantly compared to our results for EU-31, where DACCS will be the main tool for CDR, followed by BECCS. In addition to the constraints put on BECCS potentials in TIMES-VTT assumptions to reflect the newest NEGEM results, the foremost reason for this discrepancy might lie in the modelling of energy production, which affects most of the NETPs. A part of the success of BECCS stems from revenues from the sale of electricity, whereby the price of electricity has an important role. Whereas D4.5 has exogenous assumptions of the production of power, including the price paid for power, and heat, including fuel mix used, the energy sector is an integral part of TIMES and both heat and power production is part of the endogenous solution. High electricity price would explain the success of BECCS and absence of DACCS in D4.5 results. On the other hand, a lower electricity price and availability of renewable electricity would explain the success of DACCS in the scenarios presented here.

DACCS, which is uneconomical in D4.5, has a strong and dominating role in the second part of the century in our results. In all our three 1.5-degree scenarios, DACCS is the largest NETP in EU-31 combined, and also in individual countries, e.g., in the UK, Spain, Poland, Finland, and almost in France and Sweden, but not in Germany (See Appendix 1). In our results, BECCS utilisation in 2060 is, in absolute terms, on the same level in Finland and Sweden as in the UK and only half of that in Spain. In D4.5 UK and Spain are the largest BECCS deployers along with Germany, while Finland and Sweden do not deploy BECCS at all. The reason why BECCS is not deployed in Finland in D4.5 is that, despite its overall popularity, BECCS is restricted to access to CO_2 storage within 100km, a restriction not in use in our model. Even without the restriction, BECCS deployment assessment in D4.5 is based on pulverised co-firing in power plants, while the utilisation in Finland, and Sweden, would be based on combined heat and power plants in the industry and for district heating, using both forest residues as well as forest industry residues.

As the portfolio of NETPs has been expanded in this deliverable, the cost-efficient solutions employed rely on at least five different technologies in most countries, whereas they rely on only 2 to 3 technologies in D4.5. D4.5 shows large technical potentials for enhanced weathering in countries, that do not show potential in data sources used in our modelling, such as Finland and Sweden. The occurrence of alkaline minerals aside, the potential of easily quarried pure basalt and dunite rocks in Finland and in Sweden is a question that needs further investigation. Based on initial discussions with Geological Survey of Finland, the technical potentials were not included for these countries in this modelling.

Deliverable 4.3

In D4.3 NEGEM has studied possible CDR targets for Europe based on a cumulative need for 687 Gt of global carbon dioxide removals by 2100 defined in some IPCC 1.5°C scenarios. Different effort-sharing principles (namely responsibility, capacity, and equity principles) were tested to allocate the global target for removals to different regions. The cumulative target for EU28 varied from 32 Gt by 2100 (based on the equity principle) to 325 Gt by 2100 (capacity principle) (see Deliverable 4.3). Here the European scenario results propose a cumulative removal by NETPs of 32-39 Gt by 2065, thus likely being in the range of the results according to different effort sharing principles by 2100.

5 *Sensitivities and main challenges in modelling and further research needs*

Since forecasting the future is practically impossible, **the storylines can only describe potential trajectories on how the future might unfold**. They are not to be interpreted as scenarios forecasting the future or giving specific information on the amounts of certain technology needed in future. However, they can provide scale and understanding on the magnitude of solutions needed, and applicable in policymaking and strategy work by different stakeholders. Modelling of the three different scenarios according to varying storylines aims to represent “a spectrum” inside which the final future solutions may lay when different types of future conditions, uncertainties and criteria are considered. The results presented here will be further analysed in the coming deliverables on NEGEM vision and final recommendations on the responsible and realistic potentials will be provided.

Information from earlier NEGEM work, well recognised databases, literature, expert elicitations (D5.4) and VTT’s internal knowhow on technology development have been used to define the calculation parameters. Here, a special focus has been put on the NETPs description in the model. However, there are obviously sensitivities and uncertainties related to the modelling parameters of many technologies and NETPs included in TIMES models. The effort to include the NETPs in TIMES modelling with information from other NEGEM WPs has been substantial, and due to time limits no separate sensitivity analysis is done here. However, this chapter aims to list some of the key uncertainties.

To show the results in the context of the annual global carbon fluxes Figure 19 has been created. The limitations and sensitivities in long-term modelling reaching many decades ahead often raise questions on whether the assessments such as those presented in this deliverable are realistic. Focusing on responsible deployment of NETPs, this discussion is particularly relevant with the NEGEM scenarios. Often, this discussion focuses on annual deployment rates or learning rates of technologies, or the amount of investments needed to realize the suggested scenarios. The annual carbon balance brings one viewpoint to the discussion (Figure 19). Yet the magnitude of NETPs is high compared to current volumes, in comparison with natural fluxes, the volumes for NETPs assessed of around an order of magnitude 20 Gt/a, are relatively small.

