NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Quantitative assessments of NEGEM scenarios with TIMES-VTT, preliminary results

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NEGEM

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Executive Summary

The aim of the WP8 in the NEGEM project is to create a clear and shared medium-to-long-term vision on the sustainable potentials of the NETPs and its role in the greenhouse gas (GHG) mitigation at the EU level and globally. The formulation of the NEGEM vision is followed by formulation of NEGEM pathways or storylines to reach the climate goals set in the UNFCCC Paris Agreement. The NEGEM storylines are also quantified with global and European Integrated Assessment Models (IAMs), i.e. TIMES-VTT and Pan-European TIMES-VTT. In this report D8.6, the formulation of the NEGEM storylines are reported. The primary focus of the report is on analysing the preliminary quantitative NEGEM scenarios. Based on the results from earlier NEGEM discussions on scenarios and the results of the NEGEM WPs delivered so far, three alternative storylines were created from which two were modelled with TIMES-VTT: one that focuses on nature conservation and biodiversity and another one, which focuses on advanced technology and global markets. The third storyline focuses on security and self-sufficiency, which quantitative assessment will be reported in the forthcoming D8.2. The preliminary scenario assessments for nature conservation and biodiversity as well as for advanced technology and global markets are modelled with a 1.5 °C mitigation target (1.5C-Env and 1.5C-Tech). As a reference scenario, we have used a mitigation pathway, which includes Nationally Determined Contributions (NDCs) that represents 2 °C global warming during this century. The modelling of NDC scenario and 1.5CTech scenario partly builds upon earlier NEGEM assessments with global TIMES-VTT scenarios, which were reported in the D3.9.

The key messages based on the preliminary scenario assessments can be summarized as follows:

- NETPs would be needed to reach the 1.5-2.0°C mitigation goals and no NETP option should be excluded from mitigation portfolios at this stage. Considering the environmental constraints, DACCS seems be the most significant NETP option especially in the long-term.
- In the scenario assessments, the GHG mitigation targets were achieved by cost-optimization of the mitigation pathway. The results show that we would need stricter policies and measures to phase out fossil fuels across all GHG mitigating sectors. In addition, supporting policies are needed to ensure large-scale NETP investments by 2050.
- PyCCS and reforestation in our scenarios are competitive and quite sustainable options in GHG mitigation, but under the assumed storylines their combined potential still seems far from sufficient for keeping the temperature change within 1.5-2.0 °C mitigation targets. However, especially PyCCS seems to be a potential mitigation option due to its several co-benefits but more research is needed to better analyse its global and regional sustainable potentials.

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Introduction

While the individual WPs of NEGEM project are focusing on techno-economic, environmental, social assessment, or policy and incentive schemes of negative emission technologies and practices (NETPs), there is a need for looking at the NETPs potential and impacts from the whole system and societal perspectives. The aim of the WP8 in the NEGEM project is to create a clear and shared medium-to-long-term vision on the sustainable potentials of the NETPs and its role in the GHG mitigation at the EU level and globally. The formulation of the NEGEM vision is followed by formulation of NEGEM pathways or storylines to reach the climate goals set in the UNFCCC Paris Agreement. The NEGEM storylines are also quantified and the aim of the Task 8.4 to model NEGEM scenarios with global and European Integrated Assessment Models (IAMs), e.g. TIMES-VTT and Pan-European TIMES-VTT (PET-VTT). The work will integrate existing and possible development of the future energy and industrial systems, agriculture and forestry, residential and commercial sectors, and the other sectors producing greenhouse gas (GHG) emissions.

In this report D8.6, a summary of the formulation and quantification of the NEGEM storylines are given in addition to the preliminary scenario results for the selected global NEGEM scenarios. The D8.7 for Updated Vision is being prepared in parallel with the D8.6 and in that report, additional information is given for the storyline and scenario formulation process, which are also part of the vision making process. However, it should be noted that both the vision formulation and scenario analysis are continuing until the end of the project to include the final results of all the WPs.

The NEGEM scenario work started with creation of preliminary NEGEM vision, literature analysis of the role of NETPs in GHG mitigation, and the selection of the publicly available emission scenarios. These results have been reported in *D8.1: Stocktaking of scenarios with negative emission technologies and practises. Documentation of the vision making process and initial NEGEM vision* followed by the milestone report *M8: NEGEM pathways*. The first TIMES-VTT scenario results were reported in *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*. Modelling of the global scenario assessments to mitigate the climate change to 1.5-2.0 °C temperature increase during this century was largely based on definitions and GHG emission pathways reported in the IIASA database for the IPCC AR6 WG3 report[1]. However, TIMES-VTT database for NETPs was updated and extended based on results from WP1, WP3, WP4 and WP7 of NEGEM well as on recent literature on NETPs and other GHG mitigating technologies. The schematic of the scenario framework with above information flows and reporting is illustrated below in Figure 1. The illustration shows how the formulation of NEGEM vision and scenarios are tighten together with feedback loops. In addition, the more comprehensive NEGEM framework is briefly described in Chapter 1.3.

[1] IPCC AR6 WG3, IIASA database

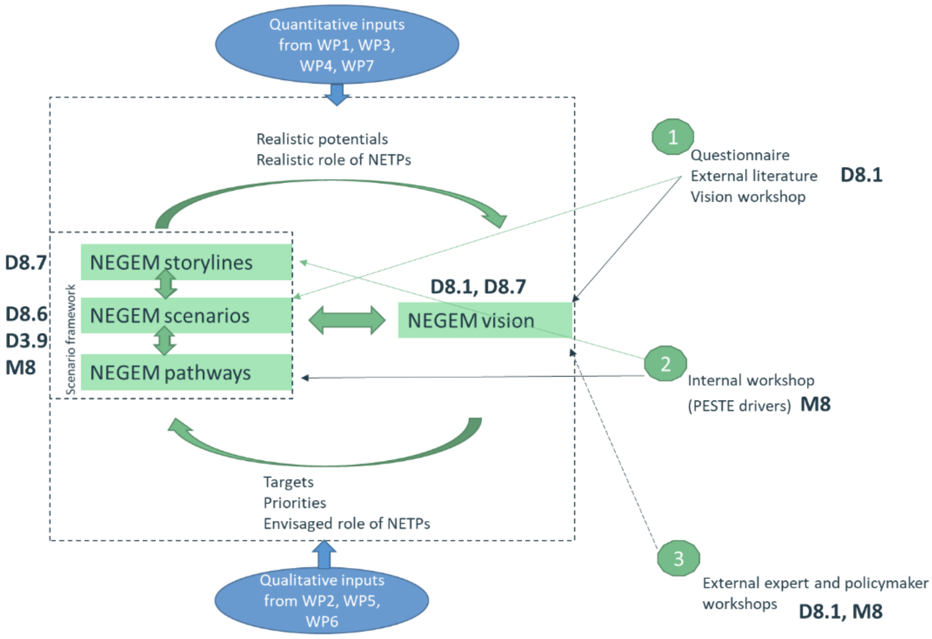

Figure 1. Illustration of the information flows and reporting for NEGEM vision, storylines, pathways and scenarios. The final NEGEM vision and scenarios will be reported in the forthcoming D8.2.

During the final stages of the NEGEM project, WP8 will develop a medium-to-long term vision concluding whether NETPs could be a responsible and rational option globally and for the EU. Final quantitative NEGEM scenarios will be reported in D8.2, which will include both global and EU level assessments in addition to more comprehensive scenario matrix sensitivity analysis for analysing the realistic potentials of the NETPs for 1.5-2.0 °C mitigation pathways. The aim is to use data and results from WP1-WP7 as much as possible but due to differences in methodological approaches, there is a need for data harmonisation and better understanding about the differences and similarities. This harmonisation work is still in process but in the preliminary scenario modelling we have used the quantitative data and results from WP3, WP4 and WP7 as techno-economic inputs for NETs or boundary limits for sustainable potentials of bioenergy crops or afforestation (see also Table 3).

In addition to collaboration with NEGEM partners, we have also worked with the H2020 sister projects LANDMARC and OceanNETs. From the LANDMARC project, the relevant quantitative assessments for NEGEM will be published in 2023, including also the updated inputs related to afforestation and/or reforestation and the other land use would be used, if possible. From the OceanNETs project, we have already received some preliminary inputs for the scenario modelling on ocean NETPs, which have also used in the preliminary scenario assessments.

The contents of the D8.6 is organised as followed: Chapter 1 includes an overview of the formulation of the NEGEM storylines, including the description of the foresight methods used. Formulation of the NEGEM storylines are also described in the D8.7 focusing more on their contribution to the vision formulation while in this report we have focused more on the process how NEGEM scenarios are formulated based on NEGEM storylines. In Chapter 2, short descriptions of the TIMES-VTT IAM model and alternative scenarios are given as well as preliminary scenario results. Key findings and policy relevant results are highlighted in the Chapter 3 and Chapter 4 concludes with information on the next steps.

1 Formulation of the NEGEM storylines

1.1 Description of the method used

As the aim of the NEGEM project is to analyse the realistic and sustainable potentials of the NETPs for 1.5 °C mitigation pathways, we wanted to create alternative storylines, where the operating environment for the NETPs will 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 with the NEGEM External Advisory Board (EAB) given an opportunity to contribute to ensure that we combine the knowledge acquired in the project so far.

