NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Link MONET-EU and JEDI

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Executive Summary & Policy Relevant Messages

Since the Paris Agreement, Parties to the United Nations Framework Convention on Climate Change (UNFCCC), agreed to hold global warming to “well below” 2°C and pursue efforts to limit it to 1.5°C. Negative emission technologies and practices (NETPs) will play a crucial role in delivering the Paris Agreement’s 1.5°C objectives, notably in offsetting emissions from hard-to-abate sectors, *e.g.* aviation, agriculture, or industry. However, there are still, uncertainties about their carbon dioxide removal (CDR) potential, cost and up-scaling, as well as concerns about their side-effects and their interactions with the Sustainable Development Goals (SDGs). Particularly, deploying NETPs at large-scale will trigger significant structural changes in our economy, with important socio-economic impacts at national and regional scales.

The MONET-EU framework, developed in the previous NEGEM deliverables D7.1 and D7.2 of WP7, is a spatio-temporal explicit modelling and optimisation framework that provide insights into the techno-economic, and bio-geophysical implications of deploying NETPs, *i.e.* afforestation/reforestation (AR), bioenergy with carbon capture and storage (BECCS), biochar, and direct air carbon capture and storage (DACCS), within the European Union (EU). In line with the work carried out the NEGEM deliverables D1.1–5 of WP1 (*i.e.,* providing a techno-economic, environmental and socio-political assessment of existing and emerging NETPs), this work aims to extend the MONET-EU framework and database with enhanced weathering (EW), together with the inclusion of forestry residues as an alternative biomass feedstock to energy-dedicated crops for the deployment of BECCS and biochar. For EW, two types of rocks have been considered, *i.e.* basalt and dunite rocks, with different rock availabilities and extraction potentials, as well as different CO_2 removal potentials. This work also aims to evaluate to socio-economic impacts of deploying this extended suite of NETPs in the EU economies. This is done by combining the MONET-EU framework with the JEDI tool, to quantify key macro-economic impacts associated with the deployment of NETPs, *i.e.* gross value added (GVA) and jobs creation.

The first set of results shows that the socio-economic impacts associated with deploying NETPs at the national scale differ greatly from a NETP to another. For instance, land-based NETPs are expected to increase GVA in the agricultural and forestry sectors, whereas engineered NETPs are more likely to increase GVA in economic sectors such as machinery & equipment, maintenance, construction, utilities, or even R&D. The socio-economic implications of each NETPs deployment can also differ significantly among EU Member States. Depending on the sectorial structure of each EU Member State economy, the deployment of each NETP in the different EU Member States can boost employment in different economic sectors. Differerent NETP configurations, *e.g.* local versus inter-regional biomass supply chain for BECCS, can also modify significantly the regional distribution of jobs creation. For example, the use of imported biomass appears to increase employment in the transport sector and involves multiple national economies.

The second set of results shows that the EU has the potential to deploy a varied portfolio of land-based, mineral-based, and geological NETPs by the end of the century, thereby achieving CO_2 removal levels consistent with the most 1.5°C objectives. By using cumulative CDR targets between now and 2100 as a proxy for the EU remaining carbon budget, we show that ~80 Gt CO_2 can be removed by 2100 with BECCS (62%), AR (24%), biochar (7%), and EW (6%). Whilst available, DACCS is not deployed, due to its costliness.

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1. Introduction

With the Paris Agreement, Parties to the United Nations Framework Convention on Climate Change (UNFCCC), including the European Union (EU), agreed to hold global warming to "well below" 2°C and to pursue efforts to limit it to 1.5°C by reaching global peaking of greenhouse gases (GHG) emissions as soon as possible, undertaking rapid global reductions thereafter, and achieving a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century (UNFCCC, 2015).

Importantly, the role of negative emission technologies and practices (NETPs) has become widely acknowledged in delivering the Paris Agreement's 1.5°C objectives, owing to their potential to offset emissions from hard-to-abate sectors, *e.g.* aviation, agriculture, or industry, and therefore contribute to achieving a net-zero economy by 2050 (Intergovernmental Panel on Climate Change, 2018, 2022). However, NETPs are currently scarcely deployed, and their carbon dioxide removal (CDR) potential, cost, up-scaling, and side effects, are highly debated (Smith *et al.*, 2016; Nemet *et al.*, 2018; Honegger, Michaelowa and Roy, 2021).

Particularly, transitioning towards a net-zero economy will result in significant structural changes in many sectors, *e.g.* energy, industry, or trade, that will be notably evidenced at the national and regional scale. Because these economic activities are not evenly distributed across regions, due to different levels of industrial strengths, it is important to analyse the socio-economic impacts of deploying NETPs at the national and regional scale.

To address these important gaps identified, the aims of Task 7.3 of the NEGEM project are to:

1) Extend the MONET-EU framework to a more comprehensive suite of NETPs, *i.e.* afforestation/reforestation (AR), bioenergy with carbon capture and storage (BECCS, biochar, direct air carbon capture and storage (DACCS), and enhanced weathering (EW), in line with the Tasks 1.1–5 carried out in WP1.
2) Evaluate the socio-economic implications associated with the deployment of this suite of NETPs within the EU.

To this end, this work builds on the MONET-EU framework, developed on Task 7.1 and 7.2, to include EW (both basalt and dunite rocks) to the suite of NETPs available in the MONET-EU framework, and forestry residues as an alternative biomass feedstock for BECCS and biochar. To quantify the socio-economic impacts of deploying NETPs within the EU, this work also implements a hard link between the MONET-EU framework and the Jobs and Economic Development Index (JEDI) tool, developed by the US National Renewable Energy Laboratory (NREL) (Jacobson *et al.*, 2017; Patrizio *et al.*, 2018; Patrizio, Pratama and Mac Dowell, 2020).,

Section 2 presents the main modelling assumptions adopted to parametrize EW and forestry residues for BECCS and biochar within the MONET-EU framework. We will first provide a qualitative discussion on the main features of EW, followed by its techno-economic analysis. For consistency, similarly to NEGEM deliverable 7.2, EW will be evaluated in terms of whole system costs and CO_2 removal efficiency, accounting respectively for the costs and potential carbon leakages associated with each step of EW's (rock) supply chains. The optimisation constraints adopted to parametrize both EW pathways and BECCS and biochar pathways using forestry residues will also be presented. Section 3 presents the main modelling assumptions of the JEDI tool and the extended optimisation assumptions of the MONET-EU framework. Finally, to validate the new model configuration, Section 4 performs a techno-economic analysis of the suite of NETPs archetypes selected in this deliverable to showcase potential applications of the MONET-EU framework. In this analysis, we will identify a cost-optimal suite of NETPs, deployed within the EU to meet cumulative CDR targets between now and 2100, used as a proxy for the EU remaining carbon budget, thereby consistent with the Paris Agreement's 1.5°C objectives.

2. Extension of the MONET-EU framework

This section provides an overview of the main features of EW process, as parameterized in the MONET-EU framework (alongside AR, BECCS, biochar and DACCS), followed by its techno-economic analysis, *i.e.* CO_2 removal efficiency and whole system costs. This section also briefly discusses how the set of biomass feedstocks available for BECCS and biochar pathways has been expanded with the inclusion of forestry residues, alongside energy-dedicated crops, *i.e.* Miscanthus and Willow.

Key features of the MONET-EU framework, as well as main modelling assumptions associated with AR, BECCS, biochar and DACCS pathways, can be found in deliverables D7.1 and D7.2 of the NEGEM project.

2.1. Enhanced weathering (EW)

Overview

Enhanced weathering (EW) speeds up natural rock carbonation via chemical and/or physical processes (see **Figure 1**). Once silicate rocks are crushed and applied to soil (or oceans), EW can generate net negative emissions as CO_2 is captured from the atmosphere and sequestered in the rock material.

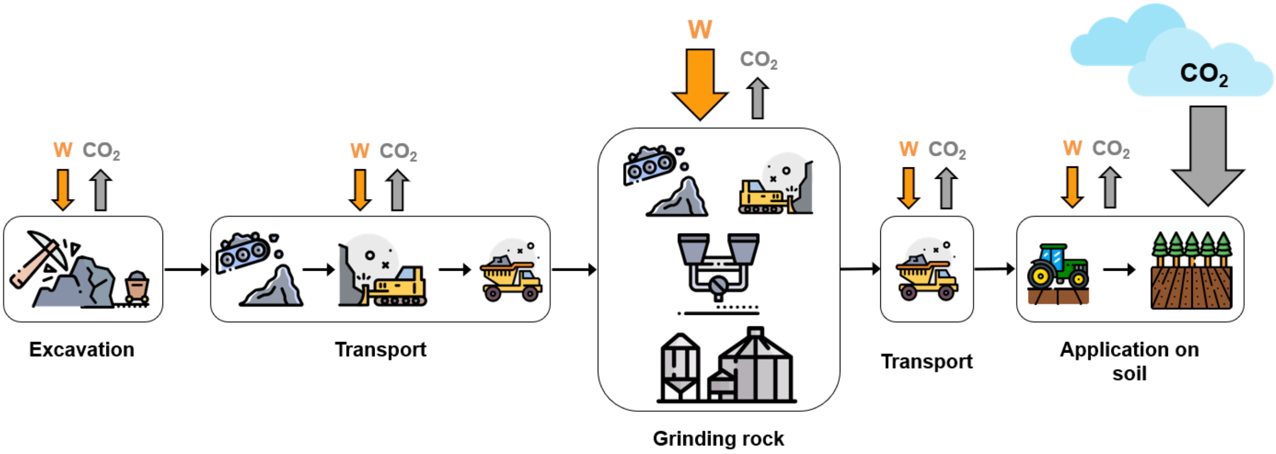

Figure 1 Value chain of enhanced weathering (EW) in the MONET-EU framework. Local rocks are typically transported over short distances via road (*e.g.* 100 km) and used for EW. Grey arrows (CO_2) account for CO_2 uptake, *i.e.* capture, and releases, *i.e.* emissions. Orange arrows (W) account for the energy consumption/production, *i.e.* fuel (diesel) and electricity.

The carbonation process (also referred to as weathering process) that sequestrates CO_2 into the rocks is not immediate, with carbonation rates ranging from a few months to a few decades (Renforth, 2012; Strefler *et al.*, 2018; Beerling *et al.*, 2020a). The carbonation rate (and therefore, the CO_2 removal efficiency) of EW is a function of the rock properties, *i.e.* its composition and its particle size, and the soil characteristics, *i.e.* soil temperature and pH, on which the pulverised rocks are applied. In this deliverable, we account for 2 rock types, *i.e.* basalt and dunite, both grinded to 10 µm-size particles, for which the CDR efficiency is evaluated over 100 years. We also assume that, given that land availability for crushed rocks application is not a limiting factor for EW deployment, rocks are extracted locally, *i.e.*

in the vicinity of the land on which crushed rocks are applied (100 km), to limit GHG emissions associated with their supply chain, and therefore to maximise EW's CDR efficiency.

Upstream processes, *i.e.* excavation of rocks from mineral formations, rock grinding, and transport, generate a large part of CO_2 emissions along EW supply chains. Moreover, the CO_2 sequestration potential of EW is inherently limited *per unit mass of rock* — up to the maximum CO_2 sequestration potentials of basalt and dunite rocks are ~0.3 and ~0.9 t CO_2/t rock, respectively (Renforth, 2012; Strefler *et al.*, 2018; Beerling *et al.*, 2020b), reached once the rocks are fully weathered. Consequently, the overall CO_2 removal potential of EW is inherently constrained by rock availability and extraction potential.