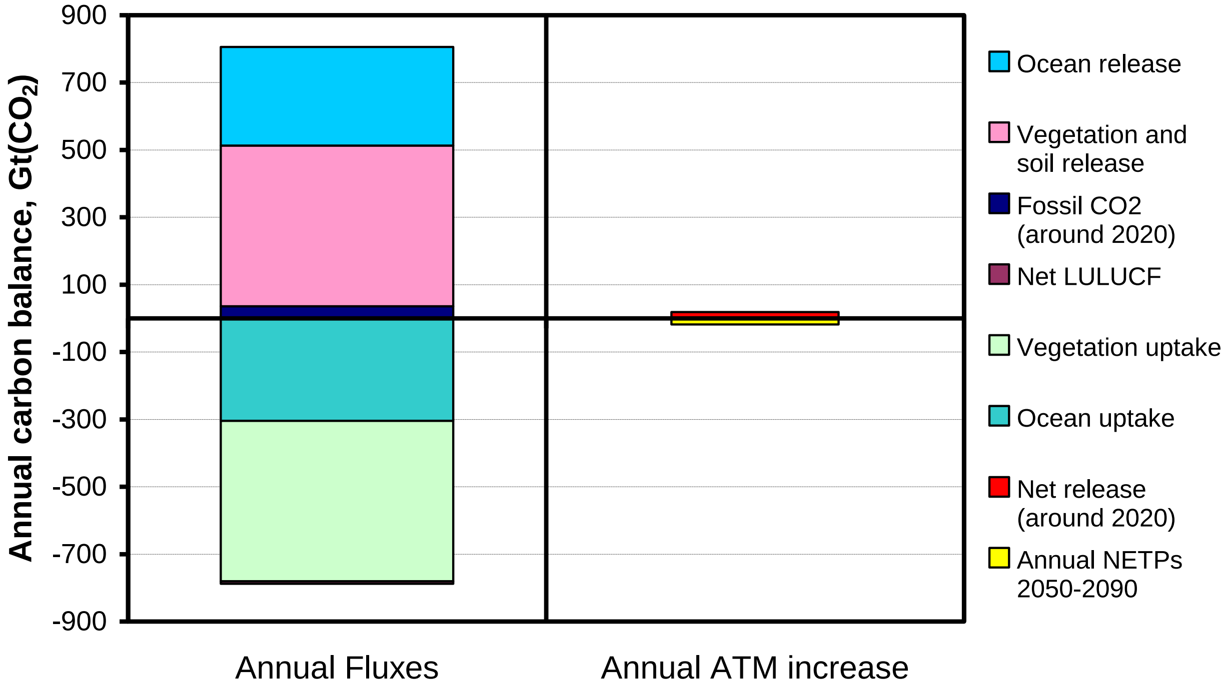

Figure 19. Negative emissions in the Annual Carbon Balance. Annual balance of the fluxes of the global carbon cycle, including anthropogenic activities, averaged globally for the decade 2012–2021 (adapted from Friedlingstein, P. et al. 2022, figures converted to Gt(CO_2)), compared with the annual net increase in the atmosphere around 2020, and the average annual uptake by NETPs in the scenarios 2050–2090.

Modelling of the land use, land use change and forestry sector (LULUCF) sink is missing from the analysis both in global and European levels (i.e. the results figures above do not present the land use sink/emissions). However, it could be assumed that LULUCF sector emissions and sinks should balance each other in the scenarios, resulting to zero emission from LULUCF sector. Here NETPs based on land use are seen as additional sinks.

One key challenge in the modelling is the possible double counting of biomass and land use based NETPs (BECCS, biochar, re-/afforestation, soil carbon sequestration and enhanced weathering). As already stated earlier, there is a possibility that the potentials for these different measures are partly overlapping, i.e. assuming the use of same land areas, or relying on use of same residual biomass. For example, potentials assumed for soil carbon sequestration may require that residues are left unused, whereas e.g. BECCS potentials consider some level of use of residues. Here this risk is controlled by using data from WP3 analyses when possible. For biochar, no use of residues is assumed here to avoid risk of double counting.

However, to solve the risk of double counting all the land and biomass based NETPs, in addition to other LULUCF sector activities, should be modelled simultaneously, which is out of scope of this project, but likely needed in future. In addition, it is somewhat unclear if several NETPs can be simultaneously applied to a same land area, e.g. if soil carbon sequestration and enhanced weathering can be done simultaneously. Thus, the possibility of double counting cannot be completely removed.

Several future research needs are recognised:

- Sensitivity / uncertainty analysis on key parameters, such as costs, potentials and widening the spectrum of futures captured by the scenarios, e.g.
    - Sensitivity of the results to the climate change mitigation target, e.g. 1.6 degrees instead of 1.5 degrees could be studied.
    - Further efforts could be made to model scenarios with several policy measures, and socio-economic patterns, such as reduced consumption (post-growth scenarios), etc.
    - EW and SCS can be considered as most speculative NETPs, and a model run excluding those options could be made.
- Continuous critical review of the technologies that look promising in the NEGEM modelling results but are still taking early steps in development and scale-up (e.g. DACCS, EW).
    - More information is needed on the realistic potential of EW in relation to its technical and logistic details, as well as environmental implications (D1.5).
    - For DACCS technologies more research is needed e.g. on the absorbent materials used in DACCS.
- For BECCS solutions, land-neutral approaches need to be sought 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 value chains for bio-CCS.
- More effort needs to be put to study the CO_2 logistic and storage solutions on a gigaton scale NETP implementation.
- The use of critical minerals in relation to NETPs (D3.9) should be updated based on the final scenarios and new LCA data from WP1.

6 Key findings and policy relevant messages

Based on the final global NEGEM scenario runs with TIMES-VTT Integrated Assessment Model we can see that NETPs would be needed to reach global GHG mitigation with a 1.5–2°C target. The 2°C corresponds with the NDCs given by the UNFCCC COP26 in Glasgow in 2021. The results clearly indicate that moving from the 2°C target to the 1.5°C target leads to much more rapid emissions reductions. The increased challenge in mitigation leads also to much higher mitigation costs even with immediate climate actions, which are modelled in 1.5C-Tec, 1.5C-Env, and 1.5C-Sec scenarios.