There are several foresight methods to support systemic formulation of storylines and related scenarios. In NEGEM, we selected Futures Wheel approach, which is a participatory "smart group" or "mind-mapping" foresight method that provides a model of the future based on the consequences of an event or trend. Futures Wheel thus aims at structured brainstorming process to uncover multiple levels of consequences resulting from all types of change (Bengston, 2015). As an example, changes in socio-ecological or techno-economic systems often produces a cascade of unanticipated consequences. 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 more holistic approach on sustainability using LCA approach while WP5 is about social systems, including public and stakeholder perceptions.

The basic question is how to take an 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. Here, we are combining Futures Wheel approach with scenario method to paint a picture of future conditions in a narrative format. In the Futures Wheel, the name of the trend or event is written in the middle and primary and secondary impacts are written at the first or second ring of the wheel. In NEGEM, scenario selection and definition of scenario storylines have been discussed through the project lifetime (see e.g. D8.1, M8 and D8.7). Below, we are describing the storyline formulation based on workshop carried out in parallel with General Assembly at VTT in Espoo, in October 2022. In the workshop, there were nineteen participants physically present in addition to seven participants joining online (including VTTers moderating the groups).

The aim of the workshop on NEGEM storylines was to develop NEGEM storylines based on realistic potentials of NETPs. Suggestions from earlier workshops were used to guide the process (see D8.1, M8 and D8.7) and orientation material was sent to the participants before the workshop. In addition, introductory presentation was given in the workshop, where the TIMES-VTT global scenario runs with 1.5°C with overshoot and in addition to the reference scenarios with UNFCCC NDCs were shown. The presentation was based on the first NEGEM global scenario runs with TIMES-VTT reported in D3.9. Given that these scenarios indicate high demand of NETPs to reach the global climate targets, the workshop focused on what would a NETPs applying society look like in 2050.

Based on the results from earlier NEGEM discussions and results of the WPs, three different storylines were chosen. One that focuses on nature conservation and biodiversity, another one with focus on advanced technology and global markets and lastly a storyline with focus on security and self-sufficiency. Alternative storylines were formulated with different assumptions on global and regional developments, including social norms and values, behavior, policies etc. using the above-described futures wheel approach. Each of the storylines should be compatible with the 1.5…2 C goal of the Paris Agreement during this century. The TIMES-VTT scenarios thus use back-casting scenario method with modelling of pathway to a climate target. In Futures Wheel, participants were asked to think about the storyline on how we will reach that future and what direct and indirect consequences reaching it might have. The participants were divided into four groups, one being a virtual group.

After the workshop, the results were grouped and compared with by using PESTEL framework (reference). to structure the ideas answers into political and legal, economic, socio-cultural, technological and environmental perspectives (see also M8 and D8.7). Within each perspective, the answers were sorted into opportunities and barriers to better understand the implications of the solutions. Given that we received a vast amount of answers for each storyline, the most commonly given answers were highlighted and the importance reflected based on the past WPs. These were used to formulate three distinctive storylines. The results of the workshop have been reported in more detailed in D8.7 and on tables down below only those perspectives that were relevant for TIMES-VTT modelling presented in this report in addition to those perspectives, which will be elaborated further in the final NEGEM scenarios, which will be reported in D8.2.

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 socioeconomic developments and key drivers are described for each storyline. The storylines each represent one corner of the uncertainty space for a given perspective providing three distinctive narratives. Since forecasting the future is practically impossible, the storylines can only describe potential trajectories on how the future might unfold.

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

As discussed above, following three alternative storylines were created:

1. Storyline focusing on environmental sustainability with planetary boundaries;
2. Storyline that focuses on NETPs with technology and market optimisation;
3. Storyline focusing on security and self-sufficiency.

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.

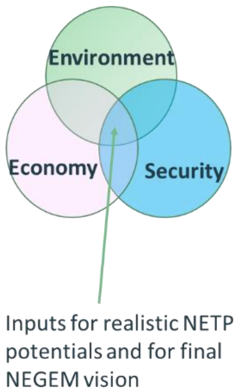

Figure 2. Three NEGEM storylines will create a framework for the assessments of the realistic potentials of NETPs and final NEGEM vision.

Below, a short description of those storylines is given, which quantitative scenario assessments are presented in this report. Comprehensive description of all the three NEGEM storylines is included in the D8.7, including the reporting of the workshop results for storyline formulation.

1.2.1 Nature conservation and biodiversity

The nature conservation and biodiversity storyline (1.5C-Env) highlights the need to increase global co-operation for efficient resource use. In this world, planetary boundaries would be strictly followed and the energy system would be renewable. Followed by highly increased environmental consciousness, consumption of material and energy would be reduced and become more efficient. In this storyline, NETPs are viewed sceptically due to the concerns of environmental impacts attached. As NETPs are not highly accepted, deployment of rapid and stringent emission reductions has an increased need.

Various economic incentives could be used to aid the deployment of NETPs. Importantly, NETPs should not further increase the pressure on the planetary boundaries, even though it is recognised that they will be needed. For non-permanent GHG emission storage, an additional insurance should be paid to ensure longer time horizon removals of at least 100 years. Monetary value would be given not only to carbon storage but also to other benefits, such as for biodiversity and ecosystem services. Soil carbon sequestration (SCS) and PyCCS, would be prioritized NETPs due to their co-benefits. There would be incentives for circular economy to enable highly efficient management of material streams and efficient use of NETPs.

Overall consumption would be reduced drastically and other changes in behaviour, such as diet changes, is seen. This would allow more agricultural land to be used for energy crops and BECCS, and biochar from PyCCS could be used for soil improvement. Very intensive agriculture, bio-based products as well as urban agriculture are also implemented. More dense population centres would lead to very efficient energy systems with reduced energy consumption.

As there is a competition for natural resources for food and bioenergy production and high importance is given to environmental sustainability with planetary boundaries, there would be an increased deployment of DACCS. This would need even more aggressive RES deployment and large changes in our infrastructures. There would not be further land use expansion for NETPs, as biomass-based NETPs would be applied only within current bounds of agricultural land to be compatible with planetary boundaries.

Table 1. PESTEL summary for the Nature conservation and biodiversity storyline. Red colour indicates those perspectives, which were not included in the modelling of the scenarios so far. Some of those perspectives will be looked at in the final NEGEM scenarios through modelling of additional policies and measures (for example investment incentives or constraints, increased taxes, new market mechanisms) and through changes in modelling parameters and input data assumptions (for example macro drivers for demand sectors, demographic assumptions, technology learning or market shares of new technologies). In brackets, we have shown how the different perspectives have been or might be implemented in the forthcoming TIMES-VTT modelling.

PESTEL	Nature conservation and biodiversity
Political & legal	• Need for global co-operation to use the available resources efficiently (global trade of energy commodities with equilibrium prices) • NETPs are not highly accepted (investment constraints for land-based ocean NETs).
Economic	• For "non-permanent" C storage: payments for the insurance of longer time horizons, like 100 years. (can be modelled by increasing the costs of the selected NETs) • Monetization of ecosystem services to finance NBS, SCS, PyCCS (can be modelled with investment or other supporting mechanism) • Enabling near-term use of CDR (need to be reconsidered if we want to include early CDR investments in this scenario).
Socio-cultural	• Behavioral changes, i.e. reduced consumption, diet changes • More dense population centres and low global population growth (there are some possibilities to change the population densities between modelled regions as well as development of building sector, transport and mobility, etc.) • Inertia of changes in infrastructures, demographics, etc. (TIMES database includes expected life-times of existing and new infrastructures. With policy assumptions, we can increase the speed of infrastructure renewal, like abandoning the use of coal or other fossil fuels).
Technological	• Changes in diets and use of biochar for soil improvement increases the agricultural land area for BECCS • Highly efficient management of material streams (there are some opportunities to model increases in material efficiencies if needed) • Need for more DACCS --> even more rapid RES deployment (investments on DACCS and RES deployment are optimized but with supporting policies we can advance the investments) • Nature-based solutions +SCS+PyCCS are prioritized NETPs due to their co-benefits (modelling includes constraints for BECCS and ocean NETs)
Environmental	• Active collaboration and pooling of resources (global trade of energy commodities, emission allowances and geological CO_2 storage services) • Deforestation is approaching zero level by 2050 (assumptions for deforestation are taken from the literature). • Very intensive agriculture & bio-based products, including urban agriculture (alternative food production systems with lower land use requirements can be modelled if needed. • Land use change for biomass-based NETPs only within current land-use limits of agricultural land (low energy crop and afforestation potentials, no reforestation in modelling) • No implementation of ocean-based CDR due to its environmental uncertainty.

1.2.2 Advanced technology and global markets

The storyline of advanced technology and global markets (1.5C-Tech) entails a massive NET scale-up by 2050, which is enabled by various business models and effective climate policies. The main climate policy mechanism would be a large and increasing carbon price. Moreover, global integration of regional emission allowance markets will be realized with cap and trade system. There would be a decline in voluntary carbon markets in favour of capital being channelled into direct GHG mitigation investments.

It is important that carbon markets will not develop in a way that does not meet high multi-dimensional sustainability criteria as then they cannot be regulated well later. Other GHGs, such as N_2O and CH_4, would have a market price and, thus, removed from the atmosphere. Nature based solutions would be represented in a variety of mechanisms, not just carbon markets.

The cost of technologies would go down and there would be internalisation of external costs as well as incentives to invest in solutions that are more expensive with early innovation funds. Large-scale, low-cost finance would allow fast-track deployment.

There would be a fundamental transformation of the energy system. Fossil fuel industry would need to be transformed with NETPs, CCS, CCU and renewables. However, geopolitical factors may a play a role, forcing a switch to coal or oil, and therefore increasing the need for CDR. Additionally, life cycle emissions would be more costly and moving industrial production and GHG emissions abroad need to be paid with border taxes or by other means.