CO_2 removal efficiency

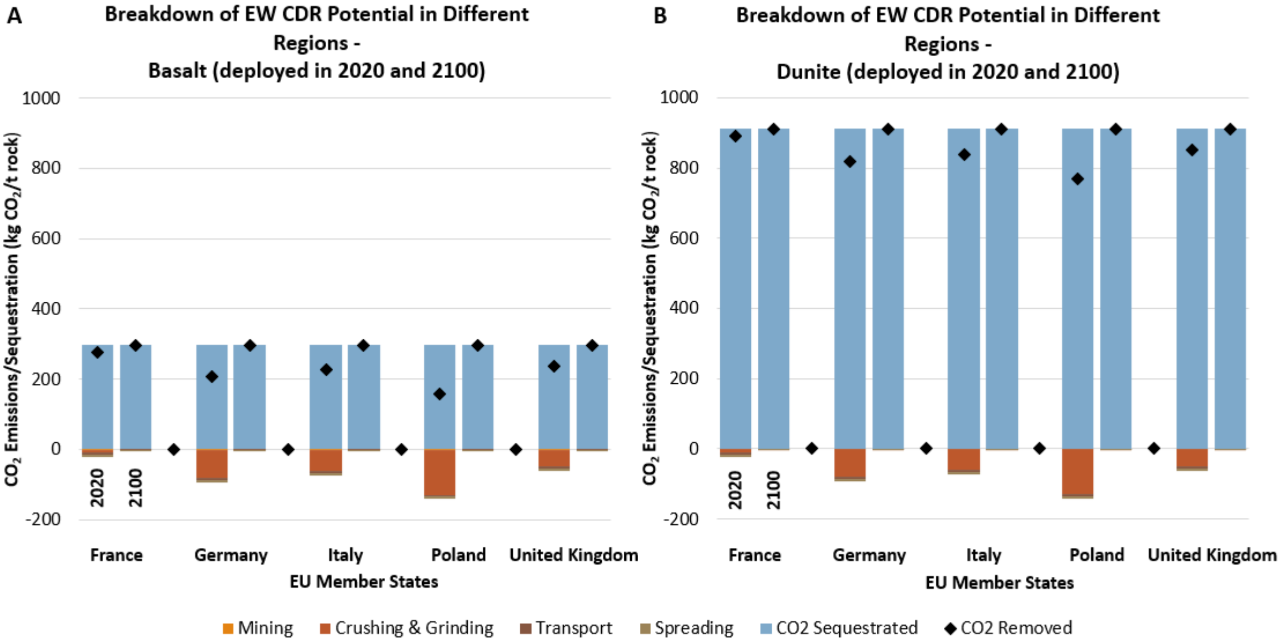

Figure 2 Breakdown of the CDR potential (CO_2 emissions/sequestration) of EW, for basalt and dunite rocks, in five illustrative EU Member States, and if deployed in 2020 and 2100. (Figure 2a) basalt, deployed in 2020 and 2100, and (Figure 2b) dunite, deployed in 2020 and 2100. As projected by the IPCC P2 scenario, we assume that the EU energy systems will decarbonize over time, *i.e.* net-zero electricity is available by 2050 while fossil fuels are completely phase-out by 2080. In 2020, the CO_2 emissions generated along the EW supply chains reduce its CDR potential to 160–270 kg CO_2/t rock for basalt rocks and to 770–890 kg CO_2/t rock for dunite rocks. In 2100, however, EW's CDR potential is expected to be almost equivalent to its CO_2 sequestration potential, owing to the adoption of low-carbon energy sources alongside its supply chain. Note that, overall, dunite rocks are more efficient than basalt rocks.

As shown in **Figure 2**, CO_2 removal potential of EW is the difference between the CO_2 sequestration from weathered rocks and the total GHG emissions generated within the different stages of the rocks supply chain: the excavation of rocks from mineral formations, rock grinding, transport, and the application to soil. Particularly, the EW model accounts for direct GHG emissions from the combustion of fuels, *i.e.* diesel, and direct N_2O emissions arising from the use of nitrogen-based explosives during the excavation of rocks. Importantly, it is assumed that the EU energy systems are increasingly decarbonized, so that by 2050, zero-carbon electricity and biofuels are available, in line with the Paris Agreement's 1.5C objectives (see NEGEM deliverable D7.2).

Techno-economic assessment

The whole system cost of EW accounts for the following cost parameters (Renforth, 2012; Strefler *et al.*, 2018; Beerling *et al.*, 2020a), as shown in **Figure 3**:

- the cost of energy, *i.e.* fuels for machinery (rocks mining, crushing, transport, or spreading) and electricity for machinery as well (rocks grinding). Note that the cost of electricity is EU State-specific;
- the CAPEX of the mining facility (mining, crushing & grinding, and infrastructure);
- and the OPEX of the mining facility (mining, crushing & grinding, and labour).

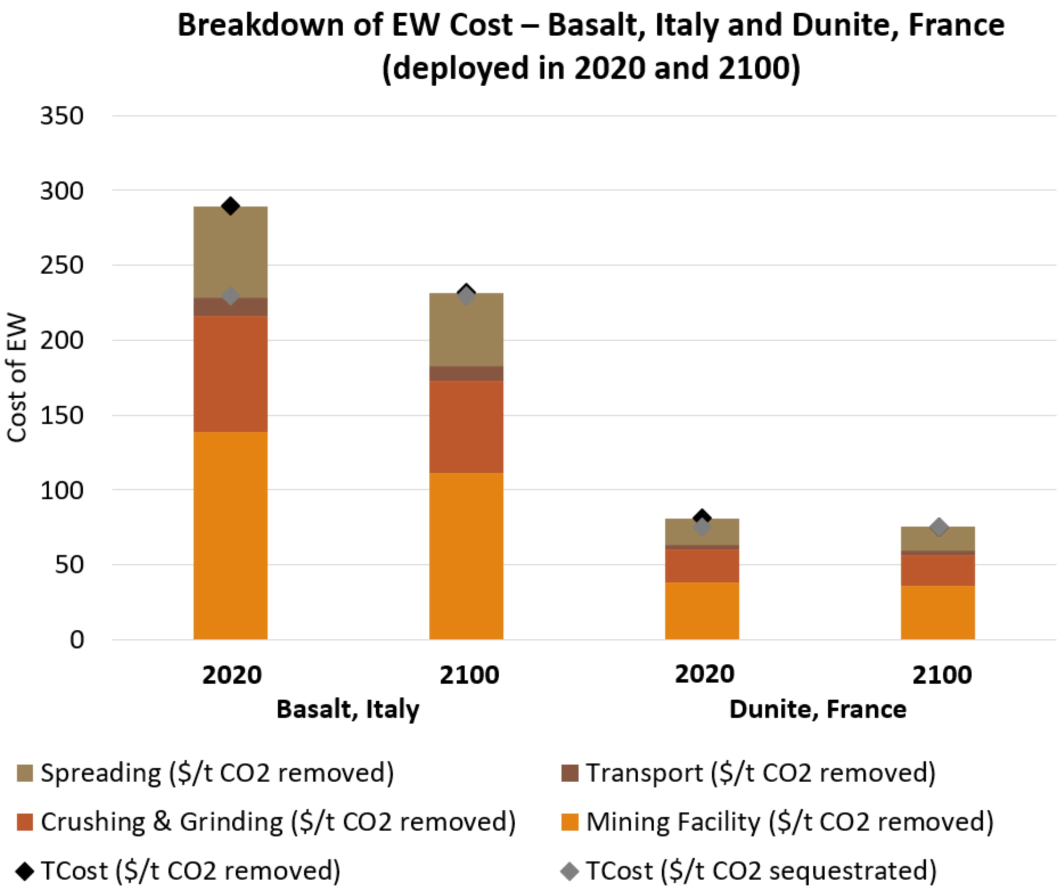

Figure 3 Breakdown of the CO_2 removal cost for EW archetypes, for basalt rocks in Italy and dunite rocks in France, if deployed in 2020 and 2100. Cost values are presented in 2018 US dollars.

Expansion of EW constraints

EW deployment is limited by rocks extraction availability and potential, as well as rock spreading availability. Here, we use the global lithological map (GLiM) published by (Hartmann and Moosdorf, 2012) to define the extraction availability of basalt and dunite rock, as illustrated in **Figure 4.**

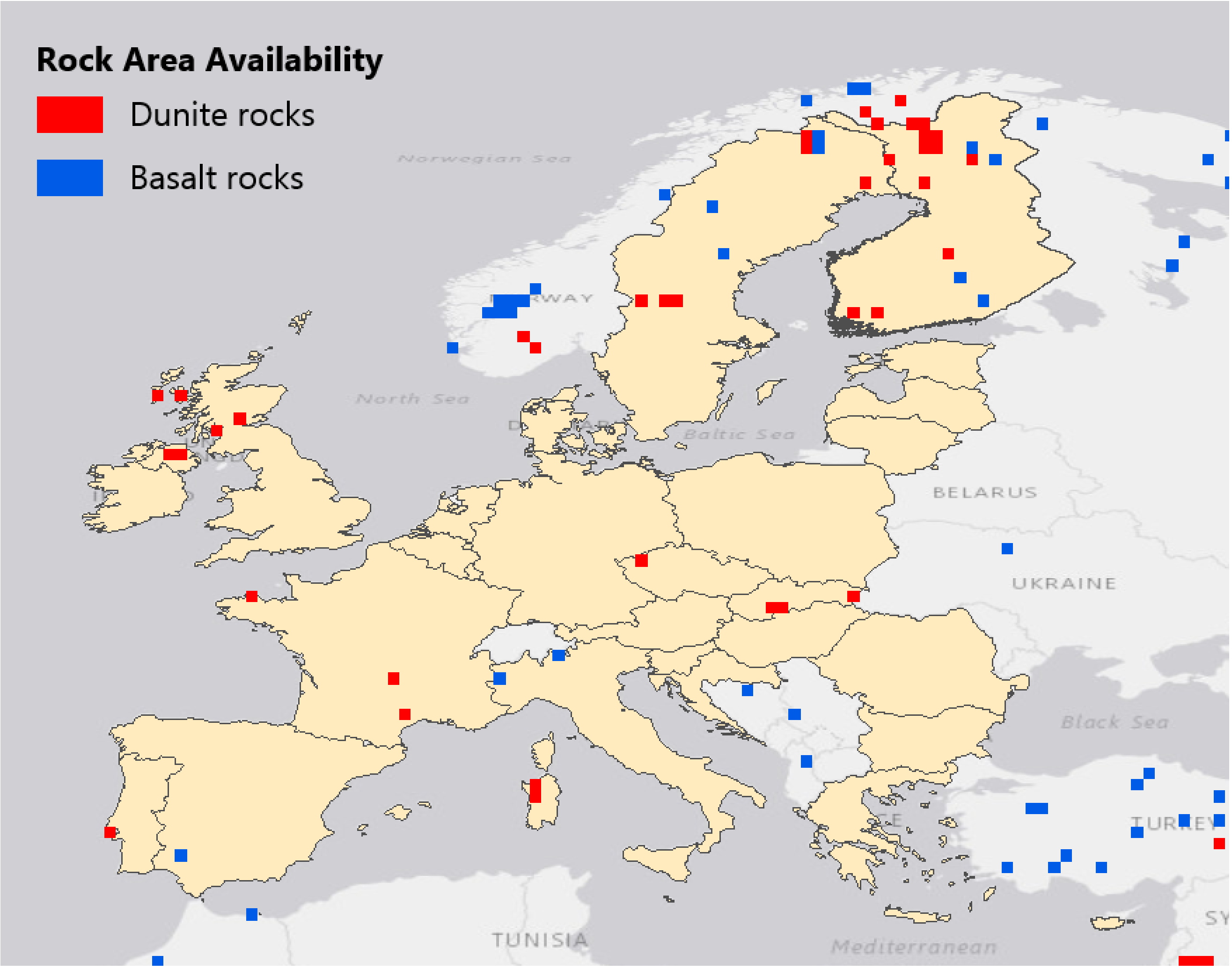

Figure 4 Basalt and dunite rocks availabilities in the EU-28. Data adapted from the gridded 0.5° spatial resolution GLiM dataset, published by (Hartmann and Moosdorf, 2012). Note that basic vocanics (*i.e.* of which basalts) and basic plutonics (*i.e.,* of which dunites*)* only accounts for 6% and 7%, respectively, of the Earth coverage.

