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Sustainable carbon cycles for a 2050 climate-neutral EU
Technical Assessment

Accompanying the

Communication from the Commission to the European Parliament and the Council

Sustainable Carbon Cycles

{COM(2021) 800 final} - {SWD(2021) 450 final}

Contents

1. CLIMATE NEUTRAL EU AND BEYOND

Reaching climate neutrality in the EU by 2050 has been an aspiration for the Commission since the publication of 'A Clean Planet for all[1]' in late 2018. Reducing the Union emissions to net zero by mid-century is now a formal commitment under the European Green Deal, and the European Climate Law adopted in 2021 sets the EU objective of climate-neutrality by requiring the reduction of Union-wide greenhouse gas emissions to net zero by 2050 and the aim of achieving net removals (negative emissions) thereafter. The analysis carried out by the European Commission[2,3] shows how this objective of climate neutrality can be achieved. Any pathway towards climate neutrality entails a drastic reduction of Greenhouse Gases (GHG) emissions in all sectors, with an EU economy-wide emission reduction ranging from 85% to 95% compared to 1990[4]. Carbon dioxide removals (CDR) will close the gap to reaching net zero GHG emissions through, in the mid-term, the enhancement of the natural sink and, in the longer term, the deployment of industrial solutions able to capture and store CO_2 permanently. The quantity of CO_2 to be removed from the atmosphere and the respective role of ecosystems and industrial solutions for carbon removals vary following assumptions on technological uptakes and consumption patterns for transport, food diet and other goods or services.

Reducing reliance on carbon

The EU's climate and energy policies aim principally to reduce its reliance on carbon by improving the efficiency of buildings, transport modes or industries and by replacing fossil fuels with low-carbon energy carriers such as renewable electricity and hydrogen. This strategy is the main driver for a 24% reduction of GHG emissions in the EU between 1990 and 2019[5] and remains essential to the achievement of 55% reduction by 2030 as requested by the Climate Law. The legislative package to deliver the European Green Deal proposed by the European Commission on 14 July 2021 sets new objectives and measures for the further decarbonisation of the EU economy: tightening of the existing EU Emissions Trading System, including aviation and maritime transport; a new Emissions Trading System for road transport and building; increased use of renewable energy; greater energy efficiency; a faster roll-out of low emission transport modes and the infrastructure and fuels to support them.

Replacing fossil carbon with recycled carbon

Part of the EU economy will still need carbon for its functioning in 2050 and beyond, for instance for the production of plastics, rubbers, chemicals and other advanced materials requiring carbon as a feedstock. A complete and well-functioning circular economy will minimize the end-of-life impact of these products by promoting their reuse, recycling and energy recovery. The bioeconomy will also have an important role to play, in particular in the construction, sector by increasing carbon stocks in long-lived material and by providing substitutes for GHG intensive conventional building materials. Virgin fossil carbon will be

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[1] COM (2018) 773, "A clean Planet for all" A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. (link)

[2] In depth analysis accompanying the Communication "A Clean Planet for All" (link)

[3] SWD (2020) 176, Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people (link)

[4] These figures are focusing on emission reductions and excludes CO2 emissions captured and stored in CCS facilities as well as carbon removals from the land sector.

[5] GHG emissions reduced further by 10% between 2019 and 2020 with a major impact of the COVID 19 crisis.

replaced by more sustainable streams of recycled carbon from waste, biomass and directly from the atmosphere to supply the organic chemistry processes for the synthesis of sustainable products and fuels.

Removing and sequestering carbon

Reaching climate neutrality requires solutions for capturing CO_2 from the atmosphere and storing it sustainably in ecosystems, geological reservoirs or products made for this purpose. Both nature-based and industrial solutions are needed to remove several hundred million tons of CO_2 per year from the atmosphere.

The ecosystem-based removals will play an important role in achieving the EU's 2050 climate neutrality objective. Actions that can protect carbon stocks or that can enhance the carbon sequestration capacity of the land include planting trees, restoring forests, practicing agroforestry, adopting agricultural and forestry practices that protect and enhance soil carbon, protecting wetlands, restoring peatlands, or promoting long-lasting and circular bio-based products.

Besides its capacity to store and sequester carbon, land provides many other important products and services: it supplies the bioeconomy sectors with food, feed and industrial feedstocks, provides habitats for biodiversity and many ecosystem services vital for life (e.g. water and air purification), and protects us from some of the consequences of climate change (e.g. floods and desertification). EU initiatives such as the land use, land use change and forestry (LULUCF) regulation[6], the bioeconomy strategy[7], the biodiversity strategy[8], the forest strategy[9] or the adaptation strategy[10] address the interdependence between these various functions.

The permanent storage of CO_2 in geological formations is an option to mitigate industrial emissions and to remove carbon from the atmosphere when the CO_2 is captured directly from the atmosphere or is of biogenic origin. Depleted oil and gas reservoirs and saline aquifers have the potential to store billion tons of CO_2 in offshore sites, the binding of CO_2 to basalt rocks being another option potentially deployable at large scale. The environmental integrity of carbon capture and storage (CCS) solutions is partly a matter of ensuring that the CO_2 captured and stored remains isolated from the atmosphere in the long term; and partly about ensuring that the capture, transport and storage elements do not present other risks to human health or ecosystems. Appropriately selected and managed these storage solutions can retain 99% or more of the sequestered CO_2 for longer than 1000 years[11].

Stakeholder views

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[6] Regulation (EU) 2018/841 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework (link).

[7] A Sustainable Bioeconomy for Europe (link).

[8] COM (2020) 380, EU Biodiversity Strategy for 2030 Bringing nature back into our lives (link).

[9] COM (2021) 572, New EU Forest Strategy for 2030 (link).

[10] COM (2021) 82, Forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate Change (link).

[11] IPCC (2005), Carbon Dioxide Capture and Storage (link).