To enable efficient deployment of NETPs, a regional portfolio will be optimized depending on the location, and cooperation will be the key to exploit regional advantages. Non-supportive EU policies might hinder the deployment as well as competition for CO_2 storage. Strong system integration of NETs with low fossil carbon future could be enabled by using residual biomass to biogas or synthetic-gas production, with process heat recovery and/or with renewable hydrogen. Large distributed CO_2 transport and storage networks need to be in place. When NETs are deployed on a large scale, there is a high vulnerability and dependency on the access to affordable renewable electricity. Namely, as DACCS will be prioritized over fossil energy CCS (FECCS), huge amount of renewable energy needs to be available. Another opportunity is to use ocean capacity for sequestering CO_2, which would be done in a way that does not conflict with environment and other ocean related activities.

There are needs for behavioral changes, especially in the high-income countries, and advanced technological solutions. One example is sustainable aviation and the future needs for long-distance travelling. Distributive fairness principles are agreed on at the global level, implicating increasing support for low-income countries.

Table 2. PESTEL summary for the advanced technology and global markets storyline. Red colour indicates those perspectives, which were not included in the modelling of the scenarios so far. Some of those perspectives will be looked at in the final NEGEM scenarios through modelling of additional policies and measures (for example investment incentives or constraints, increased taxes, new market mechanisms) and through changes in modelling parameters and input data assumptions (for example macro drivers for demand sectors, demographic assumptions, technology learning or market shares of new technologies). In brackets, we have shown how the different perspectives have been or might be implemented in modelling.

PESTEL	Advanced technology and global markets
Political & legal	• N_2O, CH_4 and other GHGs are valued emissions also for removal from the atmosphere. (in TIMES modelling, all the Kyoto GHGs are included in emissions trading. Removal of other than CO_2 emissions is not yet modelled in TIMES). • Fossil fuel industry with NETs/CCS/CCU/ renewables (in modelling integration of NETs, CCS, CCU is optimized for forest, cement, steel, chemical, and other industries)
Economic	• NET scale-up by 2050 (NET investments are optimized) • Incentives to investing in more expensive mitigation solutions (investment or other supports, like early innovation funds or lowered hurdle rates, may be modelled, if needed).
Socio-cultural	• Distributive fairness principles to agree on at the global level and support for low-income countries (can be modelled with investment supports, by lowering the hurdle rates, etc.)
Technological	• Balancing fossil CO_2 emissions with geological storage, balancing non-CO_2 GHGs with removals and use or/storage (removals and storage of non-CO_2 emissions have not been modelled so far. Exception is methane capture from landfills, water treatment plants, or animal manure and its usage for energy production). • Large distributed CO_2 transport and storage networks needed (the demand of CO_2 transport is optimized) • Strong system integration of NETs with low fossil carbon future (optimized with 1.5 mitigation target and assumptions on low cost renewables). • Undersupply of CDR in relation to market demand --> net zero targets not met (if needed, we can run a sensitivity analysis with constraints for CDR investments)
Environmental	• Ocean capacity for sequestering CO_2Ocean liming & fertilization (ocean liming have included in the modelling but not the other ocean NETs due to lacking data). • Carbon farming schemes in place (can be considered in the forthcoming modelling) • Competition for land will become an issue, particularly considering the need to feed a growing population (constraints for bioenergy potentials have been included based on literature).

1.3 From storylines to scenarios

For the quantitative scenario modelling, we need to formulate numeric values for the above storylines. However, this is a challenging task and many of the above storyline features are not applicable in TIMES-VTT modelling. In this report, we have started from those storylines, e.g. advanced technology and global markets and Nature conservation and biodiversity, which are most easily converted to TIMES-VTT scenario formulations based on NEGEM results and our earlier scenario modelling work reported in D3.9. On the other hand, we also need work more to harmonize and deepen our understanding on major results and conclusions, which have been assessed in the other NEGEM WPs. The NEGEM framework shows the idea on information flows and the schematics for storyline and scenario formulations.

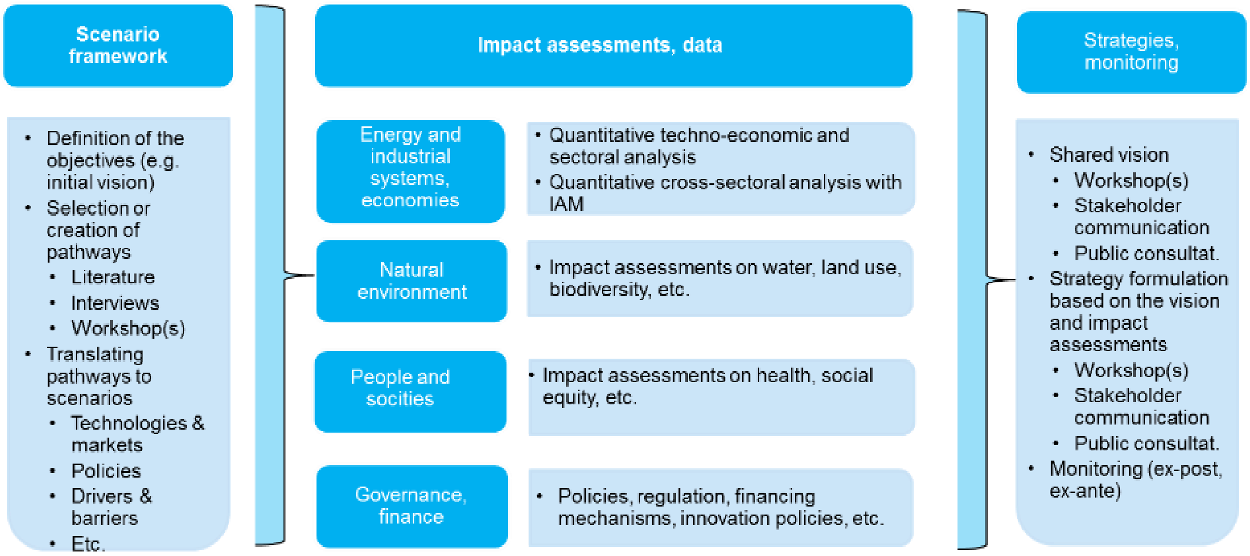

Figure 3. Schematics of the NEGEM framework.

2 Modelling of the alternative scenarios with TIMES-VTT IAM

2.1 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 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).

The model is driven by a set of demands for 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, households, GDP, and sectors 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.

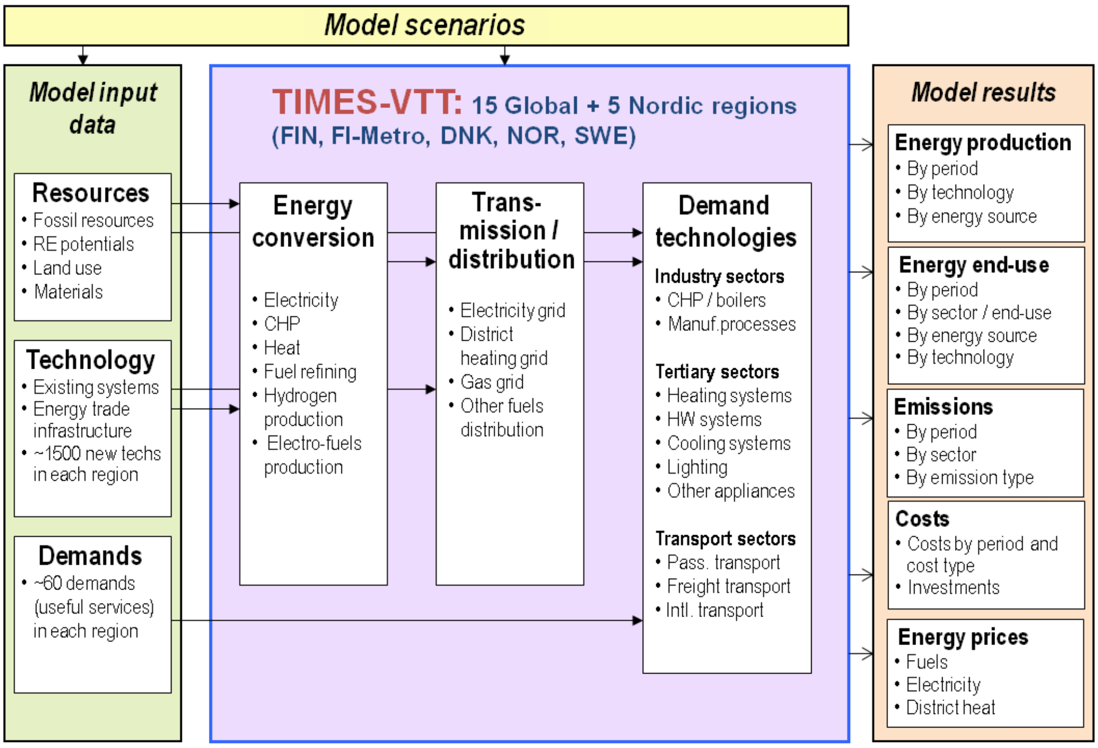

Figure 4. Components of the TIMES-VTT energy system model and simplified flowchart for one region.

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 incorporates also 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 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 Government's decisions in updating the Finland's Climate Law (Koljonen et al. 2021b) and to update Finland's bioeconomy strategy (Koljonen et al. 2021c). Detailed description of the TIMES methodology can be found in the documentation (Loulou et al. 2016).

For the current work, 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 Nationally Determined Contributions (NDCs) until 2030 and immediate action towards limiting warming to 1.5–2°C.