The scenario results show that a quick transition away from fossil fuels would require strict energy and climate policies to accelerate that transition. In the scenario modelling, renewable energy and other clean technology penetrations were based on a cost-optimal solution leading to substantial deployment of fossil-based CCS (FECCS) in the energy-intensive industries, power production, and energy transformation sector. Especially by 2050, fossil-based power production with CCS would be employed. After that, the captured amounts associated with industrial processes would exceed those in the electricity sector, which is due to increasing shares of renewable power in the global energy mix. It should be noted, however, that fossil fuel prices are endogenously determined in TIMES-VTT and reflect long-term equilibrium prices. Modelled fuel prices are thus not comparable with the volatile market prices, which reflect changes in supply and/or demand, like we have been facing after the Russian attack to Ukraine.

In the scenario results, the investments in NETPs are at the highest levels after 2060, but already in 2040 significant amounts of BECCS, biochar, SCS and EW take place, with DACCS starting to appear in the 2050s. This indicates that policies and measures related to NETPs should be in place early in advance, to enable the scale needed for removals to reach the 1.5°C target. Accelerated actions would be needed in case global GHG emissions would not show rather immediate downturn trend as expected in the scenario runs. Among the NETPs, all the options modelled appeared in the scenario results, indicating that no NETP option should be excluded from a cost-effective GHG mitigation portfolio. This indicates that the costs of all NETPs are in the competitive range when aiming to 1.5°C target. However, the results with expanded NETPs portfolio show that the cost-efficiency of ocean liming seems to be weak, and it only appeared in minor quantity in 2060 in 1.5C-Tech scenario.

In total, all the NETPs considered account for about 10 $GtCO_2/a$ during 2080–2100 in the NDC scenario, but even up to 18 $GtCO_2/a$ in the 1.5C scenarios. In 2050, NETPs account for 10–12 $GtCO_2/a$ in the 1.5C scenarios demonstrating the rapid increase in NETP demands still beyond the year 2050.

Traditionally, BECCS has been the most significant option in mitigation scenarios reported by the IPCC, IEA and many other authors (D8.1). For example, IPCC AR6 WG3 reported median use of BECCS of approximately 9 $GtCO_2/a$ by 2100. Also here, the biomass-based technology options, BECCS and biochar, both become competitive in all three 1.5°C scenarios. However, in NEGEM 1.5°C scenarios the contribution of BECCS by 2100 is lower compared with the scenarios reported by the IPCC AR6 WG3, varying from around 3 $GtCO_2/a$ in 1.5C-Env, where BECCS from energy crops is strictly limited to not to create further pressure on planetary boundaries, to less than 7 $GtCO_2/a$ in 1.5C-Sec, including an assumption of significant land release to energy crops cultivation from global dietary changes.

Considering the global and regional constraints in sustainable biomass supply, DACCS appears to emerge as a significant option especially in the long-term. In the 1.5C-Env scenario, with significant restrictions for BECCS, the need for DACCS approximately doubles compared to the other scenarios in 2060–2080.

However, in NEGEM scenario work a lot of emphasis has been put on analysis of BECCS potentials, in relation to the planetary boundaries (WP3). Thus, the increased use of DACCS due to heavy restrictions to BECCS does not automatically imply that alternatives to BECCS would become "powerful weapons" in climate change mitigation. In NEGEM work the DACCS options have been studied especially through LCA (D1.5, Cobo et al. 2022), and found as an option where side-effects could be minimised, but a tremendous engineering challenge would be faced in gigaton scale implementation (Cobo et al. 2023). The scenario modelling here shows that large scale implementation of DACCS would require substantial renewable energy investments (especially in solar power). In addition, more research is needed e.g. on the solvents and adsorbent materials used in DACCS.

While the nature-based solutions can be quite cost-competitive and provide multiple co-benefits for biodiversity and biosphere integrity, under the assumed storylines the combined potential of biochar, SCS, and af-/reforestation still seems far from sufficient for keeping the temperature change well below 2°C. In addition, the nature-based solutions face the risk of reversal of the stored CO_2 (see e.g. NEGEM deliverables 2.2, 2.3, 6.2), which has not been the focus of this modelling work. Technical solutions with geological-timescale storages provide permanent carbon dioxide removals and are needed to reach climate neutrality.

Compared with the global modelling, the European modelling focuses with more detailed in regional resolution and policy measures in Europe. This is reflected by the higher marginal mitigation costs compared with the global modelling. The higher mitigation costs can be to a large part explained by the optimization, where global modelling allows for more flexibly to invest in those regions, where the marginal costs are the lowest in GHG mitigation. In the global scenarios, the marginal costs are in the 1.5C-Tec and 1.5C-Env case around 200 €/t $CO_{2\text{-eq}}$. in 2050 and the increase by 2080 to about 250 €/t $CO_{2\text{-eq}}$. In the 1.5C-Sec scenario the costs are somewhat higher, about 230 €/t $CO_{2\text{-eq.}}$ in 2050 and about 300 €/t $CO_{2\text{-eq.}}$ by 2080. In the scenarios based on the European model, the marginal carbon price is in 2050 about 280 €(2020)/t CO_2 in the 1.5C-Tec scenario, about 400 €/t CO_2 in the 1.5C-Env scenario and about 410 €/t CO_2 in the 1.5C-Sec scenario. However, by 2060, the marginal costs converge in all three scenarios to levels between 310 and 340 €/t CO_2, meaning that in the 1.5C-Env and 1.5C-Sec scenarios the peak marginal costs occur around 2050.