In order to inform and get the views of different stakeholders on how the EU could better support carbon farming, industrial management of carbon and on the priorities for future certification of carbon removals, the Commission launched a public consultation on the Roadmap of their actions. Citizens and stakeholders were invited to provide views on the Commission's understanding of the problem and to make available any information that they find relevant.

The Roadmap presented the context of the initiative referring primarily to the EU-wide objective of climate neutrality by 2050 as well as the proposal to set out a 2035 target of climate neutrality for the land sector, covering land use, forestry, and agriculture. In order to achieve these goals a contribution from both carbon farming and technological carbon removal solutions is vital to close the gap of emissions remaining after implementation of strong reduction measures.

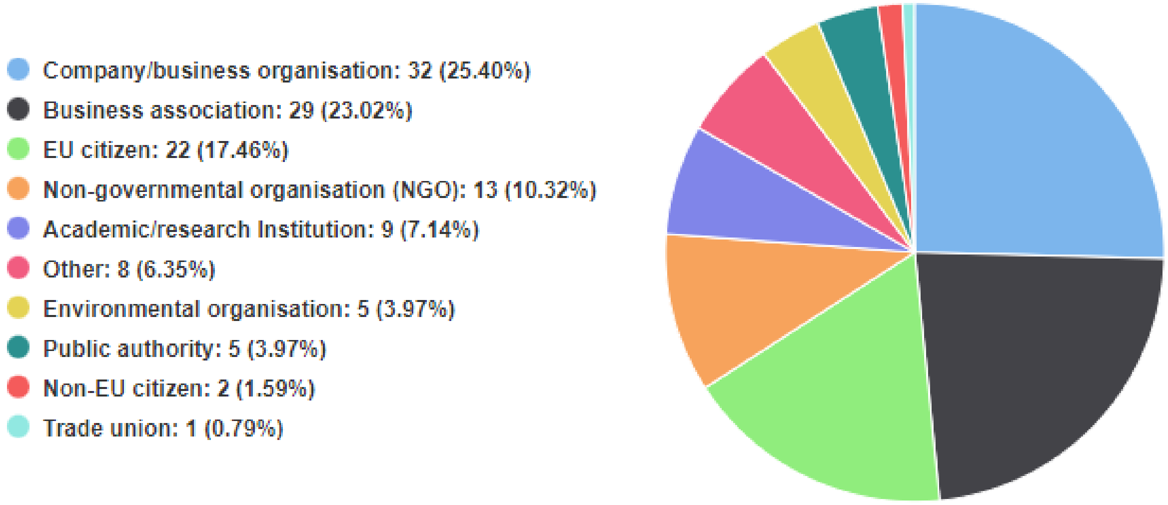
This view has found wide acceptance among the 130 participants of the consultation who showed a considerable interest in the topic providing abundant feedback.

Business representatives turned out to be the most prolific showing a feedback rate of 48.4% including responses submitted directly or through the associations. Among them, particularly noteworthy is the equal weighting of farmers’ and forest holders/owners’ participation (7.3% each), pointing at equal importance of these sectors in shaping the carbon farming future.

Energy companies have shown even greater engagement (10.8%), thereby demonstrating that in this sector, efforts to achieve climate neutrality are well underway. A prominent representation of actors from the carbon removals industry (6.9%) shows the expectation of better defined standards by the private markets.

The remaining business stakeholders (16.2%) represented a wide range of players, from food processors, fertilizer producers and wood processing companies, to actors active in other sectors such as water management, bio-based materials, or refineries.

The consultation was also a subject of analysis for several non-governmental organisations (NGOs), environmental organisations, representatives of the scientific community, public institutions such as ministries and official chambers, as well as individual citizens.



There was a consensus that carbon removals should not take priority over emissions reductions. Another important need, raised by most respondents, concerned environmental integrity. Recognition of co-benefits in the form of enhanced biodiversity, improved soil health and fertility, better water quality and positive social effects was deemed crucial alongside the overarching goal of fighting climate change.

As regards carbon farming, the volume of feedback received confirms the high relevance of the matter, reflecting the momentum associated thereto. Carbon farming was mentioned in almost every submitted response thereby validating broad recognition of carbon farming practices and attesting they are no longer a novelty. While greater familiarity seems to be emerging with regard to carbon farming, almost in parallel a necessity has been voiced to establish a legal framework regulating future operating models for the industry. The call for such a framework that is robust, easy to implement, understandable, reliable, and scalable constitutes a major message for the policymakers.

An important part of the future framework will certainly be constituted by a system of incentives for carbon farming practices, financed by public funds or private markets. A consistent interaction between those funding possibilities, in particular between existing support from the Common Agricultural Policy and private funding channels such as voluntary carbon credits, is expected by the stakeholders in order to ensure compatibility. It was suggested to explore synergies and potential trade-offs leveraging guidance and lessons already learnt from existing initiatives. A set of adequately tailored incentives for farmers and foresters is considered a pivotal element for upscaling carbon farming initiatives. It was highlighted a number of times that practitioners already carrying out carbon farming practices should also be rewarded in a due manner.

The announced proposal for a regulatory framework for the certification of carbon removals was addressed by a vast number of submitted remarks. A transparent, comprehensive but concise certification framework, ideally integrated into a global network at a later stage, has been identified as a high need according to the feedback. This framework should be furthermore supported by stringent measurement, reporting & verification (MRV) standards ensuring that additionality and permanence issues are tackled appropriately. Double-counting should also be avoided as well as rewarding avoided emissions. Based on the feedback received, industrial players seem to be more inclined towards result-based methodologies pointing at higher accuracy of measurement, whereas NGOs and environmental organisations are more lenient, advocating for action-based schemes.

Based on the stakeholders’ feedback to the Roadmap, it can be clearly concluded that there is a genuine need for sound solutions formulating a reliable legal framework for carbon removals that will be able to harmonise existing fragmented approaches. Starting from the EU certification scheme, policy measures are expected to give the right direction for the EU carbon removals environment, serving as a role model internationally and preferably establishing a regulated credits market in the future. According to the variety of consultation participants, high-quality carbon removals are attainable with the support of effective incentives underpinned by robust regulatory foundations allowing the achievement of ambitious goals.