We also assume that one mining facility, of 450,000 tonnes of rocks, can be built per year and per country, and operated over a 20 years time-period, as suggested by (Rosado *et al.*, 2017). Once crushed to dust, rocks can be spread over marginal agricultural lands (MAL)[1] (Cai, Zhang and Wang, 2011) using an application rate of 20 tonnes of rocks/ha per year, as suggested by (Lefebvre *et al.*, 2019; Beerling *et al.*, 2020b).

2.2. Forestry residues

Overview

Forestry residues can be used as potential biomass feedstocks for BECCS and biochar (see **Figure 5**). They are harvested using a cut-to-length logging system, involving the felling and the extraction of trees

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[1] MAL are themselves used for biomass cultivation for BECCS and/or biochar. More details on MAL can be found in the deliverable 7.2.

from the forest site using a combination of harvesters and forwarders (Whittaker *et al.*, 2011; Morison *et al.*, 2012).

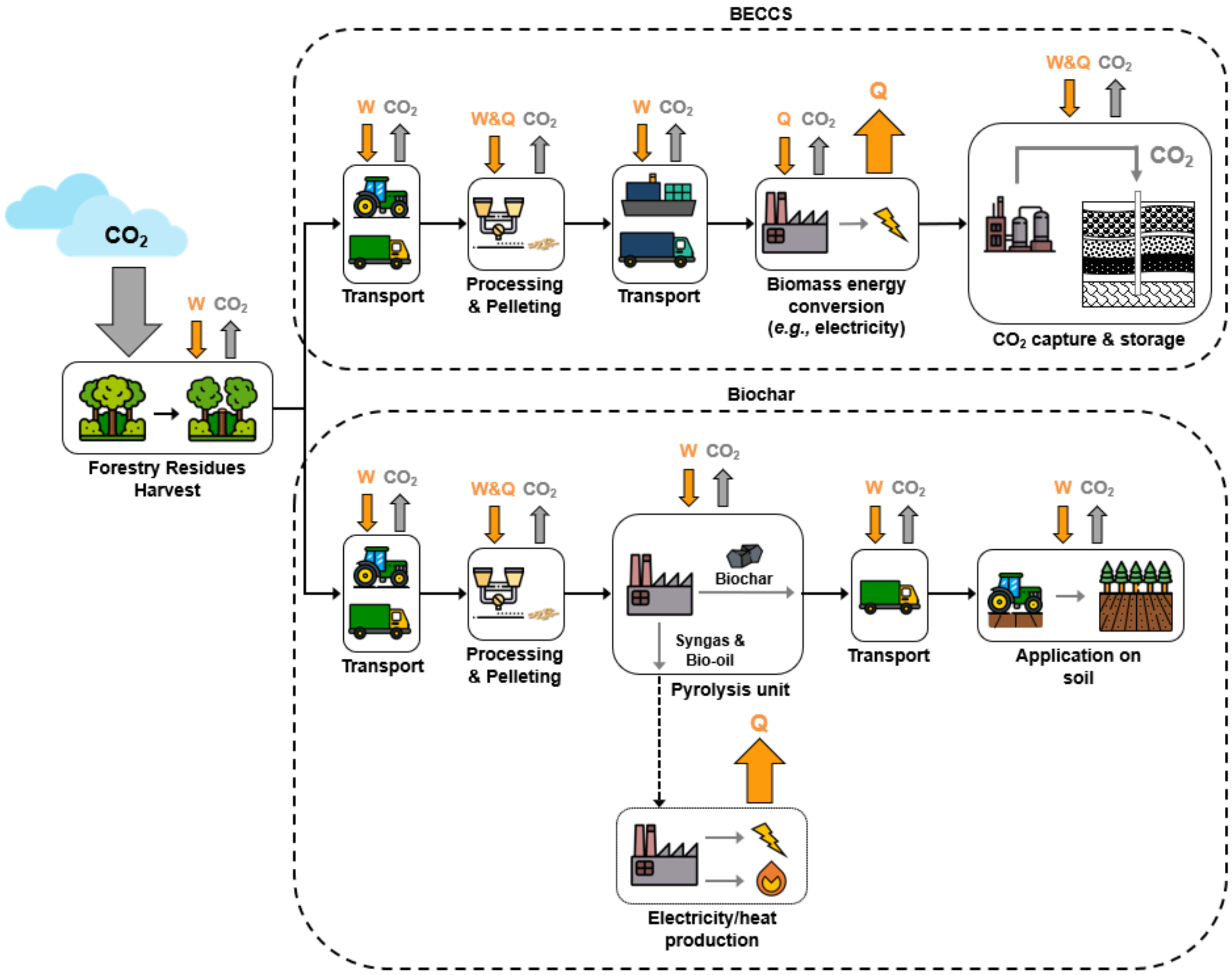

Figure 5 Value chain of bioenergy with carbon capture and storage (BECCS) and biochar using forestry residues in the MONET-EU framework. For BECCS, local biomass is transported over short distances (*e.g.,* 50 km) whereas imported biomass can be transported over longer distances (*e.g.,* 3,000 km if imported from Spain to Denmark for instance). For biochar, only local biomass is transported over short distances (*e.g.,* 50/100 km).

Here, we assume that forestry residues are composed of 80% thinnings, *i.e.* whole tree thinnings and roundwood, and 20% forest residues, *i.e.* branches, foliage, or bark (Röder, Whittaker and Thornley, 2015). Importantly, 35% of the residues are left in the forest for ecological reasons (Röder, Whittaker and Thornley, 2015) — to maintain the nutrient and soil carbon balance —, and the remainder is collected and extracted by forwarders that compress the forest residues into bundles. All extracted forestry residues are then stored at the roadside to allow for natural drying from 50% to 30% moisture content (Whittaker *et al.*, 2011; Röder, Whittaker and Thornley, 2015).

Expansion of BECCS/biochar using forestry residues constraints

The availability of forestry residues is derived from existing European forests (FOREST EUROPE, 2020), as shown in **Figure 6**. Importantly, we assume that only a tenth, *i.e.* 1/10, of planted forests (in contrast to primarily or naturally regenerated forests) can be used for BECCS or biochar, as suggested by (IRENA, 2019).

Note that, as part of the WP3 and WP7 collaboration in the NEGEM project, data for energy-dedicated crops (Miscanthus and Willow) yields are obtained by climate- and scenario-specific yields simulated in the process-based biosphere model LPJmL (Lund-Potsdam-Jena managed land). This is detailed in the deliverable 7.2 of the NEGEM project. However, as the current LPJmL version doesn't account for residues from forestry, data for forestry residues have been derived from the AR model of the MONET-EU framework. As the LPJmL model is expected to react very sensibly to any loss of carbon and nutrients associated with the extraction of forestry residues, these would need to be implemented cautiously based on an in-depth evaluation of effects. For these reasons, the WP3 and WP7 collaboration effort in NEGEM focussed on improving the representation of lignocellulosic bioenergy crops as another crucial biomass input considered for NETPs. This is detailed in the NEGEM deliverable 3.1 of WP3.

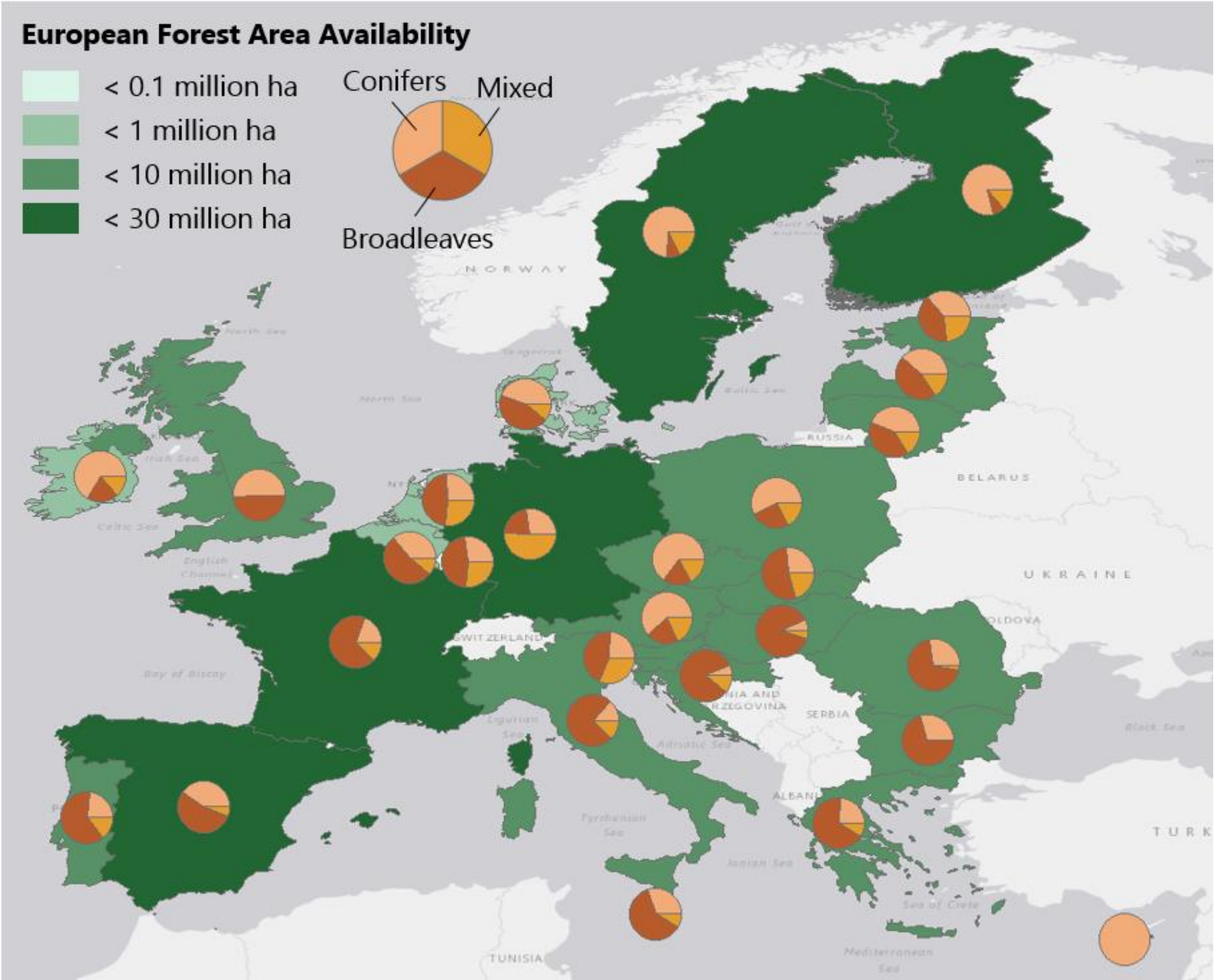

Figure 6 Forest availability in 2020 in the EU for forestry residues for BECCS and biochar pathways. Data are in ha (FOREST EUROPE, 2020).

3. MONET-EU-JEDI framework

This section first presents the integration of the JEDI tool to the MONET-EU framework, followed by an overview of the MONET-EU optimisation framework.

3.1. JEDI tool

JEDI was initially developed in 2004 from a collaboration between the National Renewable Energy laboratory (NREL) and MRG & Associates, to quantify the macro-economic impacts associated with energy project development in the US. The initial portfolio of low carbon technologies covered in JEDI included conventional hydropower, geothermal, wind, bioenergy, coal- and natural gas power and heat generation facilities (Jacobson *et al.*, 2017), and more recently fossil fuels with CCS and BECCS (Patrizio *et al.*, 2018; Patrizio, Pratama and Mac Dowell, 2020). In this deliverable, the JEDI tool was enhanced to integrate a broader portfolio of NETPs, including AR, biochar, DACCS and EW, alongside BECCS.