The above results indicate that a Europe-centric decision-making framework loses out on an opportunity to reduce the average cost of abatement, but at the same time might offer a route to offset historical emissions (see D4.3) The results also show the distribution of net emission reductions between direct emissions abatement and the deployment of NETPs. The European results indicate that the marginal costs of direct emissions reductions exceed the costs of NETPs when emission reduction levels over 76% (compared with 1990 levels) are reached (including emissions from bunker fuels).

This modelling work is among the first attempts to include an expanded portfolio of NETPs in IAM modelling. Thus, the results concerning various NETPs, and especially enhanced weathering and soil carbon sequestration are based on the currently available knowledge and literature sources, which will most likely develop in the future. Consequently, the results should be interpreted with caution. One of the key findings of NEGEM is that climate policies should not rely too heavily on only a few NETP options, as most of them include trade-offs with several environmental impact categories, human health, and planetary boundaries (see deliverables D3.3, 3.7, 3.8). Thus, keeping all NETP options included in climate policy planning is recommended, while NEGEM results help to recognise their benefits and challenges.

The key messages based on the NEGEM scenario assessment can be summarized as follows:

- NETPs would be needed in gigaton scale to reach the 1.5–2.0°C mitigation goals and no NETP option should be excluded from mitigation portfolios at this stage.
- In the scenario assessments, the GHG mitigation targets were achieved by cost-optimization of the mitigation pathway. The results show that stricter policies and measures to phase out fossil fuels are needed across all GHG mitigating sectors. These measures can include e.g. setting high CO_2 emission taxes, applying regional/international rules for phasing out of fossil fuels, setting very tight CO_2 emission limits in using fossil fuels (i.e. for car manufactures, buildings, etc.), and take-back obligations for fossil fuel producers. In addition, supporting policies are needed to ensure large-scale NETP investments by 2050.
- The global potential for BECCS depends heavily on the assumptions on energy crop potentials. IPCC AR6 WG3 reported a median use of BECCS of approximately 9 $GtCO_2$/a by 2100, relying largely on energy crops. In NEGEM 1.5-degree global scenarios the contribution of BECCS by 2100 varies from 3 $GtCO_2$/a in 1.5C-Env to less than 7 $GtCO_2$/a in 1.5C-Sec. In 1.5-Env scenario, further pressure on planetary boundaries is strictly avoided, so BECCS from energy crops is very limited and BECCS from residues and point-source emissions are emphasised. In 1.5-Sec scenario BECCS from energy crops is enabled by significant land release from pastureland to cultivation of bioenergy crops due to 25% dietary change towards planetary health diets globally.
- In IPCC AR6 WG3 1.5°C scenarios the cumulative removals by 2100 from BECCS vary between 30–780 $GtCO_2$. The removals by BECCS in NEGEM scenarios are around 200–360 $GtCO_2$. The removals by BECCS are moderate due to constraints in use of bioenergy crops, as well as due to an expanded portfolio of NETPs in the modelling. The results show that BECCS application spreads to various technological solutions, for power and heat production, bioliquids and biogases (including hydrogen), instead of traditional assumption to use BECCS mostly in power plants. Deployment of BECCS starts at small scale already in 2030 both in the global scenarios and the European scenarios, the first applications focusing on biofuel conversion where the capture costs are sufficiently low.
- In 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, removals by DACCS vary from around 80 to 240 $GtCO_2$. Deployment of DACCS starts in both global and EU scenarios by 2050. Especially when BECCS is heavily restricted, as in 1.5C-Env scenario, significant removals by DACCS are needed to achieve the climate targets, e.g. globally up to 7 $GtCO_2$/a in 2070. This is despite the relatively high prices of DACCS.
- While the nature-based solutions can be quite competitive and provide multiple co-benefits 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 (i.e. well below 2°C). In NEGEM scenarios, nature-based solutions provide around half of the global removals needed by 2050, and around one third by 2100. Enhanced weathering can also provide a moderate contribution to removals, however further research is needed on its environmental and practical implications.

- In 2020, the European Commission published an impact assessment accompanying the document ”Stepping up Europe’s 2030 climate ambition” SWD (2020) 176 final. It concludes that in the EU the total negative emissions (including the LULUCF sector and NETP options) need to be around 0.5 $GtCO_2$/year by 2050, in order to enable climate neutrality. NEGEM results show significantly higher deployment of NETPs varying from 1.1 to 1.4 $GtCO_2$/year by 2050. NETPs, such as BECCS, are implemented to some extent already in the 2030’s, emphasizing the need to clarify EU regulations for NETPs as soon as possible.
- The EU climate Advisory Board has recommended a 90% greenhouse gas emission reduction target for the EU by 2040 compared with the 1990 emission level. The NEGEM results concerning the CO_2 reductions in Europe indicate that the marginal costs of direct CO_2 emissions reductions would exceed the costs of NETPs deployment when emission reduction levels above 76% are reached.

The NEGEM work will continue with formulation of the final NEGEM vision and finalisation of the conclusions on realistic and responsible NETP potentials globally and in Europe. The results of scenario modelling presented in this deliverable, and especially the results for European countries will be further analysed in deliverables D8.3 on NEGEM vision and D8.4 on final recommendations of the whole NEGEM project.