2. SUSTAINABLE USE AND SUPPLY OF CARBON IN THE EU ECONOMY

2.1. EU climate neutral scenarios

The modelling assessments carried out by the European Commission indicate that, while maximizing the deployment of decarbonized renewables energy and energy efficiency is essential to make the Union climate neutral in 2050, part of the EU economy will still need carbon for its functioning. It is not possible to rely only on a single type of solution to remove CO_2 from the atmosphere and provide sustainable sources of non-fossil carbon. While the scenario analysis show variation depending on future societal choices, all options require a substantial enhancement of the carbon sink function of our ecosystems and a large development of industrial solutions to capture, use and store carbon.

This section looks at the potential developments in the management and use of carbon by 2050 through two scenarios. Both scenarios are consistent with a climate-neutral EU by 2050 and are in line with the modelling assessments conducted in the context of the EU long-term strategy “A Clean Planet for All” and the package of legislative proposals to deliver the European Green Deal[12].

The scenario ECOSYS assumes priority is given to the enhancement of the carbon removals through the restoration of ecosystems. This is also a scenario where changes in lifestyle and consumer choices are beneficial for the climate. It includes less carbon intensive diets that free land for the regeneration of natural ecosystems. The scenario INDUS relies more heavily on large scale deployments of industrial solutions to capture, recycle and store CO_2.

Current use of carbon

The EU consumed approximately one billion tonnes of biogenic (45%) and fossil (55%) carbon for the functioning of its economy in 2018[13]. The carbon is used for food (25%), energy (56%) and material production (19%) purposes and only a very small fraction of the carbon used today is from recycled origin. Beyond decarbonising its energy system, the EU will also need to rethink its sourcing of carbon to be climate neutral by 2050.

A sustainable EU bioeconomy has a very important role to play by ensuring sustainable provision of carbon for food and feed, fibre, energy and materials. Currently, annual biomass production in the EU27+UK land-based sectors is approximately 1.5 billion tonnes of dry matter (tdm), equivalent to approximately 27 EJ, of which 2/3 come from agriculture and 1/3 from forestry[14]. Not all grown biomass is used, as parts remain in fields and forests to maintain carbon sinks and other ecosystem services, but also because of missing incentives for mobilising unused residual biomass streams and lack of knowledge within the farming community about sustainable practices and new bio-based markets.

There is also potential to sustainably cultivate biomass on marginal and degraded land in the EU, which could contribute significantly to the overall domestic biomass potential, but strong

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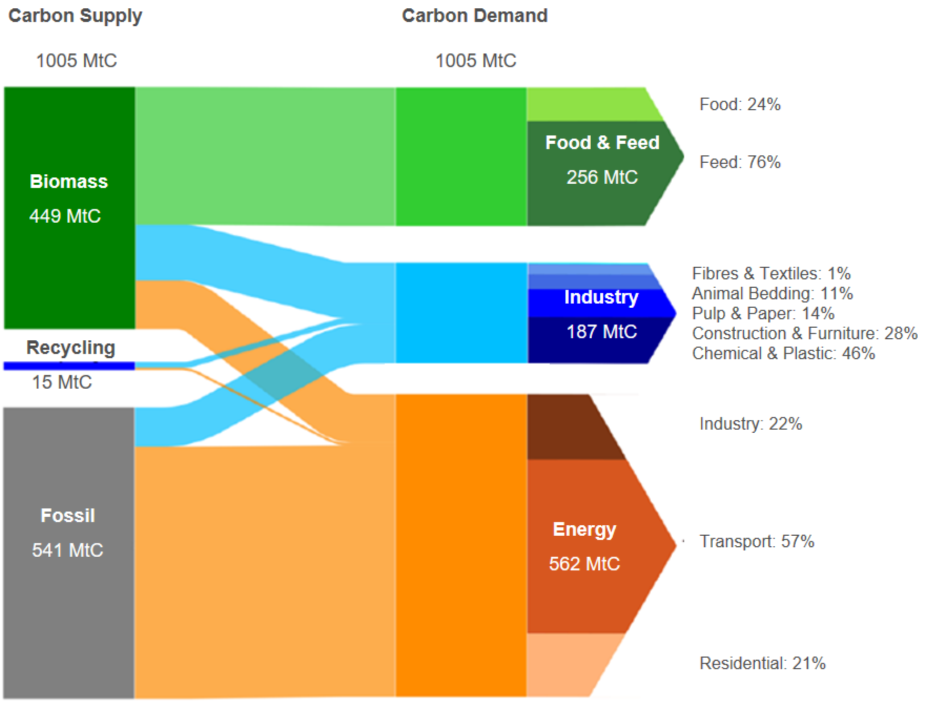
[12] COM (2019) 640, The European Green Deal (link).

[13] Carbon Economy - Studies on support to research and innovation policy in the area of bio-based products and services (link).

[14] Camia A. et al., Biomass production, supply, uses and flows in the European Union. First results from an integrated assessment (link); Gurría, P. et al., Biomass flows in the European Union: The EU Biomass Flows tool, version 2020 (link).

biodiversity safeguards need to be in place. Various studies have identified different sustainable biomass potentials in the EU, however an integrated assessment is lacking which would incorporate different sustainability aspects as well as the new policy goals in the context of the European Green Deal (e.g. biodiversity targets, land sink enhancement goals, providing sufficient biomass to assist in the Just Transition of fossil-reliant regions).

Natural resources are however limited and the bioeconomy cannot provide sustainably all the carbon to fulfil the needs in energy and material of the 2050 EU economy. Other streams of carbon should be developed to replace the fossil carbon. Scaling up the circular economy from front-runners to the mainstream economic players will make a decisive contribution, in particular to make sustainable products in a resource-efficient way. In this context, technologies which can allow the circular utilisation of CO_2, such as carbon capture and utilisation (CCU) can provide an important contribution to establish a sustainable (carbon) circular economy while decreasing CO_2 emissions. This can allow to turn the CO_2 from a waste to a resource, capturing it from point sources or directly from the air and using it subsequently as a feedstock for the production of chemicals, plastics or fuels.