In the NEGEM project, the first attempts on modelling of global climate and energy scenarios were assessed in subtask 3.2.3 of WP3, where the aim was to look at non-renewable resource chains and the potential constraints in their supply in GHG mitigation. In the report D3.9, we summarized that in the future, both the economic growth and more stringent environmental constraints are important drivers for increasing the use of various metals and minerals for the decarbonisation technologies, particularly in the transport and power sectors. The increasing use of critical metals is closely associated with the electrification of the energy systems and transition away from combustible fossil fuels. Conversely, however, many negative emission technologies and practices are among those important climate change mitigation options that have more moderate metal requirements and may thus be needed not only for achieving deep reductions in net GHG emissions (IPCC 2022) but also for better coping with the constraints on sustainable use of mineral resources. When the material requirements of different technologies are included in the model, it can be used also for the analysis of the sufficiency of critical metals and minerals and the efficiency of material resource use. In the final NEGEM scenarios, we will also update the assessments of selected mineral and metals demands to draw more comprehensive and systematic picture on the realistic potentials on the NETPs.

2.2 Description of the alternative scenarios

2.2.1 Overview of the preliminary scenarios

The policies considered in the scenarios are mainly implicit through the economic, energy and technology diffusion data, with the exception of the assumed explicit Nationally Determined Contributions (NDCs), which are modelled separately for Europe, USA, China, India, Africa and USA, 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.

As a benchmark case, we consider a reference scenario, where the climate policies imposed consist only of the updated Nationally Determined Contributions (NDCs) under the Paris Agreement, which were published at the COP26 in October 2021 (United Nations 2021). 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 some updates in the NDCs, which are not yet 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. The challenges for modelling of afforestation, reforestation and other biomass related NETPs have been discussed with the LANDMARC project as global modelling of NDCs are also included in their quantitative assessments. However, due to different modelling approaches, such data that is relevant for TIMES-VTT modelling might not be available, but we will continue discussions with LANDMARC.

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 either 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. This NDC reference scenario is compared with two mitigation scenarios with immediate actions, i.e., with a 1.5 °C mitigation target by 2100 with an allowed interim overshoot.

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:** 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

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

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 regional GHG emissions reduction trajectories are as in the NDC scenario.
- **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.

In summary, for the preliminary analysis we thus examine three scenarios, one with NDC-determined emission trajectories and two global climate policy scenarios based on the NEGEM storylines and 1.5°C target for the maximum global temperature change. For the preliminary scenarios, the third NEGEM storyline "*Security and self-sufficiency*" was not included yet in this report as it would require more discussions on constraints, as well as boundary and market conditions, and so the modelling of the "Security" scenario will be included in D8.2.

In the NDC scenario, the total global GHG emissions 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 two 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 two 1.5°C scenarios may also be categorized as reaching their temperature targets with the same level of probability.

2.2.2 Main assumptions related to NETPs in the scenarios

In all three scenarios, a considerable number of different NETs are modelled for reducing the net GHG emissions. These technologies and practices include afforestation and reforestation schemes, various BECCS technologies in the energy conversion sector (several power plant technologies, CHP, many fuel refining technologies, hydrogen production), PyCCS process for soil amendment with biochar, a few DACCS technology variants, and also ocean alkalinisation.

In accordance with the scenarios and their background storylines presented in section 1.2, the main differences in the modelling assumptions concerning NETPs are summarized in Table 3.

As reported earlier in D8.1, BECCS has been projected to have a significant role in achieving the climate change mitigation targets. The critical constraint for BECCS is the biomass feedstock production potential, which should comply with sustainability criteria. For the preliminary scenarios, our assumptions for the global bioenergy crop potential are between 18 and 45 EJ in 2050, and somewhat higher by 2080 (along with stagnating population and increasing productivity). For Europe, the assumed potentials are 2.0–2.4 EJ in 2050, which are 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. The lower global potential estimate is based on the NEGEM D3.2 study (Braun et al 2022), assessed not to lead to further transgression of the planetary boundaries related to land-system change, biosphere integrity, freshwater use and nitrogen (N) cycling, even though one should point out that the bioenergy feedstock potentials in D3.2 were mainly based on plantations outside the current agricultural lands, thus implying some land use expansion. However, even the larger potential fits within several recent estimates of sustainable global biomass potentials (e.g. Kalt et al 2020, Keramidas et al 2021, Wu et al 2019) but as seen in the NEGEM project, there are very large uncertainties relates to the sustainable potentials of biomass. 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).

The PyCCS potentials assumed in the scenarios are based on the NEGEM studies (Werner 2022a, 2022b). For the 1.5C-Env scenario, we used estimates from the high end of the potential range, while for NDC and 1.5C-Tec scenarios, slightly more conservative estimates were used, due to the larger feedstock potentials assumed for energy crops. As a side-benefit, using the biochar from PyCCS 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). The resulting biochar-mediated yield increases on cropland (15%–30%, Werner 2022a) can well be assumed to compensate the land requirements for producing the PyCCS biomass feedstock, and would thus make PyCCS as a land-use neutral NET option.

Table 3. Summary of the modelling assumptions concerning NETPs in the preliminary NEGEM scenarios (G = Global, E = Europe excluding FSU−Baltics).

NETP assumption	NDC	1.5C-Tec	1.5C-Env	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: 18 EJ/a G-2080: 23 EJ/a E-2050: 2.0 EJ/a	Ruiz et al (2019) Vera et al (2021) Braun et al (2022) Keramidas 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	G-2050: 5 Gt(CO_2)/a G-2080: 30 Gt(CO_2)/a	G-2050: 5 Gt(CO_2)/a G-2080: 30 Gt(CO_2)/a	G-2050: 5 Gt(CO_2)/a G-2080: 30 Gt(CO_2)/a	Fuss et al (2018) Realmonte et al (2019)
PyCCS potential	G-2050: 1.7 Gt(CO_2)/a G-2100: 2.0 Gt(CO_2)/a	G-2050: 1.7 Gt(CO_2)/a G-2100: 2.0 Gt(CO_2)/a	G-2050: 1.8 Gt(CO_2)/a G-2100: 2.4 Gt(CO_2)/a	Schmid et al (2019) Werner et al (2021a) Werner et al (2021b)
Afforestation potential	G-2050: 3.0 Gt(CO_2)/a G-2100: 5.0 Gt(CO_2)/a	G-2050: 3.0 Gt(CO_2)/a G-2100: 5.0 Gt(CO_2)/a	Not allowed	Doelman et al (2020) Keramidas et al (2021) Braun et al (2022)
Reforestation potential	Not considered (included elsewhere)	Not considered (included elsewhere)	G-2050: 2.9 Gt(CO_2)/a G-2100: 160 Gt(CO_2) (cumul. by 2100)	Braun et al (2022)
Ocean alkalinisation	G-2050: 2.2 Gt(CO_2)/a G-2080: 3.0 Gt(CO_2)/a	G-2050: 2.2 Gt(CO_2)/a G-2080: 3.0 Gt(CO_2)/a	Not allowed	Fuss et al (2018) Van Kooten (2022)
Enhanced weathering	Not considered yet	Not considered yet	Not considered yet	Fuss et al (2018)
Geological CO_2 storage potential	G: 3000 Gt(CO_2) E: 120 Gt(CO_2)	G: 3000 Gt(CO_2) E: 120 Gt(CO_2)	G: 3000 Gt(CO_2) E: 120 Gt(CO_2)	Fuss et al (2018) Selosse & Ricci (2017) Sunny et al (2022)

Afforestation is considered only in the NDC and 1.5C-Tec scenarios, because according to Braun et al. (2022), afforestation may be associated with non-native tree monocultures that have adverse effects on planetary boundaries, and it was therefore excluded in the 1.5C-Env scenario. 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). Additionally, one should note that the potentials for afforestation, reforestation and bioenergy crops may all be based on using similar types of land, and therefore the potentials should be verified not to include double counting, or the competing land use potentials should be endogenously modelled. For these preliminary scenarios, we have not been able to endogenize the competing land-uses for those different potentials, and further evaluation may thus be needed in order to ensure the potentials do not have any significant overlaps, apart from the environmentally 1.5C-Env scenario, which is more conservative in this respect. 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 reforestation potential in the 1.5C-Env scenario is based on the NEGEM studies (Braun et al 2022), and it assumes mainly reforestation of pasture areas, corresponding to ~7–16% of global pastures. According to the analysis, this could be done without compromising food security nor further transgressing planetary boundaries.

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), and with respect to most recent studies on DACCS cost projections.

We also included an ocean alkalinisation option, based on ocean liming. 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), but for the uncertainties on environmental impacts, utilizing that potential is not allowed in the 1.5C-Env scenario. 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, DACCS and ocean alkanization options, 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 moderate, about 3000 Gt(CO_2) globally, estimated for each model region. The potentials in Europe are based on the NEGEM project data (Sunny et al. 2022) and the distribution of the global potential is otherwise currently based on the TIAM datasets (Loulou & Labriet 2008, Selosse & Ricci 2019). Some 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 then based on those estimated for shipping.

2.3 Preliminary NEGEM scenario results

2.3.1 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 cause increasing efficiency 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 applying CCS, PyCCS or DACCS for climate change mitigation. All these various effects are reflected in our modelling results.