For preparing this report, the following deliverable/s 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
D1.4	Comprehensive sustainability assessment of Bio-CCS NETPs	VTT, ETH	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	12
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-CO_2 NETPs, relative permanence of NETPs and their implications	UOXF	R	PU	24
D2.4	Classification of NETPs against appropriate commercialisations instruments, including options for trading multiple technologies under a single instrument such as the ETS	UOXF	R	PU	36
D3.2	Global NETP biogeo-chemical potential and	PIK	R	PU	24

	impact analysis constrained by interacting planetary boundaries				
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
D3.7	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
D4.2	Bio-geophysics database	ICL	Other	PU	15
D4.3	Identify Member State Targets for CDR	ICL	R	PU	17
D4.5	Member State specific pathway for NETP deployment	ICL	R	PU	36
D5.3	Stakeholder views on NETP governance	UCAM	R	PU	18
D5.4	Final Report on Expert Elicitation for NETPs	UCAM	R	PU	36
D6.2	Principles for carbon	CMW	R	PU	18

	negative accounting				
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
D8.6	Quantitative assessments of NEGEM scenarios with TIMES-VTT, preliminary results	VTT	R	PU	30
D8.7	Updated NEGEM vision	VTT	R	PU	30

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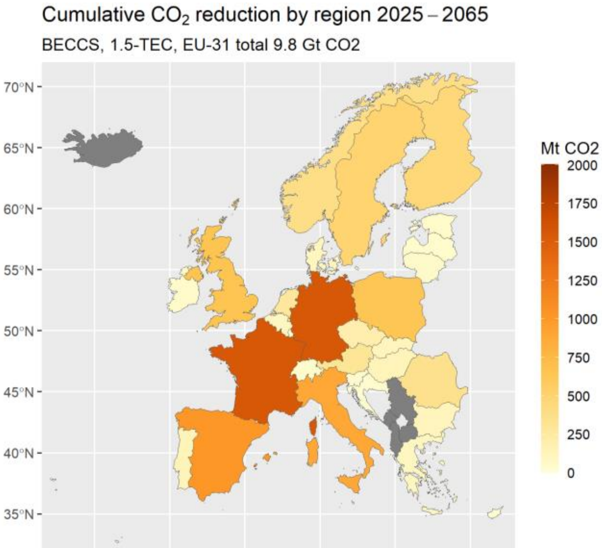
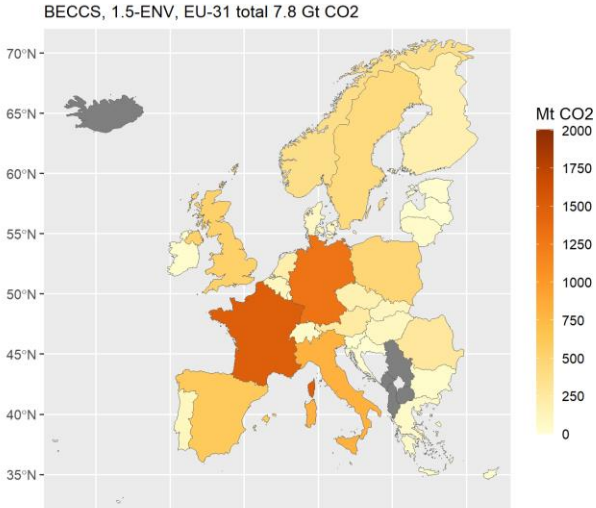
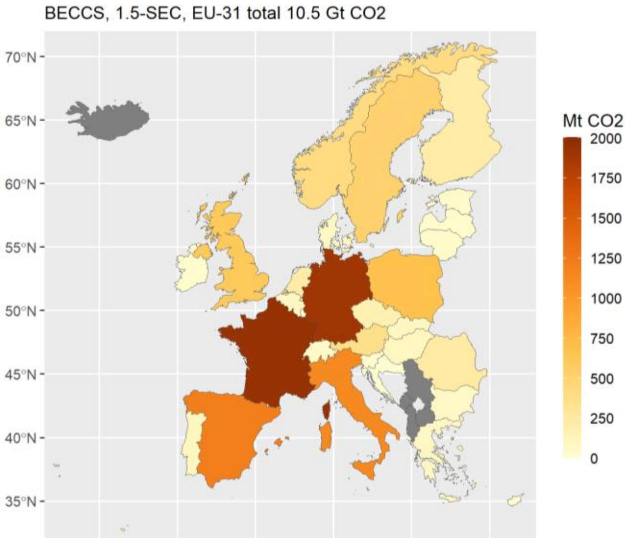
Appendix 1: Country specific NETP results by Pan-European TIMES VTT