Source: Carbon economy[13]

Figure 1: Carbon Flows in EU economy (2018)

Future needs in energy remain substantial

In both illustrative scenarios, the EU economy is consuming less energy than today with a potential decrease of the gross available energy (GAE)[15] by around 25% between 2019 and 2050 (Figure 2). This reduction in the total GAE is the aggregation of more substantial changes on the type of energy used. While the carbon-free energy consumption increases with the development of solar and wind energies, the consumption of primary carbon energy (fossil

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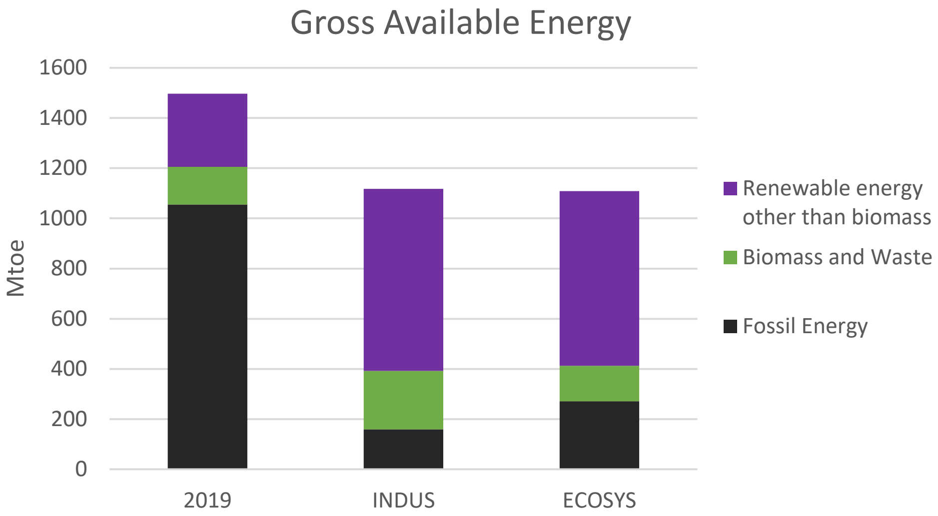
[15] The Gross Available Energy (GAE) represents the overall supply of energy for all activities on the territory.

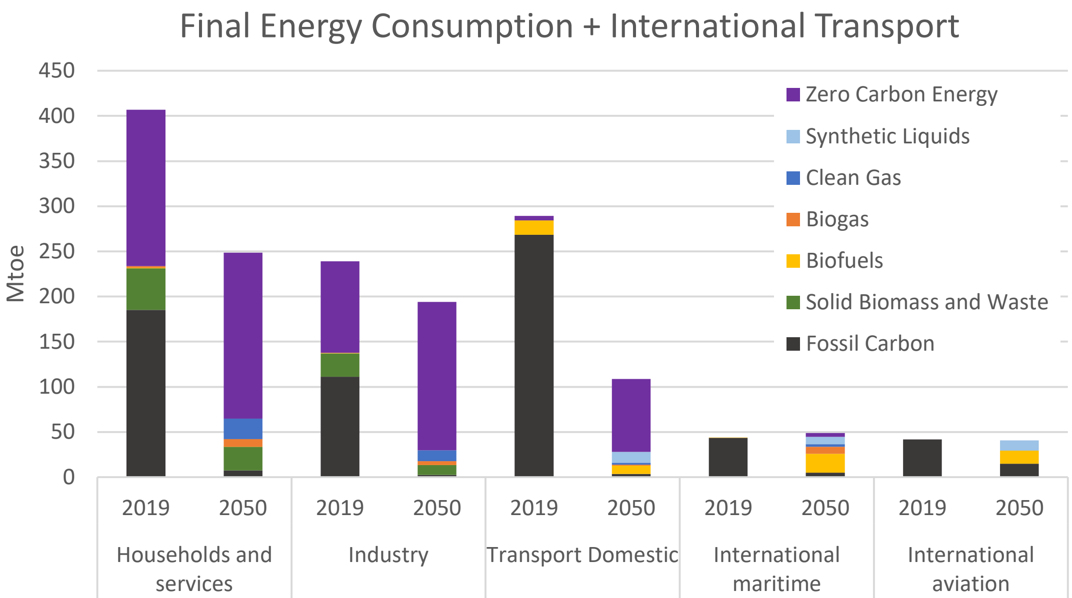
fuels and biomass) reduces by more than 65% in both scenario and the fossil fuels alone reduce by 85% in INDUS. Natural gas will represent the largest share of the residual fossil carbon. The capture of CO_2 and its transformation in fuel or material are energy intensive processes and their large scale deployment by 2050 will represent a significant share of the future EU energy needs.



Source: 2019: Eurostat and PRIMES model

Figure 2: Gross Available Energy in the European Union by 2050

In terms of final energy consumption, more use of electricity, driving also more energy efficiency, in sectors such as industry, road transport or households and services will allow for a drastic decrease of carbon energy consumption in these sectors. When carbon energy is still needed, biogenic sources of carbon or carbon captured directly from the atmosphere will replace fossil sources of carbon. All in all, by 2050, the share of carbon energy will drop (the final energy consumption including international transports decreases by two-thirds), with a virtual phase out of fossil carbon energy in all sectors except aviation.



Note: "Zero Carbon Energy" refers to energy forms that do not have any carbon-hydrogen bonds (electricity, heat, hydrogen); "Synthetic Liquids" refer to liquid fuels produced from carbon-free hydrogen and carbon atoms; "Clean Gas" refers to methane from carbon-free hydrogen and carbon atoms.