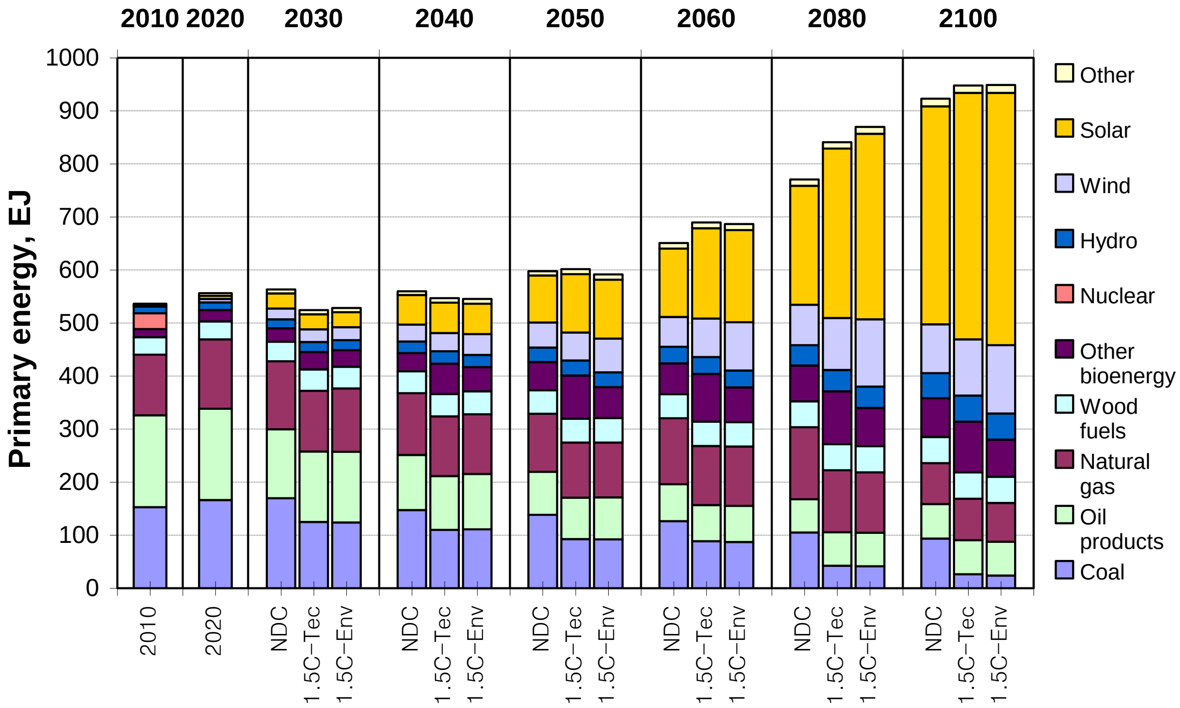

Figure 5. Development of global total primary energy supply (TPES) in the scenario variants, including non-energy uses.

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 900 EJ in 2100 in the NDC case. Some additional growth in the 1.5°C cases 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. These issues should be addressed in some more detail for the final NEGEM scenarios.

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 also wind power continues to expand significantly.

With respect to NETs, major uncertainties are related to sustainable bioenergy supply potential in the longer term. 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. 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 literature sources. In 2020, the global primary production of primary biomass for energy (excluding the biomass fraction of municipal waste) was about 55 EJ, of which about

33 EJ wood fuels, about 15 EJ agricultural residues and roughly about 7 EJ energy crops (which, unfortunately, is not clearly reported in terms of biomass but mostly in terms of liquid fuels in the primary energy statistics). In the mitigation scenarios, the global primary biomass use for energy increases to about 120 EJ in the 1.5C-Tec scenario, but to only about 90 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 40 EJ in 2020 to around 100 EJ in 2050, and states that "*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, fresh water systems, and food prices and availability*." In that respect, the bioenergy use in our preliminary NEGEM scenarios can also be considered to comply sufficiently with sustainability criteria. However, sustainable bioenergy potentials will be discussed and analysed further in the next steps of NEGEM with partnering organisations and with the "sister projects" LANDMARC and OceanNETs.

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 PyCCS 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-Tec scenario, where the reliance on bioenergy becomes higher, does include risks of failing to achieve the negative emissions by the relatively large-scale utilization of bioenergy, that may affect BECCS in particular, although to a much less extent PyCCS.

2.3.2 Global electricity supply

The electrification of the global energy systems, as well as the expanding hydrogen economy, electrofuels and decarbonisation systems, all increase electricity consumption, which may approach 200 PWh by 2100 according to the scenario results (*Figure 6*). 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 pass 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 about 70% of the global electricity generation would be solar based.

As expected, fossil fuel-based generation will be phased out almost completely by 2100, with natural gas fired power remaining on a somewhat notable level until 2080. 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. Nuclear power might have a much larger potential than projected here, if the new small modular reactor technologies can improve its economy and will be legally feasible in different countries.

Until 2050, the global electricity supply is actually very well in line with that in the IEA NetZero by 2050 scenario (IEA 2021a). The total supply is 69 PWh in the 1.5C-Tec scenario and 71 PWh in the 1.5C-Env scenario, while the figure in the IEA NZE scenario was 71 PWh in 2050. Beyond 2050, the growth in the supply may appear large, but one should point out that it is of course nevertheless all reflected in the primary energy consumption shown in *Figure 5*. The additional electricity consumption of DACCS plants becomes very significant beyond 2050 in both of the 1.5C cases. At their peak around 2070, they consume about 19% of global electricity in the 1.5C-Env case, and 11.4% in the 1.5C-Tec case. In the NDC scenario, the global electricity supply is about 60 PWh, well in line with the JRC GECO projection, 63 PWh gross (Keramidas et al. 2021).

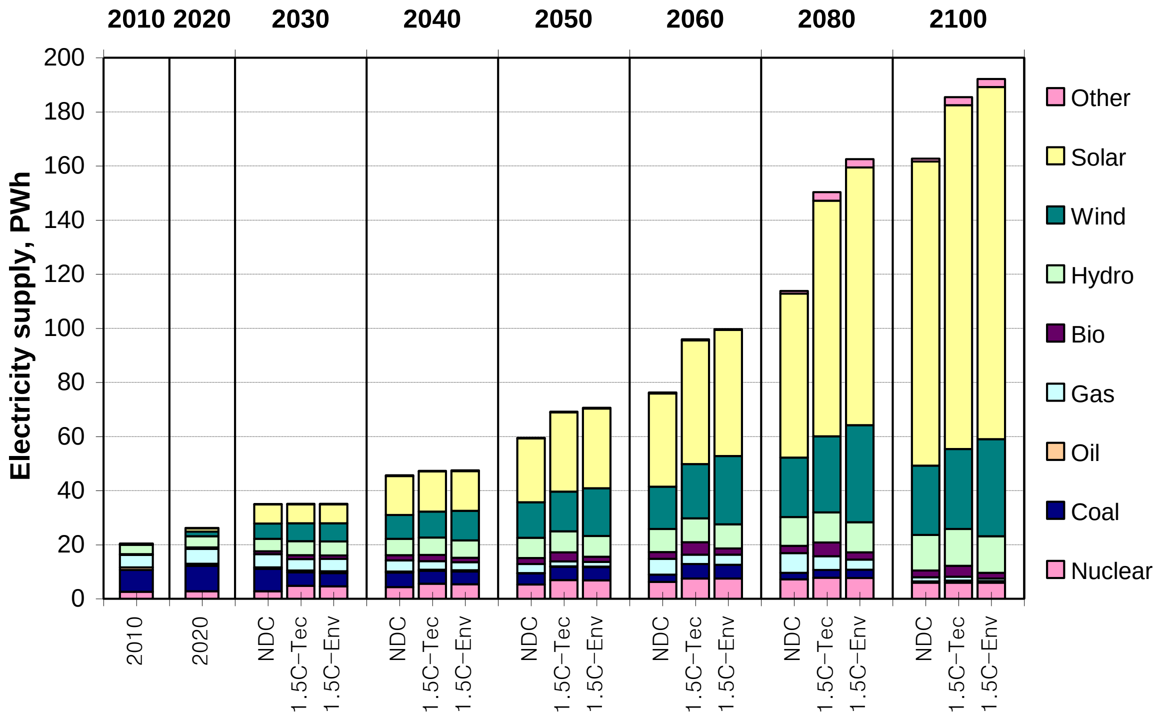

Figure 6. Development of global total net electricity supply in the scenario variants, excluding power plants own consumption.

2.3.3 Global greenhouse gas emissions and the role of NETs

With respect to GHG emissions, the scenario results suggest that a quick transition away from fossil fuels may happen relatively slowly unless strict policies are implemented for accelerating that transition. Because such policies were not assumed in the analysis, but the overall targets were imposed on the total emissions or temperature limits, the results are thus 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 is reflected by the considerable role of CCS in the results (*Figure 7*).

In the NDC scenario, the total net emissions develop exactly according to the regional and global emission caps that were exogenously defined. 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 in both cases the temperature target of 1.5 °C in 2100 after intermediate overshooting. The role of negative emissions and CCS in both cases is already considerable, around 20 Gt/a during the last decades of the century. However, it is noteworthy that the projected costs of the DACCS options are so high that they would not become competitive before 2050 under either 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 PyCCS, DACCS does not have any co-benefits, like energy or fuel production, which reduces the cost-efficiency of DACCS.

The 1.5C-Env case depicts the most challenging policy case, where the total net emissions have to be reduced equally rapidly as in the 1.5C-Tec scenario to keep the temperature rise below 1.5 °C in 2100, but with more limited sustainable potential available for negative emission options. Nonetheless, even in this case, the high damage cost imposed on overshooting reduces the peak overshooting to about 0.2 °C in 2070. In total, the role of negative emission practices (including any NETs involved) grows in both cases to the highest level during 2070–2080 slightly over 20 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.