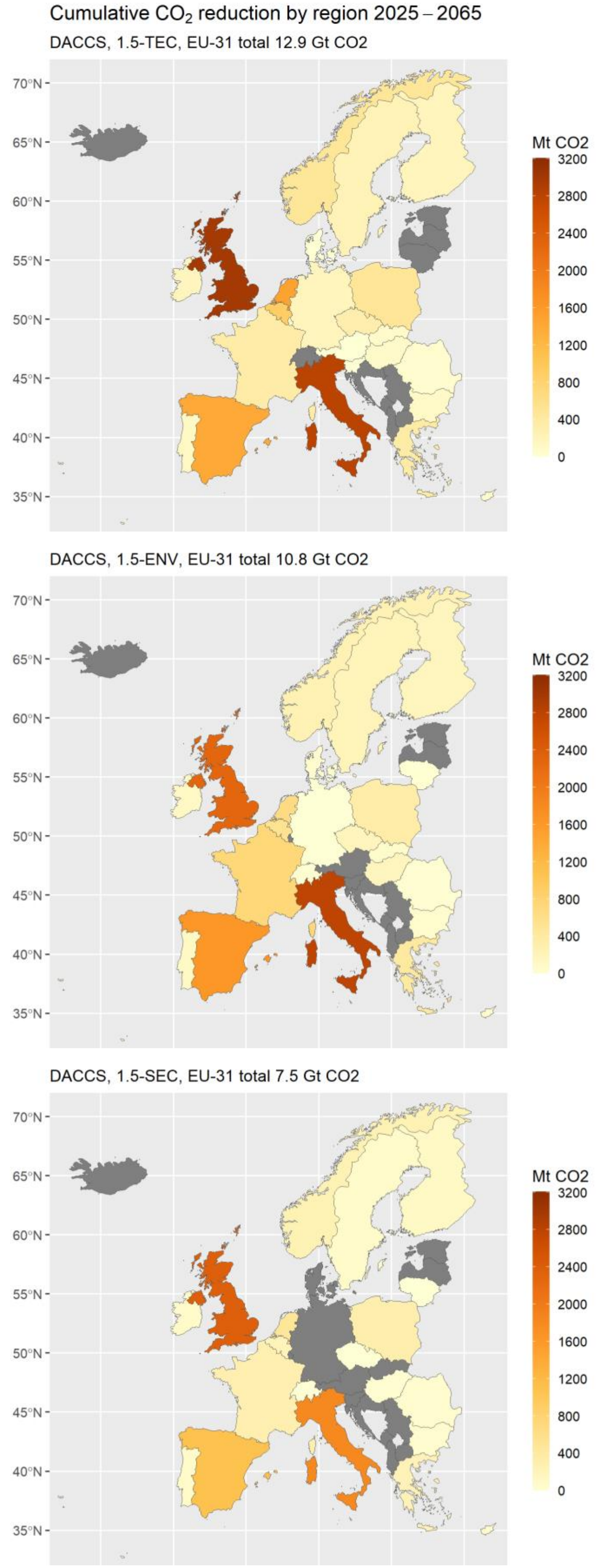
BECCS



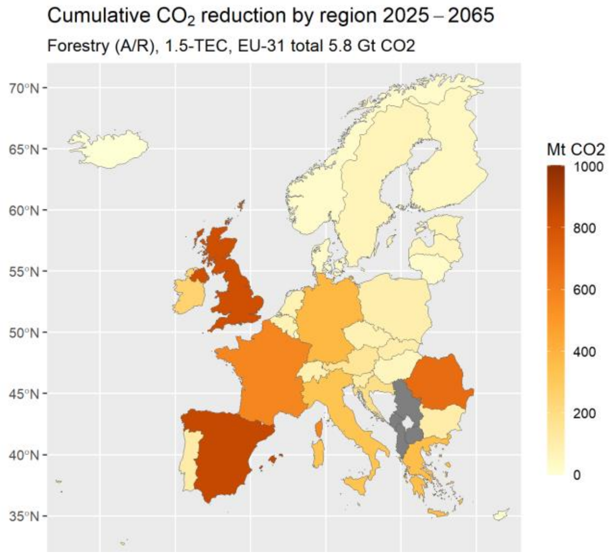


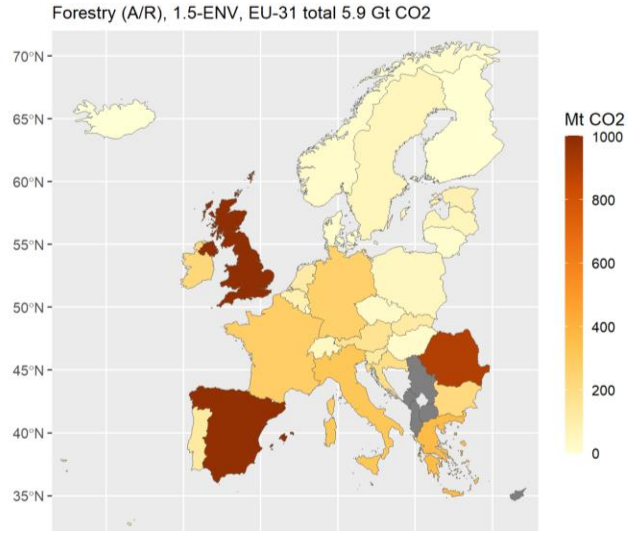


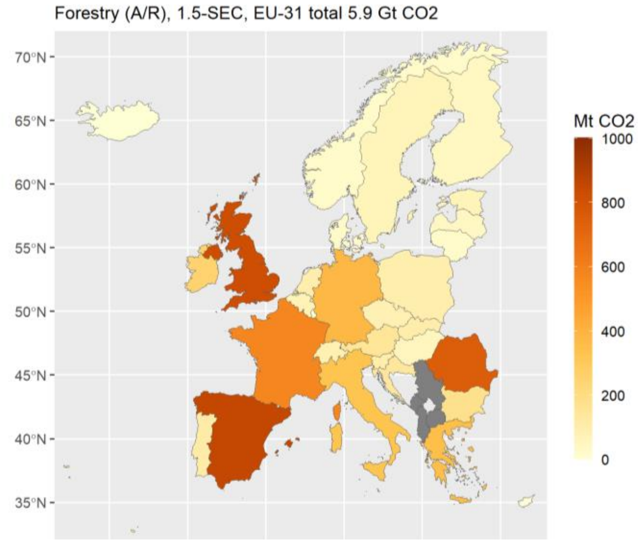
DACCS


Cumulative CO_2 reduction by region 2025 – 2065
DACCS, 1.5-TEC, EU-31 total 12.9 Gt CO2
DACCS, 1.5-ENV, EU-31 total 10.8 Gt CO2
DACCS, 1.5-SEC, EU-31 total 7.5 Gt CO2
70°N
65°N
60°N
55°N
50°N
45°N
40°N
35°N
Mt CO2
3200
2800
2400
2000
1600
1200
800
400
0