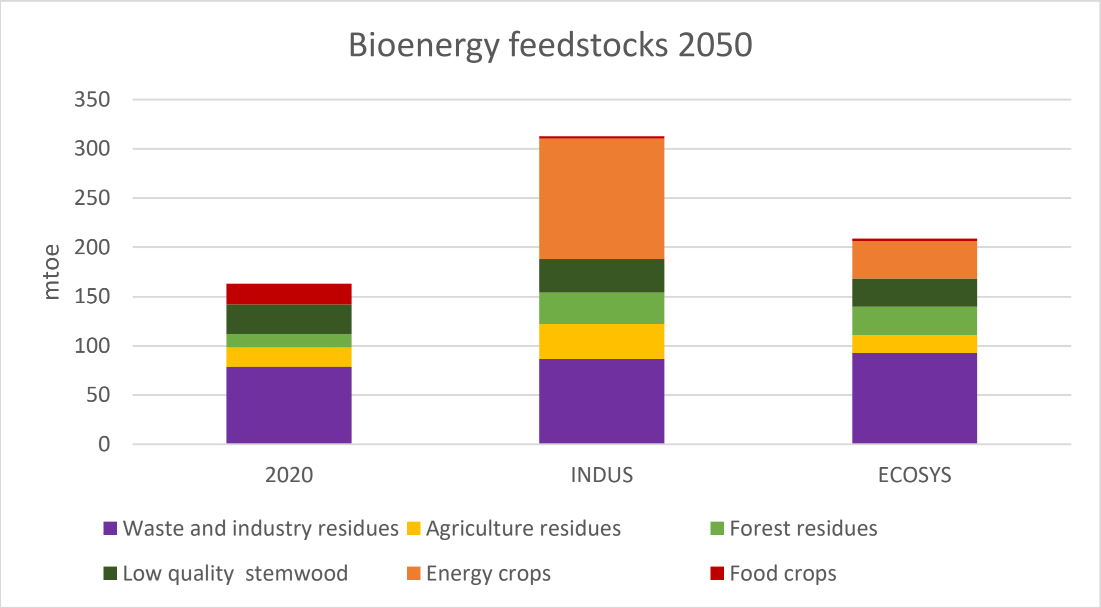
Source: 2019: Eurostat; 2050: PRIMES model

Figure 3: Sectoral energy consumption

Sustainable bioenergy

The substitution of fossil carbon with biogenic carbon should take place within the sustainable limits of natural resources availability. The modelling analysis indicates that the production of the biomass projected in the two scenarios could be achieved without detrimental impact on other environmental assets: however, the scale of the biomass demand is very significant, even in the case of ECOSYS, and would require strict measures allowing only sustainable management of forests and other land uses together with an overall reasonable deployment of energy crops in order to meet climate and biodiversity objectives.

In this context, a substantial share of the feedstock used to produce this bioenergy would come from the waste sector with an improvement in the industrial and municipal waste collection and from a better mobilisation of agriculture and forest residues accounting from sustainable local thresholds. The use of (low quality) stemwood for energy would not increase overtime and biogas or biofuels produced from food crops will be very marginal in EU by 2050. The optimisation of the sustainable exploitation of all these classical sources of biomass could supply just below 200 mtoe of feedstock for bioenergy production to the EU economy (INDUS). To meet the demand in bioenergy, fast growing energy crops are necessary to any EU climate neutral scenario with already 38 mtoe for ECOSYS and more than 100 mtoe for INDUS. The availability of land is another constraint for the development of energy crops, particularly important for INDUS, and a careful integrated assessment of all policies with land use implications is required to identify potential trade-offs. This is less a concern for ECOSYS because the lower demand in energy crops could be easily accommodated with the farmland released from the phase-out of first generation biofuels and the changes in food consumption assumed in this scenario.

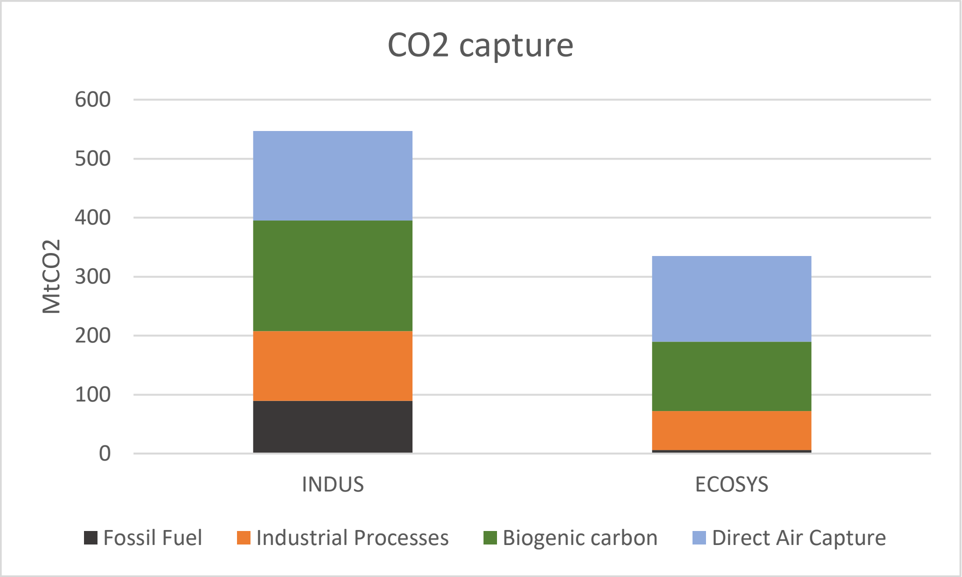


Source: PRIMES model

Figure 4: Production of Bioenergy by 2050 in the EU

<u>Industrial capture of CO_2 at large scale</u>

The achievement of the EU climate-neutrality objective will require the industrial carbon capture of at least 300 $MtCO_2$ for ECOSYS and more than 500 $MtCO_2$ for INDUS from various sources (power generation, industrial processes or directly from the air) for storage or to supply innovative routes to produce materials and fuels. By 2050, the uptake of renewable energies such as wind and solar in the power sector as well as innovation in industry will strongly reduce the use of fossil fuel and limit the CO_2 emitted from point source installation. Even though some process emissions will remain, an EU economy aiming at restoring sustainable carbon cycles will need to source most of its carbon directly from the air and from biogenic sources as long as it stays within acceptable boundaries without negative impact on biodiversity and other environmental assets.