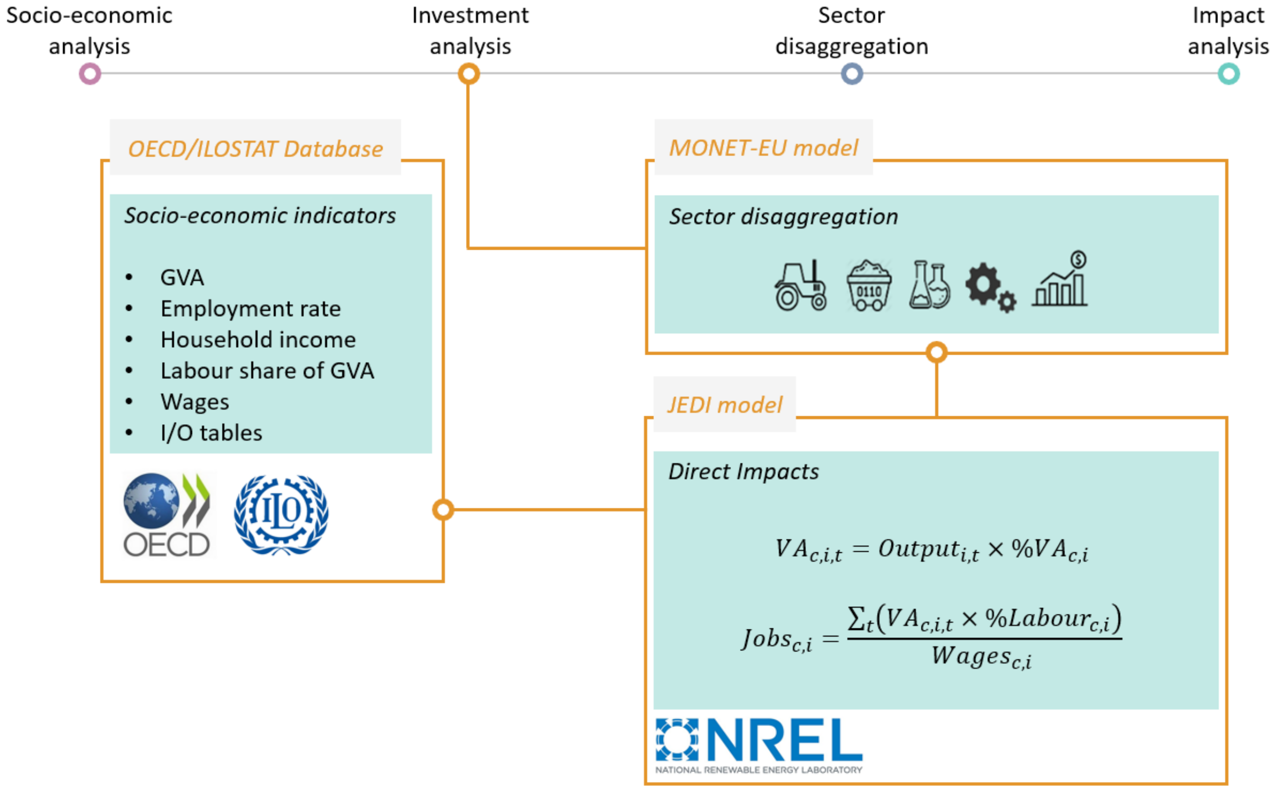

Figure 7 Framework of the JEDI tool, adapted from (IEAGHG, 2021).

A synthetic framework of JEDI is provided in **Figure 7**. The JEDI tool combines techno-economic details of selected NETPs with socio-economic indicators from the database for structural analysis (STAN)[2] maintained by the Organisation for Economic Co-operation and Development (OECD). The STAN database is a comprehensive tool for analyzing industrial performance at a relatively detailed level of activity across countries. It includes annual measures of output, value-added and its components, labor input, investment, and capital stock, from 1970 onwards. This allows users to construct a wide range of indicators to focus on areas such as productivity growth, competitiveness, and general structural

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[2] The STAN database gathers macro-economic data from national I/O databases. For more information about the STAN database, please refer to www.oecd.org

change. STAN is primarily based on OECD member countries' annual national accounts[3], while data from national business surveys/censuses (maintained by OECD, Eurostat or compiled directly from national sources) are adopted to estimate any missing details. Many of the data points in STAN are estimated and therefore do not represent official member country submissions. More details can be found in the Appendix.

The JEDI tool allows quantifying how much of the value in service and manufacturing products are generated in a certain country as a percentage of the capital expenditure of NETPs. The value-added share of production $\%VA_i$ and labor share of value-added $\%Labour_i$ of every EU Member State are broken down by economic sectors in the Appendix.

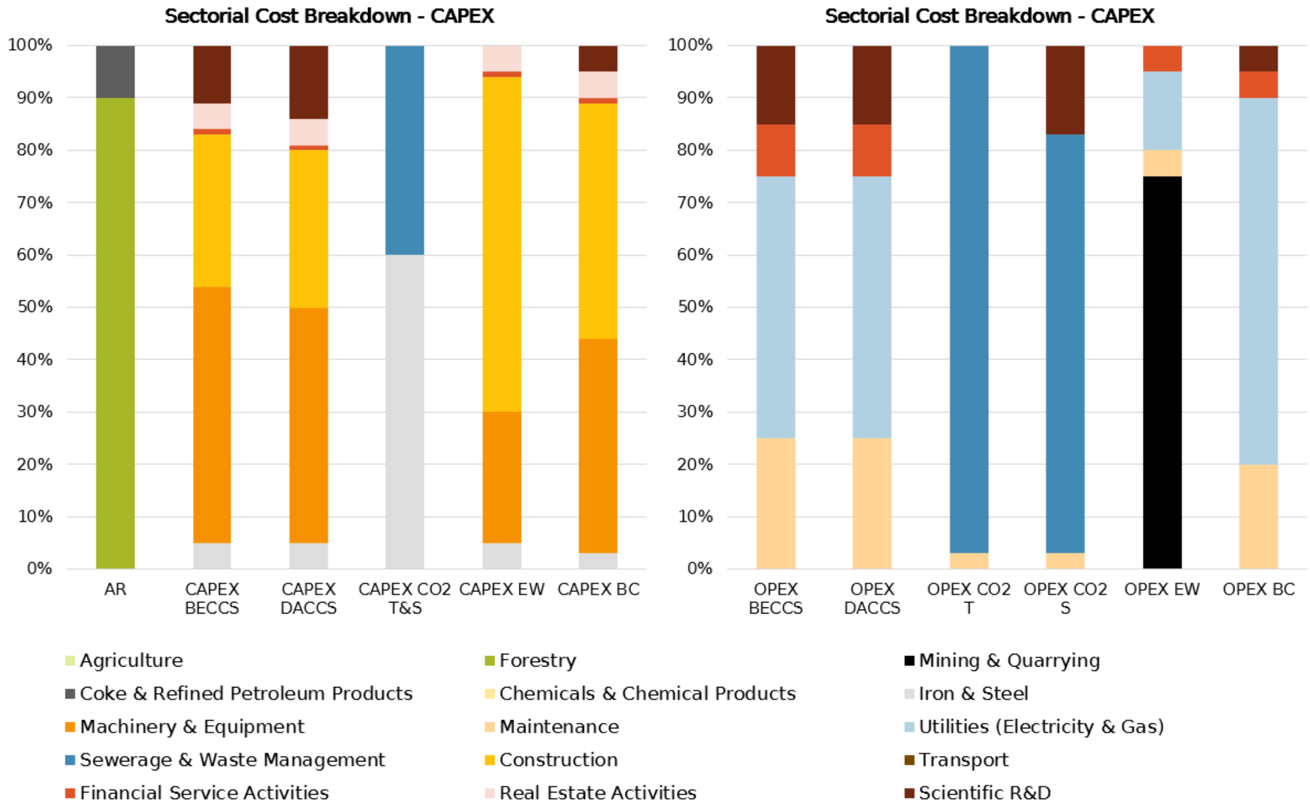

Figure 8 Sectorial cost breakdowns of the different archetypal NETPs. Left: CAPEX of AR, BECCS, DACCS, CO_2 Transport & Storage (T&S), EW and biochar, and right: OPEX of BECCS, DACCS, CO_2 Transport, CO_2 Storage, EW, and biochar. Each NETP's CAPEX and OPEX are broken down into different economic sectors. For instance, whilst almost most of the CAPEX of AR is allocated to the forestry sector, the CAPEX of BECCS, DACCS, EW, and biochar are broken down (in different proportions) into the iron & steel, construction, machinery & equipment, financial service activities, real estate activities, and scientific R&D sectors, and the CAPEX of CO_2 T&S is allocated to the iron & steel and sewerage management sectors.

The lifetime costs of NETPs projects are disaggregated across main manufacturing and downstream activities. The cost breakdown is allocated to the corresponding industrial sectors, considering only the share of expenditure contributing to the creation of national economic output. Key sectorial cost breakdowns of NETPs, *e.g. the* CAPEX and OPEX of a DAC plant, are shown in **Figure 8**.

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[3] National accounts are reported here: http://www.oecd.org/sdd/na/

Finally, in calculating the domestic value of DACCS, we distinguish between imported and domestic natural gas so that heat procurement activities are allocated to the utility sector following national energy trade statistics. More details can be found in the Appendix.

3.2. MONET-EU optimisation framework

MONET-EU is a linear optimisation problem (LP), that determines the optimal co-deployment of CDR pathways — AR, BECCS, biochar, DACCS, and EW — to meet regional or national removal targets. It covers 28 countries, disaggregated into 103 regions, following the 2021 Nomenclature of Territorial Units for Statistics 1 (NUTS1) classification[4]. Key optimisation constraints — long-term CDR targets, sustainability (land and biomass supply availability, maximum water stress), feasibility (maximum deployment rates, operating lifetimes), and CO_2 storage capacity — of the MONET-EU framework are summarised in **Table 1**. More details can be found in the NEGEM deliverable 7.2. It should be noted that the maximum deployment constraints have been reduced for BECCS, biochar, and DACCS, compared to the NEGEM deliverable 7.2, for feasibility purposes.

Table 1 Summary of the MONET-EU optimisation constraints

	Description of the constraint	**Key elements**
CDR targets	Cumulative CDR targets for each region over the 2020-2100 period	Targets are consistent with the IPCC P3 climate mitigation scenario (Grubler *et al.*, 2018; Intergovernmental Panel on Climate Change, 2018), and allocated nationally based on the responsibility-based burden-sharing principle (Raupach *et al.*, 2014).
CDR deployment rates	Deployment rates reflect the maximum speed at which each CDR method can deploy.	*Project lifetime:* AR: in perpetuity BECCS/DACCS: 30 years Biochar/EW: 20 years *Maximum deployment at global scale:* BECCS: one BECCS plant of 500 MW[5]/region/yr (~ 4.5 Mt CO_2 captured/region/yr and ~ 2.7 Mt_{DM} biomass /region/yr) DACCS: same CO_2 capture capacity as BECCS (~ 4.5 Mt CO_2 captured/region/yr) Biochar: same biomass feedstock capacity as BECCS (~ 2.7 Mt_{DM} /region/yr)

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[4] More information about the 2021 Nomenclature of Territorial Units for Statistics 1 (NUTS1) classifications can be found at :https://ec.europa.eu/eurostat/web/nuts/background

[5] We assume that a 500 MW BECCS plant has an average annual CO_2 capture capacity of 4.5 Mt CO_2, and an annual biomass feedstock capacity of 2.7 Mt_{DM} of biomass (Fajardy, Chiquier and Mac Dowell, 2018; Chiquier, Fajardy and Mac Dowell, 2022).