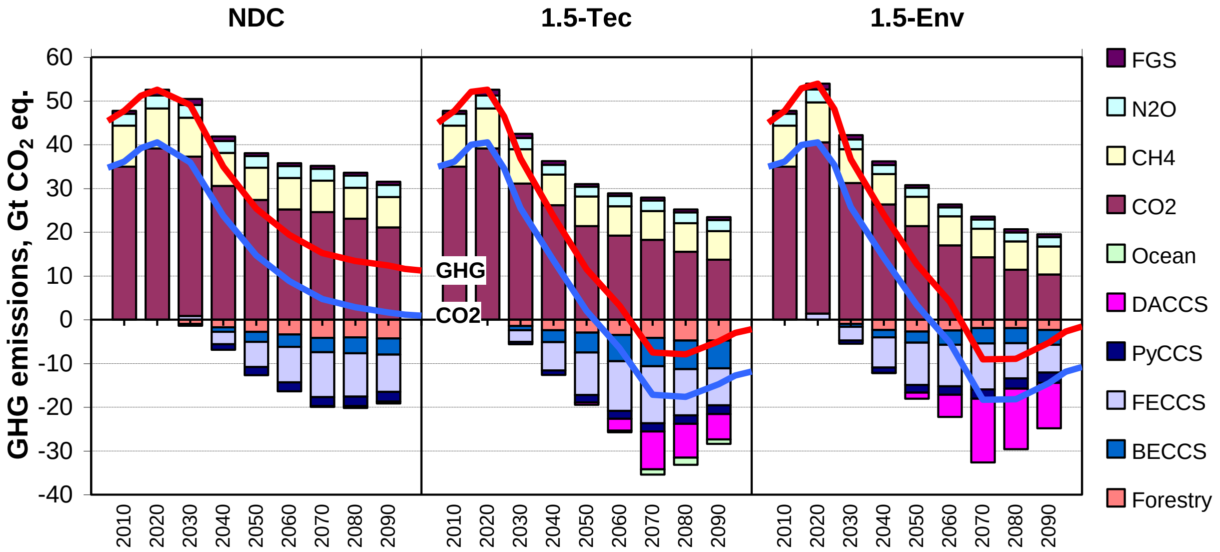

Figure 7. Development of greenhouse gas emissions (Kyoto gases) in the scenario variants. The red and blue lines represent the total net emissions of GHGs and CO_2, respectively, and the vertical bars show the gross emissions (positive) and removals (negative) either from flue gases or the atmosphere (BECCS = bioenergy with CCS, FECCS= fossil energy with CCS, forestry = afforestation and reforestation, ocean = ocean liming).

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. The marginal costs are in the 1.5°C cases about 150 €/t in 2050 and increase to about 240 €/t in 2080. The cost effect is pronounced by 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.

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 electricity, energy-intensive process industry, and energy transformation sector. In the short term, power plants would dominate the volume of CCS 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 natural gas based hydrogen production. Such remaining niches of fossil fuel based energy transformation represent areas where additional policies could be introduced to accelerate the transition to renewable energy, for example electrolysers in hydrogen production, to reduce the need for CO_2 capture and storage.

Among the NETPs, all of the options modelled also appeared in the scenario results, but one may argue that according to the results DACCS appears to emerge as the most significant option. While the nature-based solutions (reforestation and PyCCS) can be both quite competitive and quite 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. Moreover, among the other options, DACCS seems to be the one having the least critical constraints on sustainability, including planetary boundaries. However, BECCS may certainly be also quite important, to the extent sustainable biomass feedstock are available. In total, all the NETs considered account for about 10 Gt(CO_2) during 2080–2100 in the NDC scenario, but even up to 22 Gt/a in the 1.5C scenarios (*Figure 8*). The amounts shown are the direct impact of the NETs, while their net impact is somewhat smaller for BECCS, DACCS and Ocean alkalinisation, the offsets being accounted in *Figure 7*.

Among the NETs, the biomass-based technology options BECCS and PyCCS both become competitive in all three cases. Obviously, PyCCS 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, PyCCS is deployed roughly at the maximum scales assumed realistic in both cases after 2050, which were 2–2.4 Gt(CO_2)/a. As a side-benefit, according to the modelling assumptions, PyCCS also brings about significant reduction in the N_2O emissions from agricultural lands (at maximum, about 0.6 Gt(CO_2 eq.)/a in the 1.5C-Env case).

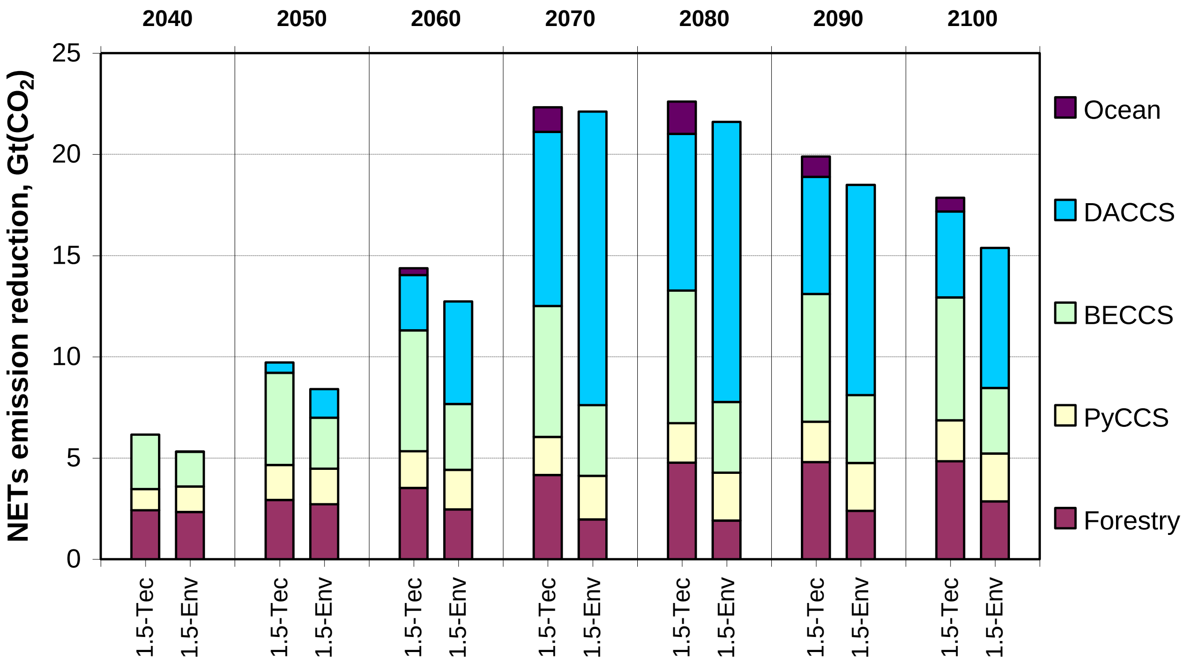

Figure 8. Contribution of NETs to the emission reductions in the experimental climate policy scenarios. Note that the amounts shown are the direct impact of the NETs, while their net impact is somewhat smaller for BECCS, DACCS and Ocean.

Concerning BECCS applications, by 2050 the total negative emissions amount to at most 4.6 Gt/a in the 1.5C-Tec scenario and 2.5 Gt/a in the 1.5C-Env scenario. According to the more detailed technology results, power plants (including CHP) would mostly account for about 35–50% of the captured amount globally, while other energy conversion technologies cover the rest. An exception to this range is the 1.5-Tec scenario after 2050, where the share of power plant applications increases to 60–70%. In both of the 1.5°C cases, the power plant share of BECCS applications is at its lowest before 2050, and then increases over time.

As mentioned above, due to its relatively high costs, DACCS appears only in the 1.5°C cases, where it reaches deployment levels of 2.7–14.5 Gt/a during 2060–2100. In the preliminary scenarios, 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 options, while the socio-economic pathway and consumer behaviour is otherwise assumed similar. This issue will be addressed further in the subsequent work where the socio-economic pathways and demand drivers behind each of the storyline will be refined. 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 at most 1.5°C by 2100. Nonetheless, the maximum DACCs capture rate (14.5 Gt/a) remains much lower than in some other studies with the 1.5°C target (e.g. Realmonte et al. 2019).

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 option, the development of the total energy crops and biochar crops production in the results of the preliminary NEGEM scenarios is illustrated below in *Figure 9*. According to available international energy statistics, the 2020 level of global bioenergy crop production can be estimated to have been about 7 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 18 and 45 EJ. The results indicate that the assumed potentials would become almost fully utilized in the scenario results, reaching 44 EJ in the 1.5C-Tec case and 18 EJ in the 1.5C-Env case by 2050, and further up to 59 EJ in the 1.5C-Tec case and 21 EJ in the 1.5C-Env case by 2080. For comparison, the biomass crop feedstock amount required for the PyCCS deployment are also shown in the Figure, and can even be seen to exceed the bioenergy crop production in the 1.5C-Env case. However, as discussed above, in accordance with the analysis by Werner et al. (2022a, 2022b), we assumed the PyCCS concept to be a land-use neutral NET option when deployed within the global potential constraints assumed in the scenarios.