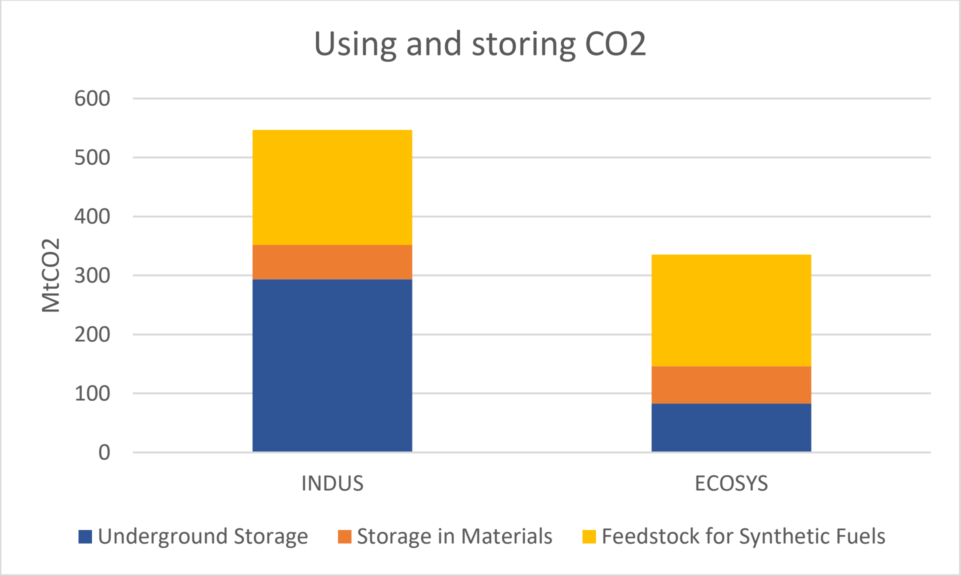
Source: PRIMES model

Figure 5: Capturing CO_2 from different sources by 2050

Besides fossil fuels and bioenergy, synthetic fuels represent a third type of carbon energy carriers. These fuels are also substitutes for fossil fuels and can alleviate the demand in bioenergy but their production, using CO_2 as feedstock and renewable and low-carbon hydrogen, requires a lot of electricity.

The CO_2 captured can also be stored either permanently in geological sites or in new long-lasting products to eventually provide industrial carbon removals when it is directly or indirectly captured from the atmosphere. They play a more important role in INDUS to neutralise the relatively high residual emissions in sectors such as agriculture and aviation.

In ECOSYS, industrial carbon storage has a more limited role. INDUS and ECOSYS use similar volumes of atmospheric and biogenic CO_2 to produce carbon neutral synthetic aviation fuels and carbon neutral synthetic gas for industrial heating.



Source: PRIMES model

Figure 6: Using and storing CO_2 by 2050.

The global pathway “Net Zero by 2050” laid out in the Roadmap from the International Energy Agency[16] sees a global 7.6 Gt CO_2 captured per year by 2050 with 95% of the CO2 stored permanently and 5% used for the production of synthetic fuels. About 2.4 Gt CO2 will be captured from the atmosphere through bioenergy with carbon capture and direct air capture.

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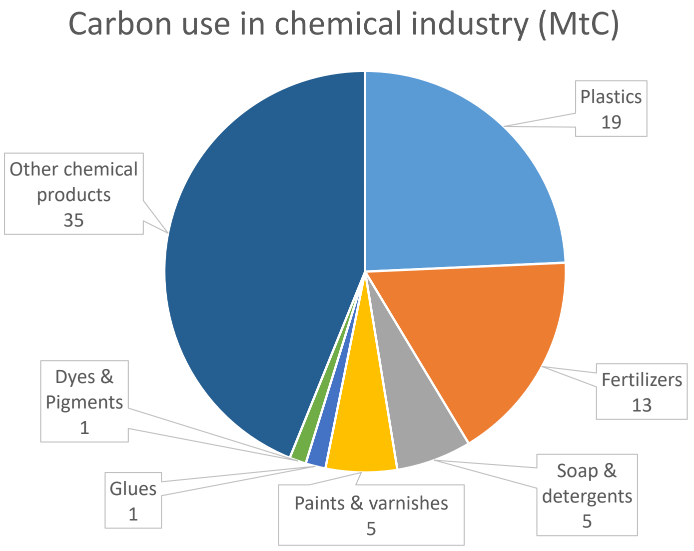
[16] IEA (2021), Net Zero by 2050 (link).

Which future for the chemical and plastic industry?

The Carbon Economy report[1] conducted by the Directorate for Research and Innovation of the European Commission reflects on the future of the chemical industry in Europe. In 2017, the chemical products manufactured in the EU embedded about 79 Mt of carbon in plastics, fertilizers, detergents, paints, glues and other organic chemicals. Most of the carbon used is from fossil origin (90%) and a small fraction is sourced from biomass (10%).



Direct emissions and the incineration of used products releases CO_2 in the atmosphere. For the chemical and material use, decarbonisation is not an option because organic chemistry fundamentally depends on carbon. Therefore, alternative sources of carbon are needed: carbon from sustainable biomass, from recycling and from CO_2 (CCU or direct air capture). A variety of parameters influence each of these sources of carbon with different technological readiness, profitability and acceptance levels.