		EW: one rock mining facility of 450,000 t rocks/ region/yr AR: 0.83%/yr of the forest area/country[6]
(Sustainable) land availability	Both AR, BECCS and biochar require to grow biomass, which is limited by the availability of land and water. Biomass grown for BECCS and biochar can stem from dedicated-energy crops, forestry residues or agricultural residues. Biochar and rocks (for EW) can be applied on marginal agricultural land only.	AR is limited by the availability of ecologically viable areas with a potential for reforestation (Griscom *et al.*, 2017). Dedicated-energy crops for BECCS and biochar are grown on marginal agricultural land (Cai, Zhang and Wang, no date). Agricultural residues for BECCS and biochar consist of wheat straw collected from harvested wheat areas (Yu *et al.*, 2020). Forestry residues for BECCS and biochar can be collected from forest plantations (FOREST EUROPE, 2020). All lands used for AR, BECCS and biochar are limited to areas with low water stress (GASSERT *et al.*, 2015).
Geological CO_2 storage availability	BECCS and DACCS store CO_2 into geological reservoirs, situated in the vicinity (*i.e.,* 100km) of the BECCS and DAC plant, respectively.	EU-28: 180 Gt CO_2 (of which 78 Gt CO_2 in the UK) (Vangkilde-Pedersen and GEUS, 2009; Vangkilde-Pedersen *et al.*, 2009; Poulsen *et al.*, 2014; Gammer, 2015).

4. Results and discussion

4.1. Socio-economic impact of NETPs

Here, we present a non-exhaustive selection of the socio-economic impacts of NETPs, based on the combination of the JEDI tool with the MONET-EU framework, as presented above.

Direct value-added

Figure 9 shows the different economic sectors that benefit from the deployment of each of the NETPs considered in this deliverable, in the UK (selected for illustrative purpose). For example, AR contributes the most to the forestry sector, with the added GVA accounting for 41% of its total cost. The deployment of biochar and BECCS, when using energy-dedicated crops, *e.g.* Miscanthus, contributes mostly to the agricultural sector (12–20% of BECCS's total cost). For biochar, this accounts for 58% of the total added

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[6] The maximum annual deployment rate of AR is aligned with the IPCC P2 climate mitigation scenario (Grubler *et al.*, 2018; Intergovernmental Panel on Climate Change, 2018), in which 0.83%/yr of the forest area is afforested in the OECD+EU region between 2020 and 2030. Among all IPCC scenarios, *i.e.* P1, P2, P3 and P4 scenarios, this is the highest afforestation rate observed for the OECD+EU region between 2020 and 2100.

GVA whereas, for BECCS, it only accounts for a third (34%). The economic sectors of machinery & equipment, maintenance, construction, utilities, and waste management benefit the most from BECCS deployment, accounting for 43% of BECCS's total added GVA. The deployment of DACCS (both archetypes) also generates GVA in the machinery & equipment, maintenance, utilities, and construction sectors (24–25% of DACCS's total cost), but also in the scientific R&D sector, with 5–6% of DACCS's total cost. Finally, EW is the only NETP that contributes to the mining & quarrying sector, with 10% of the total cost, which is more than a quarter of EW's total added GVA (27%).

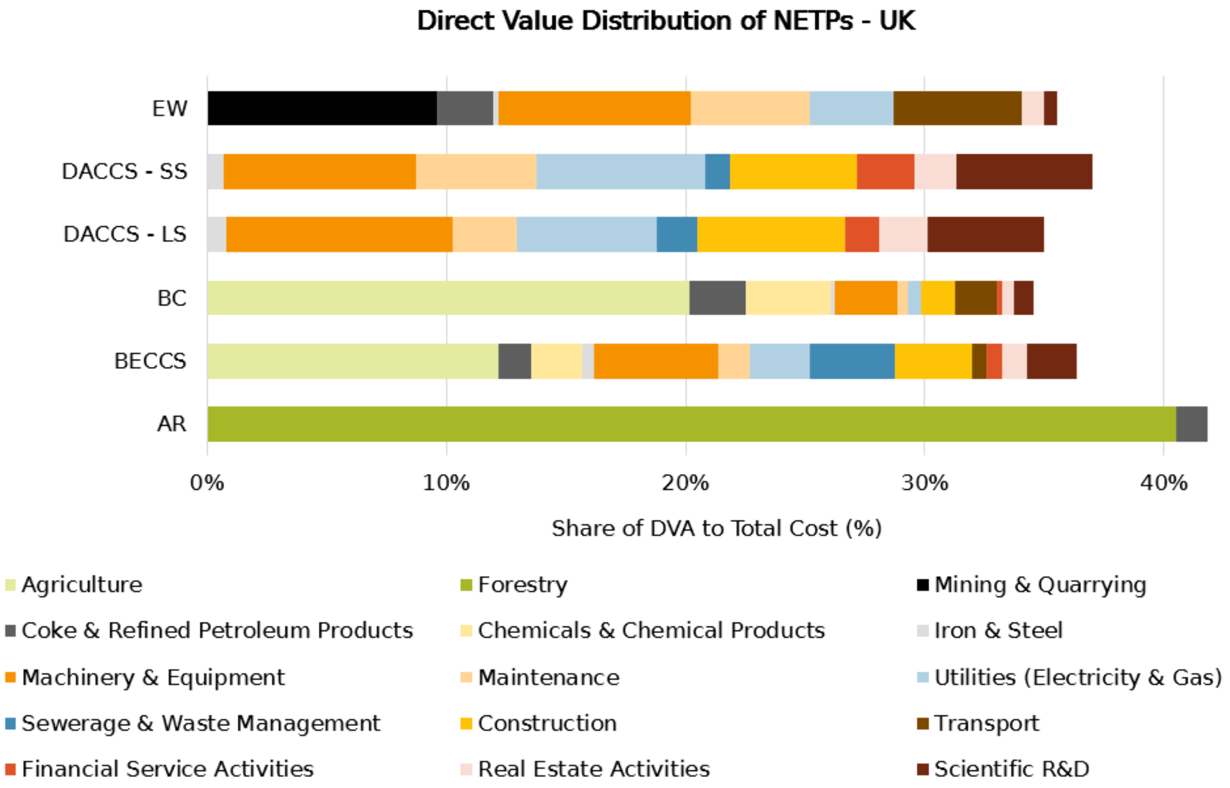

Figure 9 Variation of GVA distribution of different NETPs in the UK. From bottom to top: AR, BECCS, biochar, liquid solvent DACCS, solid sorbent DACCS, and EW. Costs are expressed in 2018 US$.

Thus, whilst land-based NETPs are expected to increase GVA in the agricultural and forestry sectors, engineered NETPs are more likely to increase GVA in economic sectors such as machinery & equipment, maintenance, construction or utilities, or even R&D.

Direct jobs created

Figure 10 highlights that the distribution of jobs created with the deployment of NETPs can vary significantly from one EU Member State to another, and from one economic sector to another. For example, most jobs are consistently created in the forestry sector when AR is deployed (98–99% of total jobs). However, when BECCS is deployed, it appears that the share of jobs created in the transport sector varies significantly from one country to another, and from a BECCS's configuration to another: If local biomass, *i.e.* forestry residues here, is used, then fewer jobs are created then if imported biomass is used, *i.e.* from Portugal or Italy here. Note that the import of forestry residues benefits the most to the transport sector if biomass comes from Portugal (35% of total jobs), whereas it benefits the most to the forestry sector if biomass comes from Italy (30% of total jobs). This is because the forestry sector generates significantly more GVA and jobs in Italy than in Portugal (see Appendix). As also shown in **Figure 10**, the deployment of solid sorbent DACCS contributes to a greater share of jobs created in the construction sector in Germany than in the Netherlands (22% versus 11% of total jobs), but to a greater share of jobs created in the R&D sector in the Netherlands than in Germany (33% versus 17% to total jobs). Also, the deployment of EW using basalt rocks benefits overall to the same economic sectors in Finland and Portugal. Note that employments in the mining & quarrying sector benefit slightly more from the deployment of EW in Portugal than in Finland (26% versus 20% of total jobs), owing to its higher employment share in Portugal than in Finland (see Appendix).

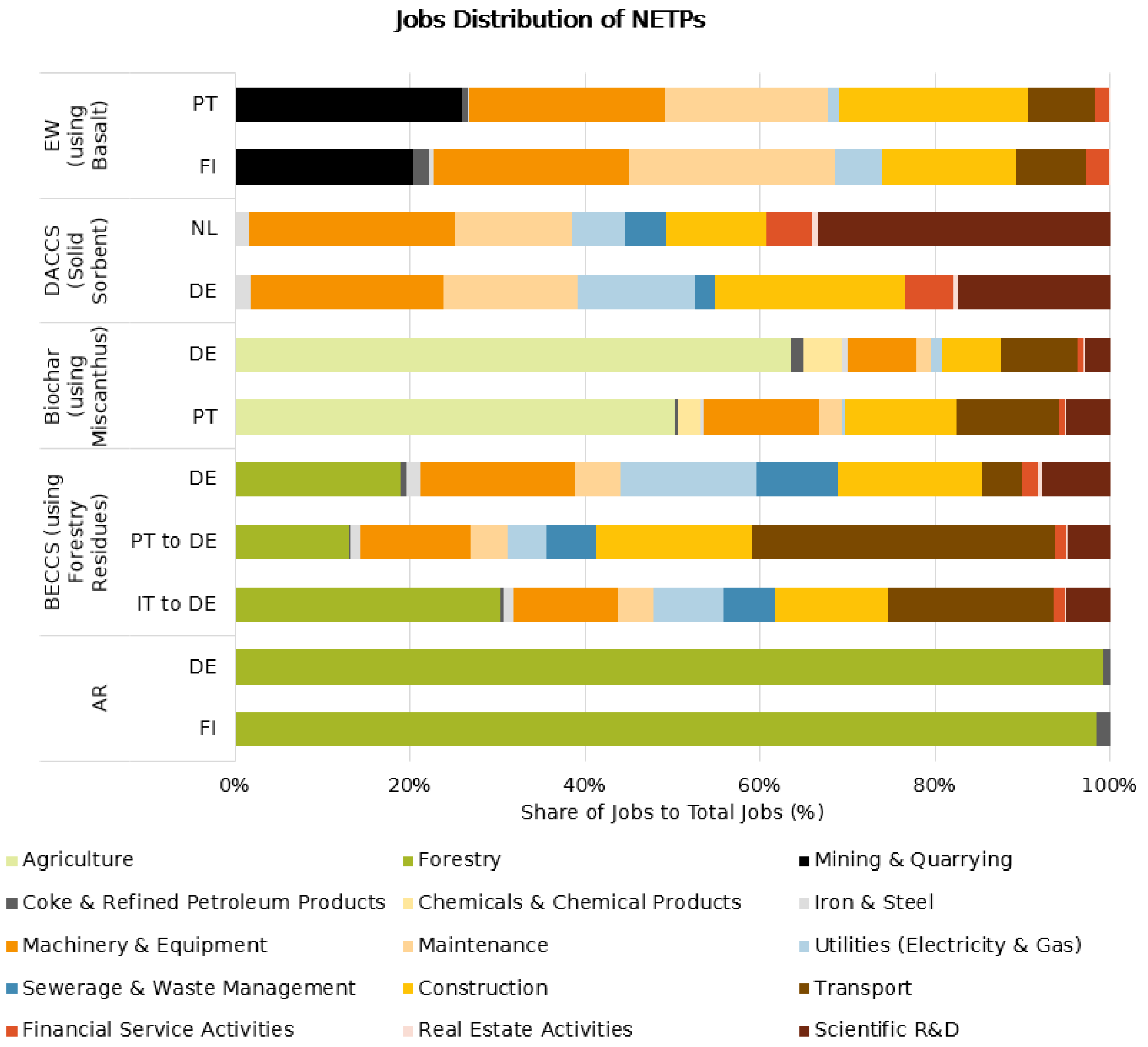

Figure 10 Variation of created jobs distribution of NETPs in different EU Member States. From bottom to top: AR in Finland (FI) and Germany (DE); BECCS using forestry residues in Germany, with supply chains from Italy (IT), Portugal (T) and Germany; Biochar using Miscanthus in Portugal and Germany; solid sorbent DACCS in Germany and in the Netherlands (NL); and EW using basalt rocks in Finland and Portugal. Note that these five illustrative EU Member States have been selected for illustrative purposes only, based on their different economic sectorial structures.