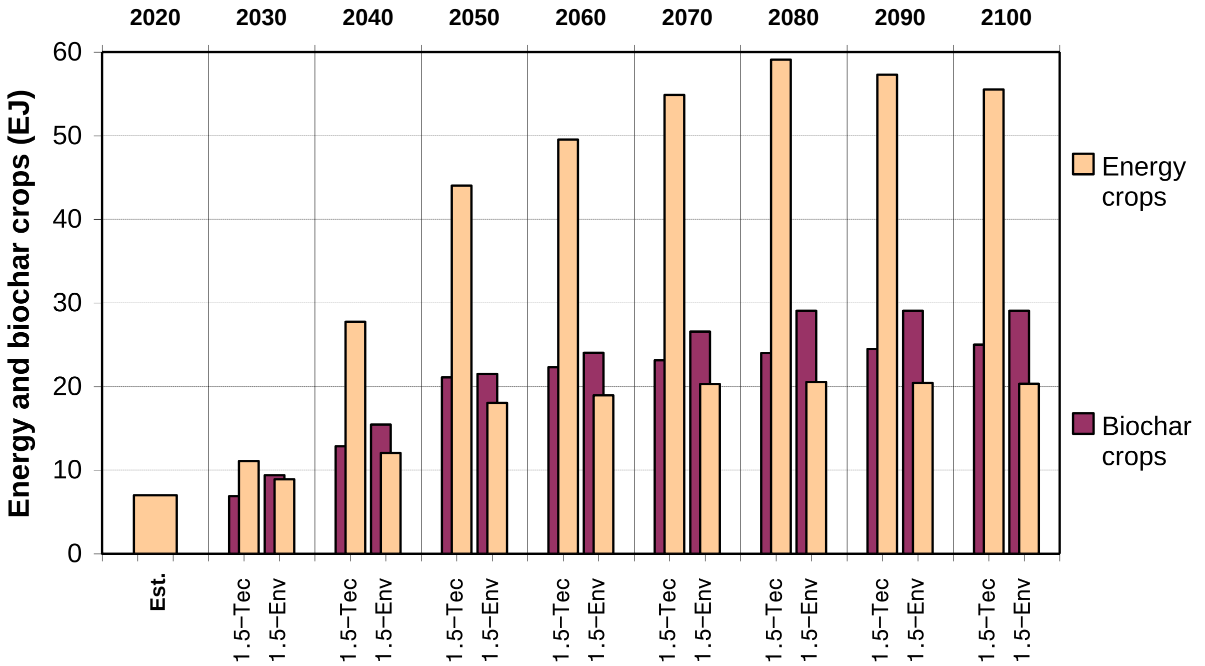

Figure 9. Global production of energy crops and biochar feedstock for soil improvement, all in energy equivalents.

3 Key findings and policy relevant messages

Based on the preliminary 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. 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 was assumed in 1.5C-Tech and 1.5C-Env scenarios. The investments in NETPs are at the highest levels after 2060 indicating that earlier investments in NETPs would require some additional policies and/or measures. Accelerated actions would be needed in case global GHG emissions would not show rather immediate downturn trend as expected in the scenario runs. Based on the most recent global GHG emission statistics (UN Environment Programme, 2022) GHG emissions are increasing after the COVID-19 lockdowns had been removed and it is expected that emission record will be hit once again 2021.

On the other hand, 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 in the short term, power production with CCS would be employed. By 2050, the captured amounts associated to 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, anyway, that fossil fuel prices are endogenously determined in TIMES-VTT modelling and therefore modelled fuel prices are not comparable with the real market prices we have been facing after the Russian attack to Ukraine.

Among the NETPs, all of the options modelled also appeared in the scenario results, indicating that no NETP option should be excluded in the GHG mitigation portfolio. In total, all the NETPs considered account for about 10 Gt(CO_2) during 2080–2100 in the NDC scenario, but even up to 22 Gt/a in the 1.5C scenarios. In 2050, NETPs account for less than 10 Gt/a in the 1.5C scenarios demonstrating the rapid increase in NETP demands beyond the year 2050. Based on our earlier analysis reported in D8.1, we can see that BECCS has been the most significant option in mitigating scenarios reported by the IPCC, IEA and many other authors. Also in our scenario assessments, the biomass-based technology options BECCS and PyCCS both become competitive in all three scenario cases. However, the contribution of BECCS is much lower compared with the scenarios reported by the IPCC AR6 WG3, as an example.

Considering the global and regional constraints in sustainable biomass supply, we can argue according to our scenario results that DACCS appears to emerge as the most significant option especially in the long-term. While the nature-based solutions can be quite competitive and quite sustainable, under the assumed storylines the combined potential of PyCCS and reforestation still seems far from sufficient for keeping the temperature change within planetary boundaries. Over all the NETP options, PyCCS seems to have several co-benefits and comparative advantages because of the yield increases achieved by using the biochar for soil improvement. Based on analysis reported in D3.2, PyCCS also brings about significant reduction in the N_2O emissions from agricultural lands, which was also included in our modelling. However, there are large uncertainties related sustainable potentials of PyCCS and modelling assumptions include high uncertainties, as good numerical estimates appear to be scarce in the literature for PyCCS. Therefore, more research on PyCCS and its potential in GHG mitigation would be required. The same conclusion can be drawn with the ocean NETs, which has large uncertainties on both their sustainable potentials in GHG mitigation and modelling parameters, like costs as well as energy and material balances. In our preliminary scenarios, ocean alkalisation was included in 1.5C-Tech scenario, which indicated that its potential might be rather small in in the long-term.

The key messages based on the preliminary scenario assessments can be summarized as follows:

- NETPs would be needed to reach the 1.5-2.0°C mitigation goals and no NETP option should be excluded from mitigation portfolios at this stage. Considering the environmental constraints, DACCS seems be the most significant NETP option especially in the long-term.
- In the scenario assessments, the GHG mitigation targets were achieved by cost-optimization the mitigation pathway. The results show that we would need more strict policies and measures to phase out fossil fuels in all the GHG mitigating sectors. In addition, supporting policies are needed to ensure large-scale NETP investments by 2050.
- PyCCS and reforestation in our scenarios are competitive and quite sustainable options in GHG mitigation, but under the assumed storylines their combined potential still seems far from sufficient for keeping the temperature change within 1.5-2.0 °C mitigation targets. However, especially PyCCS seems to be a potential mitigation option due to its several co-benefits but more research is needed to better analyse its global and regional potentials.

4 Conclusions and further steps

In this deliverable D8.6 of the WP8, the preliminary NEGEM scenarios and their formulations are reported. In parallel to this report, D8.7 has been prepared on the updated NEGEM vision. The aim of the initial NEGEM vision was to steer the initial NEGEM project work and the updated vision is prepared based on NEGEM results and deliverables published by November 2022, including this report for scenario formulation and modelling. Therefore, both the updated vision and scenario reports (e.g. D8.6 and D8.7) include partly overlapping information on the storyline formulation (e.g. Chapter 1 in this report) but this was justified from the perspectives of both reports as an individual deliverable.

The NEGEM scenario selection and formulation have been discussed with the NEGEM partners, EAB and workshops through the project lifetime. The preliminary scenarios reported in this report are based on collaborative effort in building alternative storylines to reach the goals of PA with different operating environments for NETPs. The workshop for storyline formulation was carried out in parallel with the General Assembly at VTT in Espoo, Finland in October 2022. For a structured brainstorming process, we selected Futures Wheel foresight method to uncover multiple levels of consequences resulting from all types of change (Bengston, 2015). Based on the results from earlier NEGEM discussions and results of the WPs, three alternative storylines were chosen: one that focuses on nature conservation and biodiversity, another one with a focus on advanced technology and global markets and third one with a focus on security and self-sufficiency.

For the preliminary NEGEM scenarios, two storylines with 1.5 °C mitigation target were quantified modelled with the TIMES-VTT Integrated Assessment Model (IAM). The selected scenarios represent nature conservation and biodiversity (1.5C-Env) and advanced technology and markets (1.5C-Tech). As a reference scenario, we used a pathway, which includes Nationally Determined Contributions (NDCs), which represents 2 °C global warming during this century.

The NEGEM storyline formulation and the modelling of the alternative NEGEM scenarios with an IAM proved to be useful tool to integrate different results from different WPs. Harmonisation across NEGEM WPs and their tasks has been proved a challenging task as different WPs have different methodological approaches with different input assumptions and data. Harmonisation will be required, anyway, to pave the way more clearly to the “realistic potentials”. The greatest variation in the results seem to relate to terrestrial NETPs, especially BECCS and its potentials (see e.g. WP3 and WP7 modelling results). In the 1.5C-Env and 1.5C-Tech scenarios, we especially focused on this uncertainty, which revealed the role of DACCS as an option with lower environmental risks. However, the relatively high costs of DACCS would constrain its large-scale implementation without any supporting technologies. DACCS was also found as the most sustainable option in WP1 sustainability analysis. Based on our scenario analysis we can also conclude that before implementing NETPs at large scale we need more research on their sustainable potentials, including techno-economic, environmental and social impact assessments.

It has already been agreed with the NEGEM partners that harmonisation work for the NEGEM assessments will continue. In WP8, the next steps for scenario modelling include:

- Formulation and modelling of the security and self-sufficiency scenario as well as finalising the other global NEGEM scenarios.
- Formulation and modelling of the EU level scenarios with a Pan-European TIMES-VTT.

- Dissemination of the scenario results with NEGEM partners, sister projects LANDMARC and OceanNETs, European Commission and with other stakeholders.
- Reporting the final NEGEM scenarios (D8.2).

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
D3.2	Global NETP biogeo-chemical potential and impact analysis constrained by interacting planetary boundaries	PIK	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
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

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Appendix: workshop answers

Nature conservation and biodiversity.