Afforestation, reforestation



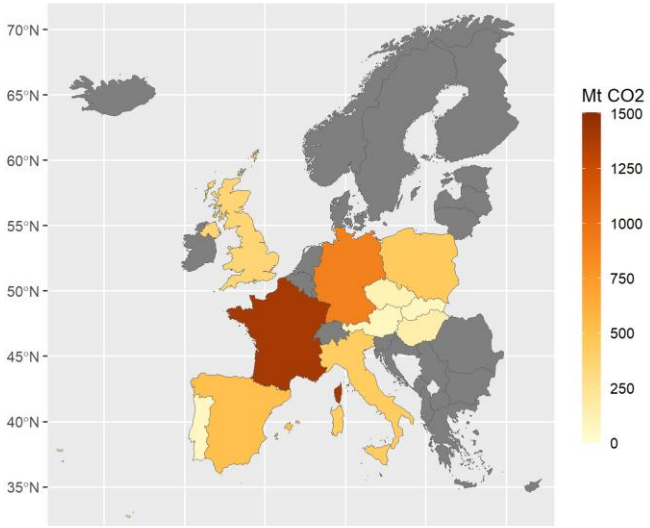




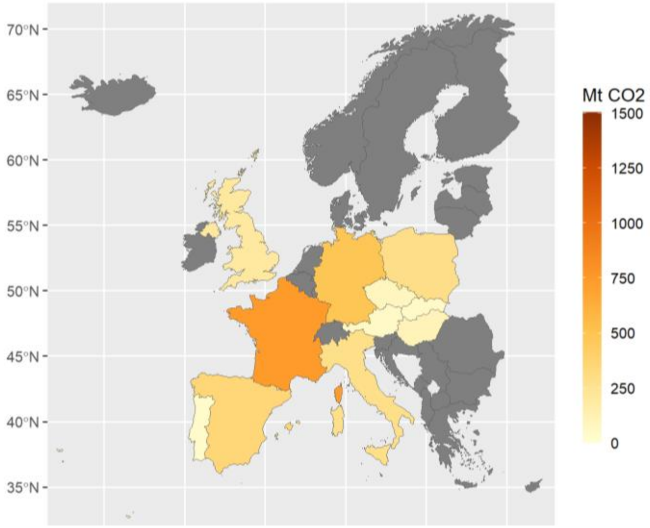
Enhanced weathering

Cumulative CO_2 reduction by region 2025 – 2065

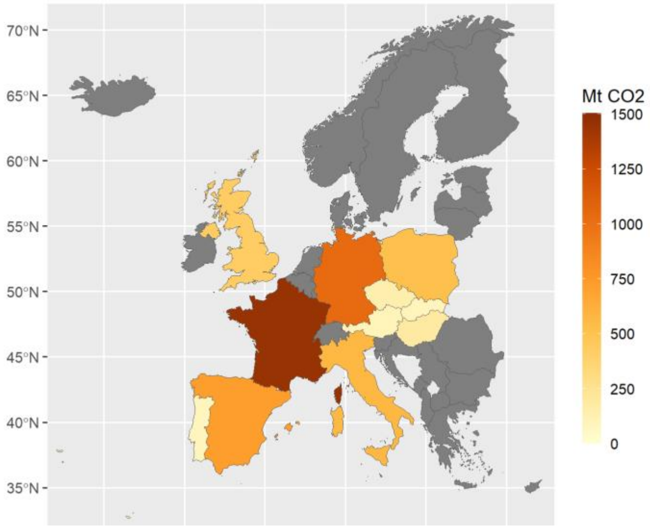
EW, 1.5-TEC, EU-31 total 4.5 Gt CO2



EW, 1.5-ENV, EU-31 total 2.6 Gt CO2



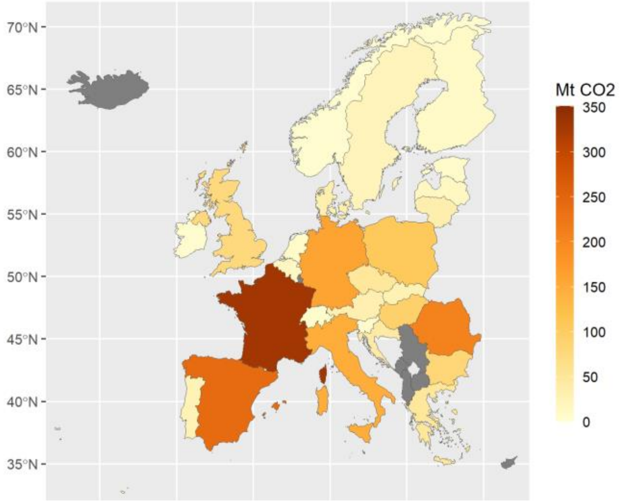
EW, 1.5-SEC, EU-31 total 5.3 Gt CO2



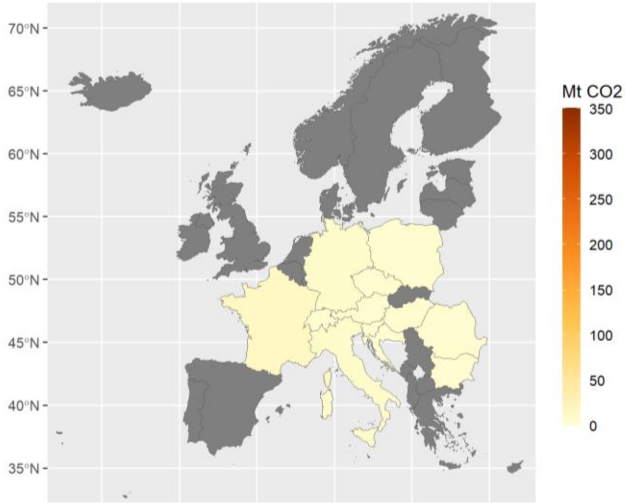
Biochar

Cumulative CO_2 reduction by region 2025 – 2065