Importantly, when inter-regional supply chains are deployed, jobs can be created across multiple countries, as illustrated in **Figure 11**.

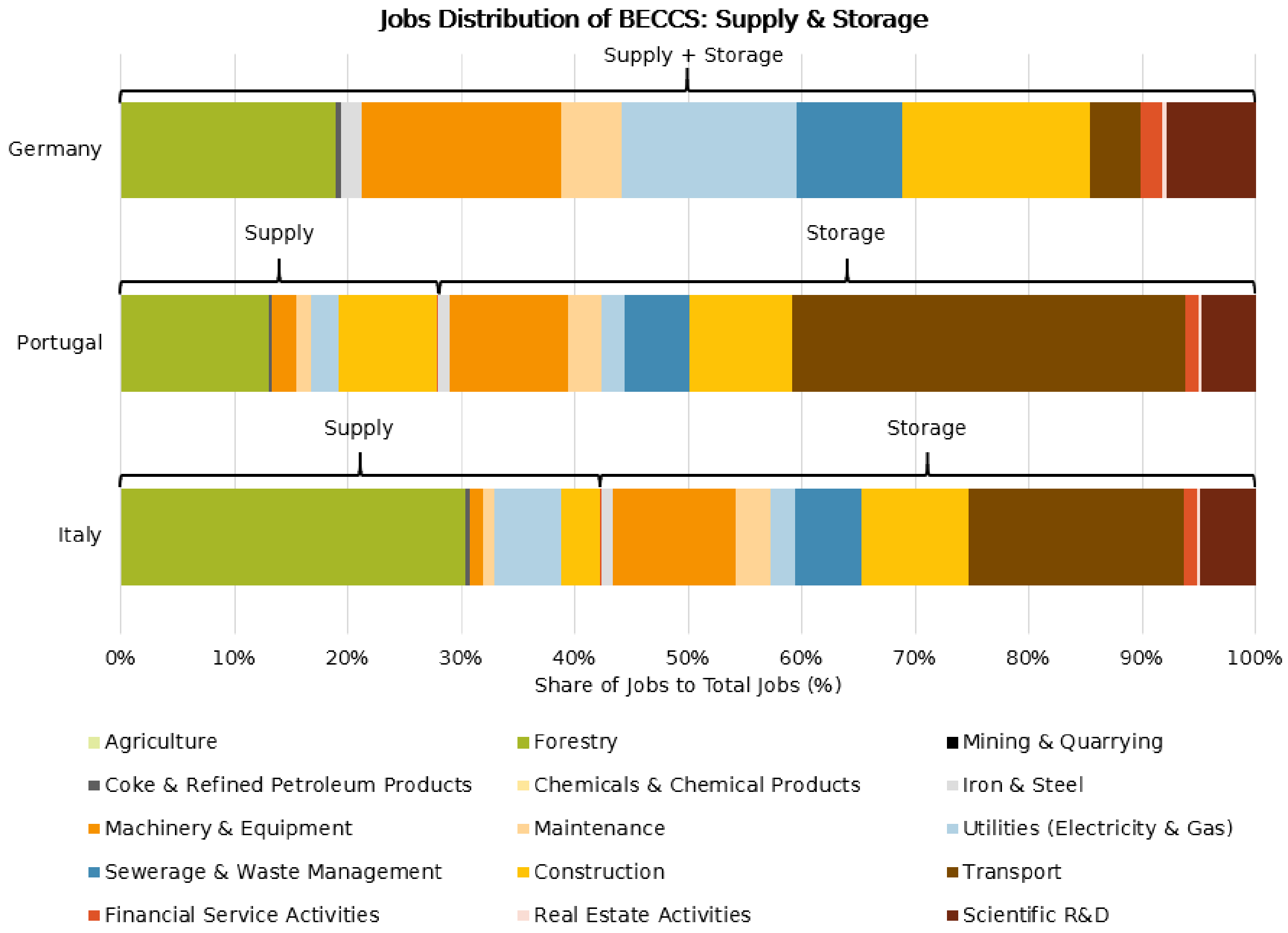

Figure 11 Variation of created jobs distribution of BECCS for different configurations in different EU Member States. From bottom to top: Imported biomass from Italy to Germany; Imported biomass from Portugal to Germany; Local biomass from Germany.

4.2. Large-scale deployment of NETPs in the EU

Here, we investigate a least-cost CDR portfolio — AR, BECCS, biochar, DACCS, and EW — to meet cumulative CDR targets between 2020 and 2100, in line with the Paris Agreement's stringent 1.5°C objectives. These cumulative CDR targets, used as a proxy for the EU remaining carbon budget, are obtained from the IPCC P2 pathway by applying a responsibility-based burden-sharing principle, as detailed in the NEGEM deliverables 7.2 and 4.2 of WP7 and WP4, respectively. It is assumed that EU Member States must meet, together, up to 81 Gt CO_2 by 2100. Note that the trade of biomass among the EU Member States is permitted, *i.e.* EU Member States can use imported biomass from another EU Member State to deploy BECCS.

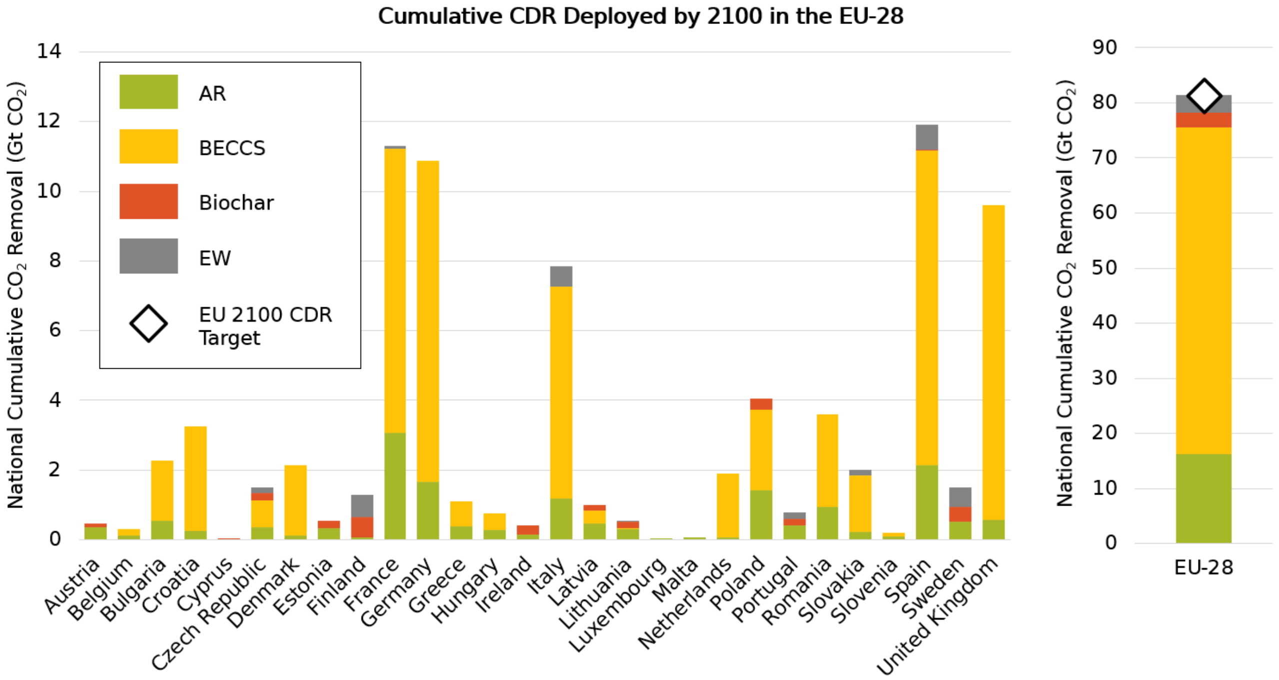

Figure 12 Cost-optimal CO_2 removal in 2100, for each EU Member State, broken own by NETP deployed. The EU 2100 CDR targets, used here as a proxy for the EU carbon remaining budget, are also shown (black diamond). Left: National CDR breakdown per NETPs; Right: EU-28 CDR Breakdown per NETPs.

As shown in **Figure 12**, deploying CDR at a scale consistent with the Paris Agreement's 1.5°C objectives is achievable through a suite of NETPs, comprised of BECCS (59 Gt CO_2), AR (16 Gt CO_2), biochar (4 Gt CO_2) and EW (2 Gt CO_2). It should be noted that, here, DACCS is not deployed, owing to its costliness.

It appears that BECCS is the NETP most predominantly deployed by the end of the century (73% of the total CDR achieved), owing to its relatively high cost-efficiency, *i.e.* BECCS can achieve high removal rates with relatively low resource usage, compared to other technologies, at low cost. BECCS's deployment is driven by the availability of CO_2 storage capacities, such as in France, Germany, Spain, and the UK. Energy-dedicated crops are the preferred feedstock for BECCS, *i.e.* Miscanthus (55%), followed by forestry residues (40%) and Willow (5%).

AR is the second most deployed NETP, with 20% of the total CDR achieved by 2100, mostly in temperate climates, that are favorable for CO_2 sequestration. However, AR deployment is often limited by its national expansion rates, already much above historical afforestation rates.

Biochar is scarcely deployed (5% of the total CDR achieved), either complementing BECCS, therefore also competing for land (and subsequently biomass), or replacing BECCS when CO_2 storage is not available. Land competition issues are observable in Poland, while the barrier to BECCS deployed imposed by the lack of suitable CO_2 storage is evident in Sweden. It should be noted that the transport of CO_2 is only modelled (and therefore permitted) via pipeline in the MONET-EU framework, over short distances (*i.e.,* 100km). Therefore, the transport of CO_2 via ship to Norgegian CO_2 storage reservoirs, as it could be suggested, is not considered in this study.

In contrast to the feedstock choices observed for BECCS, forestry residues are preferred to energy-dedicated crops (62% and 38%, respectively). This is because owing to biochar's relatively low CDR efficiency (see NEGEM deliverable 7.2), adopting forestry resides would allow reducing the carbon footprint of upstream activities, such as biomass cultivation, harvest, and processing.

Note that, in some EU Member States, BECCS and biochar deployments are nationally limited by the availability of land, and subsequent biomass, *i.e.* energy-dedicated crops, such as Miscanthus or Willow, or forestry residues. Therefore, the limited land/biomass availability drives the deployment of EW(2% of the total CDR achieved), as a complementary NETPs, where, where basalt and dunite rocks are available for extraction, such as in Italy or Spain. As for AR, EW deployment is limited by national deployment rates, *i.e.* the maximum number of mining facilities that can be built annually. Importantly, there are still some concerns about the toxicity impact of basalt and dunite rocks, when weathering in soil (see Deliverable 1.5 for more details). Therefore, EW deployment might be voluntarily constrained to prevent negative impacts on biodiversity and health in the future.

Overall, the EU can deploy ~80 Gt of CO_2 removal by 2100, the order of magnitude of which being consistent with the Paris Agreement’s 1.5°C objectives, that the EU committed to. This is the availability of a large portfolio of NETPs, comprising land-based, mineral-based, and geological NETPs, that allows the EU Member States to meet their national CDR targets. Indeed, with a limited portfolio of NETPs, as it is the case in Deliverable 7.2, the lack of CO_2 storage availability observed in Finland, coupled with limited energy-dedicated crops availability, and limited areas with a potential for AR made Finland’s 2100 CDR target unfeasible. Here, however, the high availability of forestry residues allows Finland to deploy biochar, and therefore meet its 2100 CDR targets.