PESTEL framework	Nature conservation and biodiversity
Political & legal	Opportunities : • Need for global co-operation to use the available resources efficiently • EU in leader role in deployment + technology • Demonstration programs ideally, inter-regional 1. to boost international cooperation 2. to share inter-regionally responsibility • Every industry / business with considerable material stream for NETPs "forced to" / should commit • Assigning the CO2 emission to where it belongs i.e. consumer goods • Support indigenous / local communities to discourage deforestation • Faster systemic change in policy • Significant policy & investment support for REN & sustainable NETP • Strong global policy and commitment / Solidarity • Carbon uptake obligations policy mech. in EU / Global agreements needed • "Keep it in the ground" + "best CDR is no CDR" --> rapid & stringent emission reductions
Economic	Opportunities : • For "non-permanent" C storage: pay the insurance of longer time horizons (100 years?) • massive investment in bringing down costs of RES • Much higher C taxes • incentives to encourage less meat consumption (cf sugar / tobacco / alcohol taxes) • centralised roadmaps + financial support from the governments? e.g. EDF in France • Monetarization of ecosystem services to finance NBS, SCS, PyCCS (i.e. soil resilience, water holding capacity etc.) • incentives to discourage population growth / encourage reduced fertility / educational empowerment of women + girls • Incentives for circular economy Barriers : • Vested interests want to see near-term use of CDR • Energy intensive industry in trouble
Socio-cultural	Opportunities : • Greater role for civil society organisations • Focus on good examples sharing role models • Education communication --> better understanding of climate stakes--> informed population --> influence policymakers • Change in behavior, reduced consumption, diet change • More aggressive conservation programmes • Rich countries support poor ones in technology • Enable emerging economies to implement CDR technologies • More willing to share knowledge, less protectionism amongst nations • More dense population centres

	• Much lower population growth • Economic growth Kaya rule: CO2=population x GDP/population x energy/GDP x CO2/energy Barriers : • Currently no good example of rapid and stringent decarbonization measures (except crisis) • Empirical evidence on behavioral change is weak (e.g. nudge) • Inertia of effective energy systems, population patterns etc. • Difficult to engage population to change due to effects elsewhere in the future • Not declaring that we need to change our way of living drastically • Population growth
Technological	Opportunities : • Use agricultural land for BECCS--> change diets--> use biochar to improve soil • Include blue forests • Energy efficiency, housing, transport • Fast action--> fast mitigation • Use all measures available to reach the goal • Reforestation and afforestation • All mitigation actions activated in all sectors • Highly efficient management of material streams + efficient use for NETPs (BECCS, PyCCS, etc.) • Even more aggressive RES deployment • Need for more DACCS --> increased need for wind power • Functioning grid & storage capacity • Nature-based solution +SCS+PyCCS prioritized NETPs due to other benefits / ecosystem services • Land resources / efficient CDR e.g. DACCS? But not off energy • Higher need for other renewables than bioenergy • Higher need for other NETPs than BECCS--> DACCS--> Afforestation / Reforestation • PyCCS for soil improvement, no climate engineer, DACCS for temp. solution • Full renewable energy system • Minimal CDR for next 30 years
Environmental	Opportunities : • Synergies e.g. afforestation "land/biomass-intensive"activities --> reduce land footprint • Active collaboration and polling of resources • Stop deforestation • Massive rewilding close to nature forestry as a source of biomass • Very intensive agriculture & bio-based products (including urban agriculture) Barriers : • Land use change for biomass-based NETPs only within current bounds of agr. land + where compatible with i.e. planetary boundaries • No ocean-based CDR • No further land use expansion (especially not for NETPs) • Won't meet 1.5 C...2 C target, Either success >< overshoot

Advanced technology and global markets.

PESTEL framework	Advanced technology and global markets
Political & legal	Opportunities : • N_2O, CH_4 and other GHGs are valued emissions / removing • Explicit frameworks for valuing the co-benefits of NETPs, Frameworks for non-CO_2 removal integrated • Policies ensure that NETPs are accounted similarly and comparable • Nature-based solutions won't have been effectively incentivised through a carbon market / Nature-based solutions in a variety of mechanisms not just carbon market • cooperation will be key to exploit regional advantages • enhanced security of supply (gas, electricity) (then how?, new partners for EU?) • Fossil fuel industry reconversion/partnership with NETPs/CCS/CCU/ renewables • A regional portfolio optimized depending on the location Barriers : • Non supporting EU politics • Competition for storage of CO_2 • Confusing IAM results for projections and direct policy advice • geopolitical factors may a play a role, forcing a switch to coal or oil, and therefore increasing the need for CDR
Economic	Opportunities : • Other market/money flow to new solutions • NET scale-up by 2050--> Business models --> Verification and vast integration with CO_2 markets and CAP and trade system • Decline in voluntary carbon markets in favour of capital being channeled into direct solutions • CAP reform to take in a broader scope of funding • Collapse of CORSIA in 5 years • Government driven market, Commercially driven market • Internalisation of external costs • Incentives to investing in more expensive solutions • inclusion of NETPs in ETS, Fiscal incentives, subsidies • Life cycle emissions cost more / moving emissions abroad has a cost • Incentives for enhancing natural sinks that are not based on carbon • CAP has changed to result based payments • Early innovation funds but large-scale, low-cost finance to fast-track deployment • Economy drives to the lowest cost solutions • if we optimize for costs, cheap NETPs like forestation/SCS will be prioritized • early scale-up of more expensive NETPs needs to start in the 2020s • Qouta market for countering residual fossil CO_2 with CDR • High enough speed for scaling up - What kind of incentives needed? Barriers :

	• Allowing carbon markets to establish that do not meet high multi-dimensional sustainability criteria and then cannot be regulated well later (e.g. current pressure of bioenergy lobbies in the EU against sustainability criteria)
Socio-cultural	Opportunities : • Awareness and acceptance of NETPs needs to increase • Displace meat of exsisting practises (industry etc.) • Distributive fairness principles to agree on at the global level and support for low-income countries • Biodiversity/social food production • Net negative emissions for slower net-zero targets in poorer countries • either changed habits from "rich" world, either more techs (e.g. "sustainable aviation"), or maybe a mix of both • mitigation vs removal • Need to run scenarios that do not assume continued strong growth but reflect sufficiency (i.e. contract and converge) • some countries will be very well positioned to deploy NETPs Barriers : • High vulnerability/ dependency on access to affordable renewable electricity
Technological	Opportunities : • Abundant clean energy • Cost of technologies down, increased energy efficiency • Balancing fossil CO2 emissions with geological storage, Balancing non-CO2 GHGs with removals • New solutions / technologies appear • Large distributed CO2 transport and storage networks • DACCS will take up a larger proportion of the balance than FECCS • Minimal residual emissions & maximal sustainable removals • High penetration of renewables • We should leverage current trends in industry towards more sustainable manufacturing patterns • Technology 'menu' • DAC might be deployed faster if environmental trade-offs become more critical • the chemical sector will need to be retrofitted • the use of biogas might play a role • materials/metals sector development: batteries/adsorbents • Hydrogen enables oxyfuel technology for 2nd generation BECCS • strong system integration of NETPs with low fossil C future (residual biomass to bio/syn-gas, heat recovery, renewable H2) Barriers: • the scale-up of DAC will require a huge amount of renewable energy • Undersupply of CDR in relation to market demand --> miss net zero targets
Environmental	Opportunities : • less meat on the menu (/new diets), and thus also new lands for terrestrial NETP • Ocean capacity for sequestering CO2 • C farming schemes in place • Ocean liming & fertilization w up/downwelling

	• Regarding env - envon -soc as a tradeoff system where the NEGEM path is the overlap - the env is the basis, PBs the envelope for econ and soc, not a trade-off • Barriers : • competition for land will become an issue, particularly considering the need to feed a growing population • Ocean, conflict w other users • Climate change affecting forestry yields • Wrongly considering "Earth system stability" (planetary boundaries) as "Nature protection/biodiv" • Implications of natural NETPs for biodiversity? • Danger of regarding the biosphere as the next frontier to be exploited (here: for NETPs)

Security and self-sufficiency.

PESTEL framework	Security and self-sufficiency
Political & legal	Opportunities : • Clustered regional co-operation • NETPs implemented with reductions in GHG emissions Barriers: • CCS+CCU deployment will increase energy price in regions where climate targets are being achieved --> reduces energy security of citizens? • Markets would not drive • Can 1.5 C be reached? • Low-tech NETPs, CC mitigation not the key target, will 1.5 C be a priority?
Economic	Opportunities: • Act on the S side --> incentives-act on the D side: efficiency, behavioral...
Socio-cultural	Opportunities : • Revolutionary agricultural processes (less energy, water) + different food consumption habits (insects?) --> land allocated to NETPs without compromising food security • Energy independent • Some degree of diet change to allow for BECCS/PyCCS feedstock production?/ reforestation • Energy consumption reduce as population grows • Intensified agriculture in some parts of the world for food self-sufficiency
Technological	Opportunities : • PyCCS based on residues & waste • BECCS, CO2 utilization in food production etc.local supply chains • Exportable technological solutions • Renewable energies available in excess (decrease demand for energy --> energy savings, energy efficiency) --> excess energy can be deployed for NETPs • Renewables to be prioritized • Focus more on ocean-based NETPs (perhaps?)

	• CO2 pipelines connecting countries, countries with geopolitical threats are avoided • Forestation is scaled up as it imposes less geopolitical threats Barriers : • DACCS limited by local renewable energy supply • DACCS may face public opposition --> cost too much energy • CO2 pipelines-will there be trust to build infra • BECCS only in countries with a) CO2 storage capacity b) feedstock availability
Environmental	Barriers : • A/R may face some opposition from farmers if taking too many lands • Risk: biodiversity