Substitution of plastics with other materials

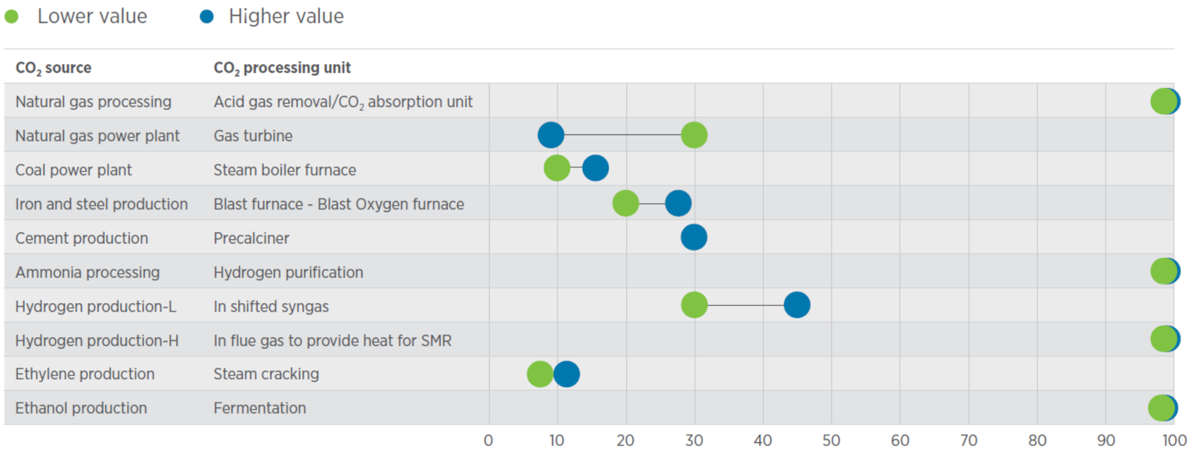
Plastics are synthetic materials with a wide range of properties. Therefore, they replaced other materials in a broad field of technical and everyday applications. The highest demand for plastics in the EU occurs for packaging (40%), building & construction (20%), and automotive (10%). Hence, substitution of plastics with other materials (or vice-versa) is possible, e.g. with glass or paper in the packaging sector or wood and mineral wool or wood fibres in the construction sector.

The broad range of properties make plastic beneficial for certain applications (e.g. their light weight and robustness is beneficial for packaging) while disadvantageous for others (e.g. littering from non-biodegradable plastics when disposed in nature). Therefore, the substitution of plastics with other materials is currently discussed in the public. Also, legislative measures are being implemented like the EU's single-use plastic ban. Environmental effects of the substitution of plastics with other materials strongly depend on the use case and on the properties and origins of the exchanged materials.

2.2. Industrial solutions to capture carbon

2.2.1. Capturing point source emissions

Capturing CO_2 from combustion in power and industry installations and from process emissions that would otherwise be released to the atmosphere is the easiest technological solution to capture CO_2. The reason is that CO_2 emissions in off-gases from combustion and process emissions have a higher CO_2 concentration (from 5% for gas-fired power plants to almost 100% in some processes such as fermentation, see also Figure 11) than ambient air (approximately 0.04%). Thereby, the process of capturing CO_2 becomes less energy intensive and less costly. In a climate-neutral EU[17], the combustion of fossil fuel will have decreased significantly and electricity generation from fossil fuels will become marginal.



Source: IRENA (2021)[18], based on Bains et al. (2017)[19]

Figure 7 : CO2 off-gas concentration of some industrial processes

There are four basic systems for capturing CO_2 from point sources, namely post-combustion, oxy-fuel combustion, pre-combustion and capture of pure CO_2 from industrial process streams. The most advanced and widely adopted capture processes are chemical absorption and physical separation; other technologies include absorption membranes and looping cycles such as chemical looping or calcium looping. Industrial CO_2 sources where capture processes can be deployed include chemicals production, iron & steel production, cement production and fuels production. Figure 12 provides indications on the maturity of technological solutions to capture CO2 from power generation and industrial processes.

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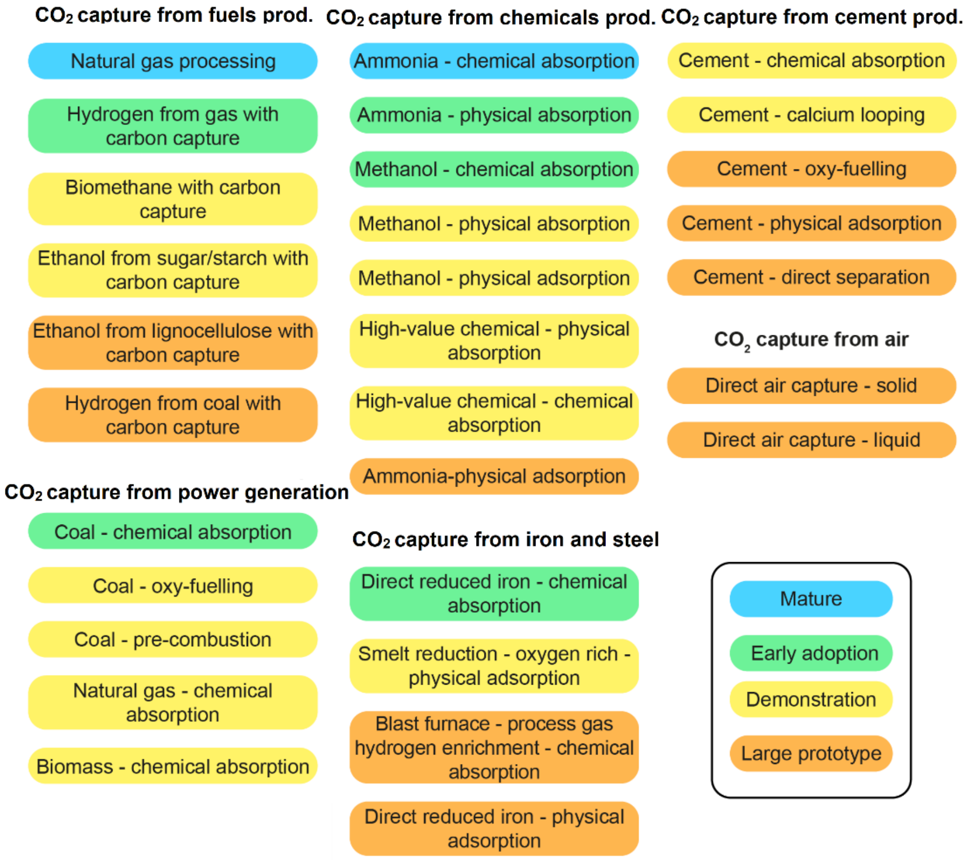
[17] see section 2.1