5. Conclusions

To provide insights into the techno-economic, and bio-geophysical implications of NETPs deployment at the Paris Agreement’s scale within the EU, this deliverable has extended the MONET-EU framework (previously developed in the NEGEM deliverables D7.1 and D7.2), to include enhanced weathering (EW), in addition to afforestation/reforestation (AR), bioenergy with carbon capture and storage (BECCS), biochar, and direct air carbon capture and storage (DACCS). Specifically, two types of rocks have been considered, *i.e.* basalt and dunite rocks. They differ in terms of rock availability and extraction potential, as well as carbonation rate, and therefore CO_2 removal potential. Additionally, forestry residues have also been included in MONET-EU, as an alternative biomass feedstock to energy-dedicated crops, *i.e.* Miscanthus and Willow, for the deployment of BECCS and biochar. This allows to explore further biomass supply chains, which were previously not considered in MONET, and therefore widen the portfolio of NETPs.

To evaluate the socio-economic impacts of this range of NETPs, this deliverable has also combined the MONET-EU framework with the JEDI tool, to quantify the key macro-economic impacts associated with the deployment of NETPs, *i.e.* gross value added (GVA) and jobs creation.

The results showed that each NETP deployment differs in terms of socio-economic implications. Specifically, we found that land-based NETPs, *e.g.* AR, BECCS, or biochar, are expected to increase GVA in the agricultural and forestry sectors, and that engineered NETPs, *e.g.* BECCS, biochar, DACCS, or EW, are more likely to increase GVA in economic sectors such as machinery & equipment, maintenance, construction or utilities, or even R&D. The results also showed that the socio-economic implications of each NETPs deployment can vary significantly among the EU-Member States. Each NETP can boost employment in different economic sectors and different amounts, depending on the sectorial structure of each EU-Member State economy. Moreover, we found that the configurations of NETP, when deployed, *e.g.* local versus inter-regional biomass supply chain for BECCS, can modify significantly the regional distribution of jobs creation. For example, the use of imported biomass increases employment in the transport sector and involves multiple national economies: Where the biomass comes from, and where it is converted into bio-energy, with subsequent CO_2 removal. The socio-economic value of removing CO_2 from the atmosphere is therefore specific to the NETP selected, as well as the NETP configuration and location.

Thus, the climate and socio-economic policies adopted to carry out the Paris Agreement’s 1.5°C objectives will be key, as they will likely influence the deployment of CDR both in terms of portfolios of NETPs (*i.e.,* which NETP? Where? When?) and their scale (*i.e.,* how much ?). Careful consideration should be given to the socio-economic characteristics associated with each NETP, as deploying CDR at the Paris Agreement’s scale could strengthen or weaken current EU economies and associated employments.

The results also showed that a large portfolio of NETPs is more likely to deliver CDR at scales that are consistent with the Paris Agreement’s 1.5°C objectives. Whilst BECCS was found to be the NETP most predominantly deployed by the end of the century, owing to its relatively high cost-efficiency, biochar can either complement BECCS, therefore also competing for land (and subsequent biomass), or replace BECCS when CO_2 storage is not available nationally. Importantly, the use of forestry residues is favored over that of energy-dedicated crops, to maximize biochar’s cost-efficiency.

As in the previous deliverable 7.2, we also found that AR was mostly deployed in temperate climates, that are favorable for CO_2 sequestration but constrained by national expansion rates, already much above historical afforestation rates.

Finally, we found that EW was being deployed where land and subsequent biomass, availability is limited, provided that rocks are available for extraction. However, its deployment is found limited by national deployment rates, *i.e.* the maximum number of mining facilities that can be built annually. It should be noted, given the high energy intensity and cost of rocks feedstock preparation for EW, one possibility (which is not included yet in MONET) would be to explore potential synergies with the mining industries, *i.e.* cost and process of crushing the rocks is allocated to the mining industries, by using basalt and dunite dust. Importantly, given that there are still some concerns about the toxicity impact of basalt and dunite rocks, when weathering in soil (see Deliverable 1.5 for more details), EW deployment might be voluntarily constrained to prevent negative impacts on biodiversity and health in the future.

To prepare this report, the following deliverable has 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	Report	CO	6
D1.2	Comprehensive sustainability assessment of terrestrial biodiversity NETPs	ETH	Report	PU	12
D4.1	NETP database	ICL	Excel spreadsheet	PU	9
D4.2	Bio-geophysics database	ICL	Excel spreadsheet	PU	12
D4.3	Identify Member state targets for CDR	ICL	Report	PU	18
D7.1	Develop MONET-EU	ICL	Report	PU	12
D7.2	Extended MONET-EU	ICL	Report	PU	18

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Appendix: JEDI tool

Key outputs

Key outputs of JEDI are *gross value added (GVA)*, the value of an industry's production to the country of analysis, and *employment creation.* These metrics are calculated for different industrial activities and economic sectors, based on the sectorial indexing of the International Standard Industrial Classification (ISIC)[7]. The following indicators are extracted from STAN for the calculation of *direct impacts*:

- $\%VA_i$ Value added share of production: Value added contributed by each sector *i* relative to total production. The GVA is a widely recognized macroeconomic variable that measures the contribution to the Gross Domestic Product (GDP) made by individual producers, industries, or sectors in a country. It provides an indication of the production structure of a given sector, and allows to measure the value that each industrial activity adds to the domestic economy.

- $\%Labour_i$ Labor share of value added: Amount of labor compensation within the value added created by a given industry. It is used to calculate the total earnings generated within a certain economic activity.

- Wages: this indicator is used to calculate the number of jobs created by a given industry.

Value added and jobs created in a given industry *i* are proportional to the output produced by technology *t* in that sector[8].

$$VA_{i,t} = Output_{i,t} * \%VA_i$$

$$Jobs_i = \sum_t \left(VA_{i,t} * \%Labour_i\right) / _{Wages_{i_i}}$$

Overall, the JEDI tool allows to specify how much of the value in service and manufacturing products are generated in a certain country as a percentage of the capital expenditure of NETPs. The $\%VA_i$ and $\%Labour_i$ of every EU Member State are broken down by economic sectors in Figures A.1-3.

Data from the OECD/ILOSTAT database

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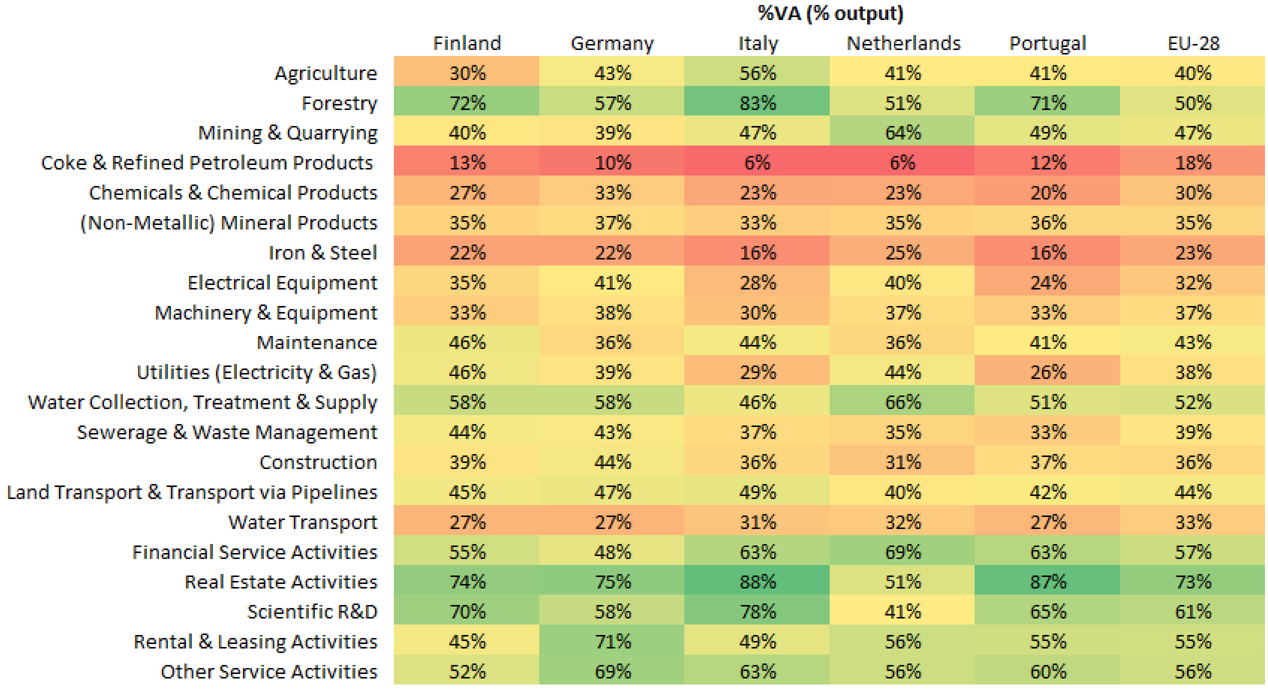
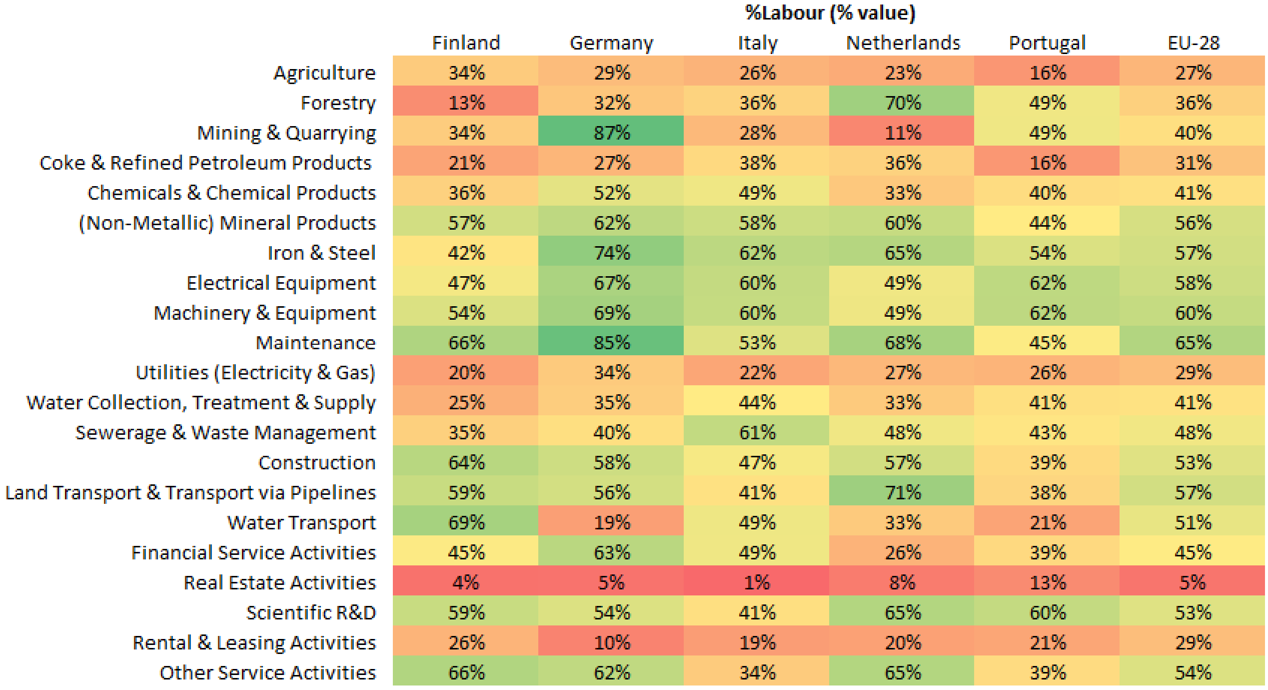
[7] More information about International Standard Industrial Classification codes can be found at https://unstats.un.org/unsd/publication/seriesm/seriesm_4rev4e.pdf

[8] Therefore, I-O methodology assumes that all estimates are linear and proportional. Value added, earnings, and jobs, are then simply proportional to certain output.