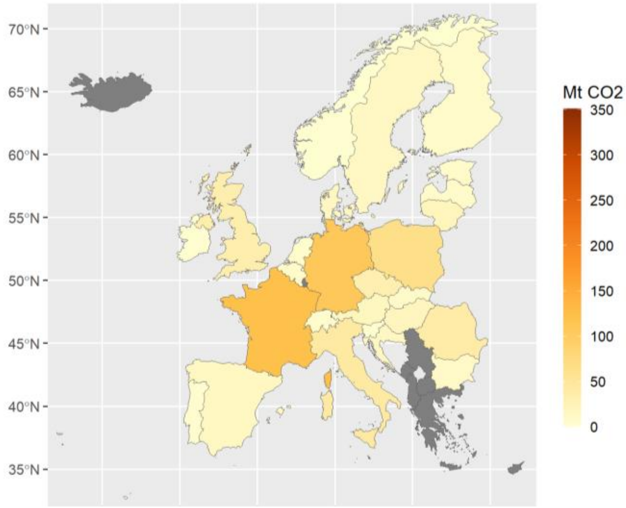
Biochar, 1.5-TEC, EU-31 total 1.8 Gt CO2



Biochar, 1.5-ENV, EU-31 total 0.1 Gt CO2



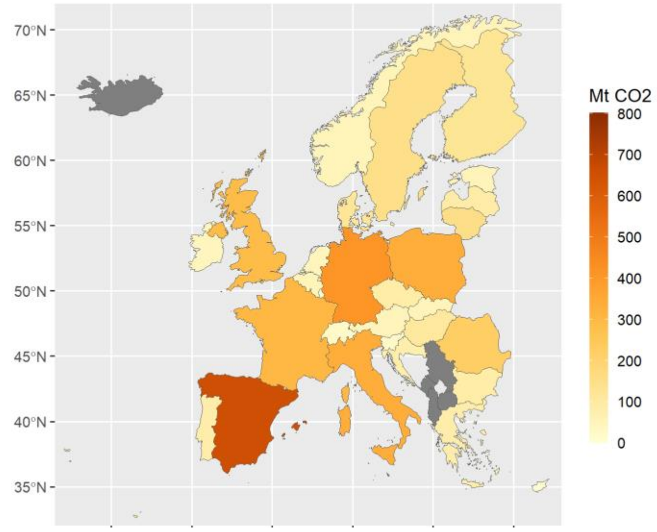
Biochar, 1.5-SEC, EU-31 total 0.6 Gt CO2



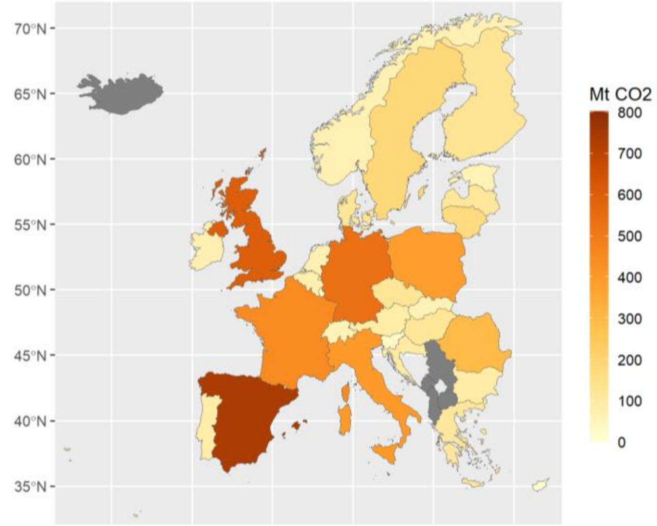
Soil Carbon Sequestration

Cumulative CO_2 reduction by region 2025 – 2065

SCS, 1.5-TEC, EU-31 total 4.1 Gt CO2



SCS, 1.5-ENV, EU-31 total 5.3 Gt CO2



SCS, 1.5-SEC, EU-31 total 4.1 Gt CO2