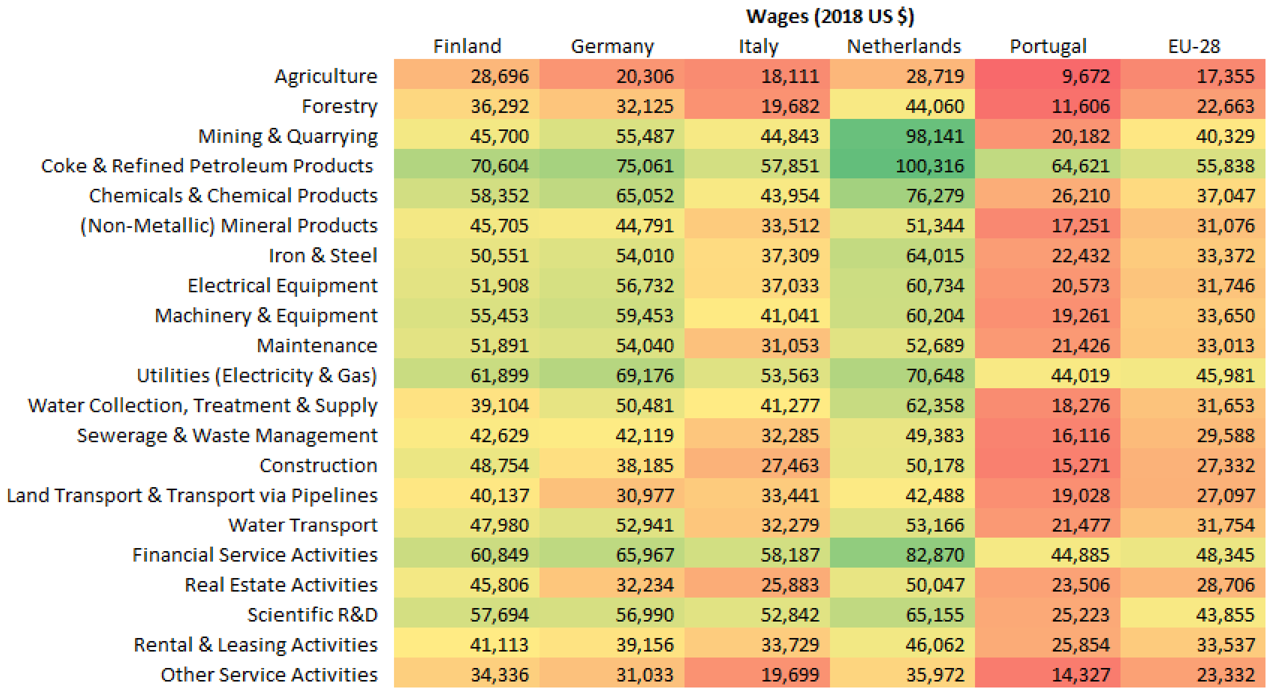
	%VA (% output)					
	Finland	Germany	Italy	Netherlands	Portugal	EU-28
Agriculture	30%	43%	56%	41%	41%	40%
Forestry	72%	57%	83%	51%	71%	50%
Mining & Quarrying	40%	39%	47%	64%	49%	47%
Coke & Refined Petroleum Products	13%	10%	6%	6%	12%	18%
Chemicals & Chemical Products	27%	33%	23%	23%	20%	30%
(Non-Metallic) Mineral Products	35%	37%	33%	35%	36%	35%
Iron & Steel	22%	22%	16%	25%	16%	23%
Electrical Equipment	35%	41%	28%	40%	24%	32%
Machinery & Equipment	33%	38%	30%	37%	33%	37%
Maintenance	46%	36%	44%	36%	41%	43%
Utilities (Electricity & Gas)	46%	39%	29%	44%	26%	38%
Water Collection, Treatment & Supply	58%	58%	46%	66%	51%	52%
Sewerage & Waste Management	44%	43%	37%	35%	33%	39%
Construction	39%	44%	36%	31%	37%	36%
Land Transport & Transport via Pipelines	45%	47%	49%	40%	42%	44%
Water Transport	27%	27%	31%	32%	27%	33%
Financial Service Activities	55%	48%	63%	69%	63%	57%
Real Estate Activities	74%	75%	88%	51%	87%	73%
Scientific R&D	70%	58%	78%	41%	65%	61%
Rental & Leasing Activities	45%	71%	49%	56%	55%	55%
Other Service Activities	52%	69%	63%	56%	60%	56%

Figure A.1. Sectorial value added share of production (%VA) for five illustrative EU Member States, and for the EU (average).



	%Labour (% value)					
	Finland	Germany	Italy	Netherlands	Portugal	EU-28
Agriculture	34%	29%	26%	23%	16%	27%
Forestry	13%	32%	36%	70%	49%	36%
Mining & Quarrying	34%	87%	28%	11%	49%	40%
Coke & Refined Petroleum Products	21%	27%	38%	36%	16%	31%
Chemicals & Chemical Products	36%	52%	49%	33%	40%	41%
(Non-Metallic) Mineral Products	57%	62%	58%	60%	44%	56%
Iron & Steel	42%	74%	62%	65%	54%	57%
Electrical Equipment	47%	67%	60%	49%	62%	58%
Machinery & Equipment	54%	69%	60%	49%	62%	60%
Maintenance	66%	85%	53%	68%	45%	65%
Utilities (Electricity & Gas)	20%	34%	22%	27%	26%	29%
Water Collection, Treatment & Supply	25%	35%	44%	33%	41%	41%
Sewerage & Waste Management	35%	40%	61%	48%	43%	48%
Construction	64%	58%	47%	57%	39%	53%
Land Transport & Transport via Pipelines	59%	56%	41%	71%	38%	57%
Water Transport	69%	19%	49%	33%	21%	51%
Financial Service Activities	45%	63%	49%	26%	39%	45%
Real Estate Activities	4%	5%	1%	8%	13%	5%
Scientific R&D	59%	54%	41%	65%	60%	53%
Rental & Leasing Activities	26%	10%	19%	20%	21%	29%
Other Service Activities	66%	62%	34%	65%	39%	54%

Figure A.2. Sectorial labour share of value added (%Labour) for five illustrative EU Member States, and for the EU (average).



	Wages (2018 US $)					
	Finland	Germany	Italy	Netherlands	Portugal	EU-28
Agriculture	28,696	20,306	18,111	28,719	9,672	17,355
Forestry	36,292	32,125	19,682	44,060	11,606	22,663
Mining & Quarrying	45,700	55,487	44,843	98,141	20,182	40,329
Coke & Refined Petroleum Products	70,604	75,061	57,851	100,316	64,621	55,838
Chemicals & Chemical Products	58,352	65,052	43,954	76,279	26,210	37,047
(Non-Metallic) Mineral Products	45,705	44,791	33,512	51,344	17,251	31,076
Iron & Steel	50,551	54,010	37,309	64,015	22,432	33,372
Electrical Equipment	51,908	56,732	37,033	60,734	20,573	31,746
Machinery & Equipment	55,453	59,453	41,041	60,204	19,261	33,650
Maintenance	51,891	54,040	31,053	52,689	21,426	33,013
Utilities (Electricity & Gas)	61,899	69,176	53,563	70,648	44,019	45,981
Water Collection, Treatment & Supply	39,104	50,481	41,277	62,358	18,276	31,653
Sewerage & Waste Management	42,629	42,119	32,285	49,383	16,116	29,588
Construction	48,754	38,185	27,463	50,178	15,271	27,332
Land Transport & Transport via Pipelines	40,137	30,977	33,441	42,488	19,028	27,097
Water Transport	47,980	52,941	32,279	53,166	21,477	31,754
Financial Service Activities	60,849	65,967	58,187	82,870	44,885	48,345
Real Estate Activities	45,806	32,234	25,883	50,047	23,506	28,706
Scientific R&D	57,694	56,990	52,842	65,155	25,223	43,855
Rental & Leasing Activities	41,113	39,156	33,729	46,062	25,854	33,537
Other Service Activities	34,336	31,033	19,699	35,972	14,327	23,332

Figure A.3. Sectorial wages (expressed in 2018 US $) for five illustrative EU Member States, and for the EU (average).

Share of local production of natural gas

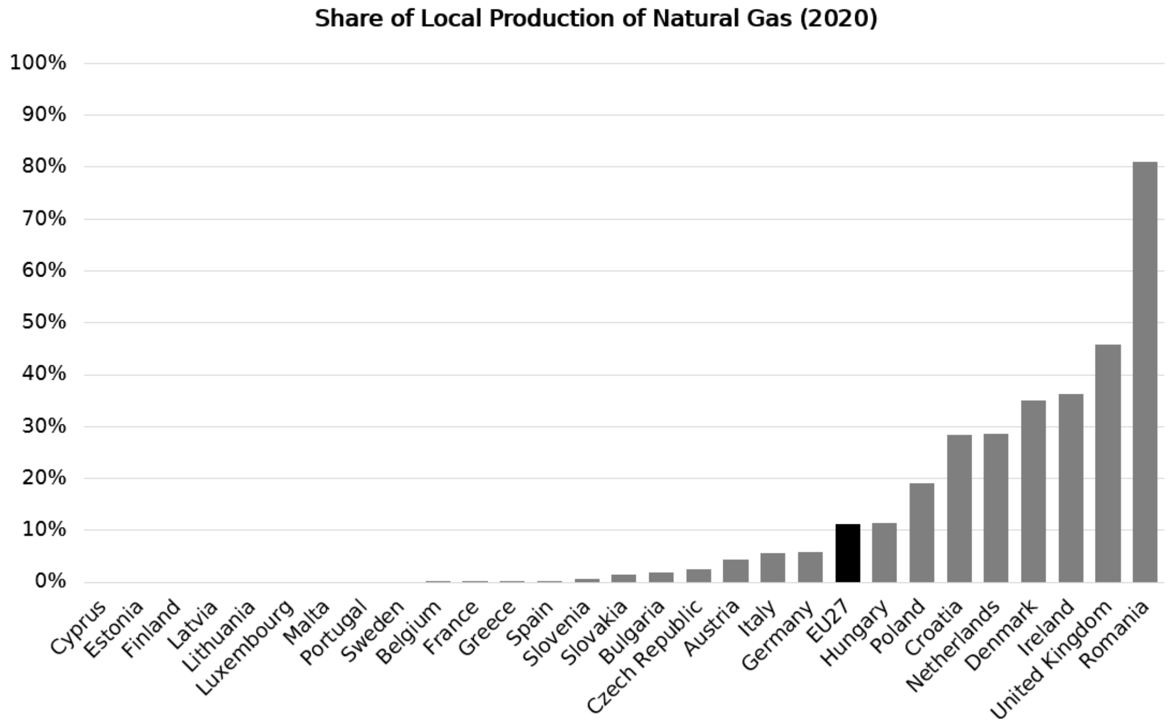


Figure A.4. Sectorial cost breakdowns of natural gas for every EU Member State, based on the local shares of natural gas and roundwood production in 2020. For example, as only 35% of the natural gas used in Denmark is produced nationally (the remaining 65% being imported), only 35% of the added value generated by the industrial activity using natural gas, within the entire value chain of the selected NETPs, *e.g.* heat consumption for DACCS liquid solvent archetype, is allocated to Denmark.