[18] IRENA (2021), Reaching zero with renewables - Capturing Carbon (link)

[19] Bains et al. (2017) CO2 capture from the industry sector (link)



Source: IEA 2020[20]

Figure 8: Maturity of CO2 capture solutions

Technical barriers to the deployment of CO_2 capture include solvent degradation of amines and the high demand in thermal energy[21]. Advanced solvents with reduced degradation are necessary to reduce capture costs, but have not been demonstrated at large-scale yet. A further issue of carbon capture is that even if they can come close, capture rates are often below 100%[22]. Thus, even if carbon capture is deployed, there are still remaining CO_2 emissions to the atmosphere.

BECCS (Bio-energy carbon capture and storage) is the combination of generating energy from biomass and carbon capture and storage. Apart from the feedstock being specifically bio-based, the technologies deployed for capturing, transporting and storing the CO_2 are the same as described in this chapter. The CO_2 for BECCS can stem from biological processes such as fermentation (e.g. for the production of biofuels) but also from the combustion of biomass for the generation of heat and power (see Figure 9).

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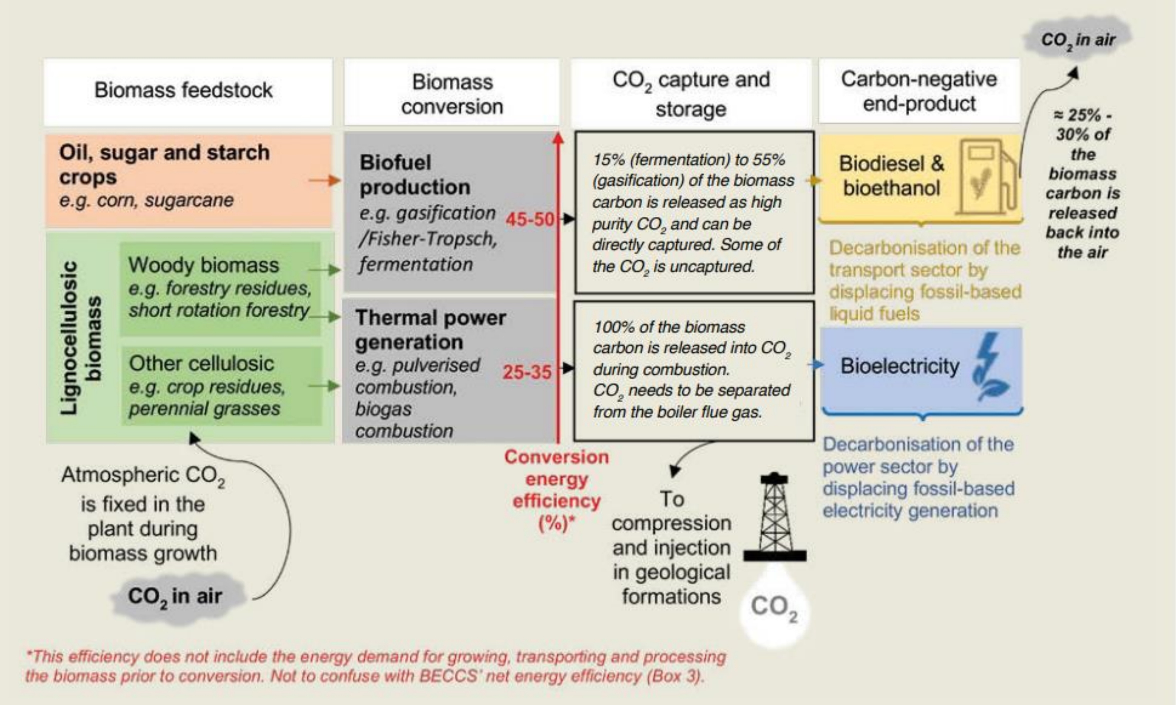
[20] IEA (2020), Special Report on Carbon Capture Utilisation and Storage (link).

[21] Global Status of CCS 2020 (link).

[22] IRENA (2021), Reaching zero with renewables - Capturing Carbon (link).



*This efficiency does not include the energy demand for growing, transporting and processing the biomass prior to conversion. Not to confuse with BECCS' net energy efficiency (Box 3).

Source: Fajardy et al. (2019)

Figure 9: Two examples of biomass conversion routes for BECCS: bioelectricity and biofuels

Whether BECCS can actually yield negative emissions, depends on the biomass feedstock but also on other factors such as biomass yield, fertiliser application, and biomass drying for high moisture biomass[23]. Other elements to consider are the transport and processing of the biomass. Even though plants take up CO_2 while they are growing, planting, growing, harvesting and transporting them requires energy which in turn causes emissions. Besides the impact of harvesting the biomass on the land carbon stocks, another important factor to consider is indirect land use change (ILUC), which has been widely discussed in the context of first generation biofuels: where pasture or agricultural land previously destined for food and feed markets is diverted to biofuel production, the non-fuel demand will still need to be satisfied either through intensification of current production or by bringing non-agricultural land into production elsewhere. The latter case constitutes indirect land-use change and when it involves the conversion of land with high carbon stock it can lead to significant greenhouse gas emissions. The IPCC special report on Climate Change and Land found that negative impacts on biodiversity and food security through land competition might arise if BECCS is deployed at global large-scale[24]. The availability of sustainable biomass is one of the major limiting factor for the deployment of BECCS that contributes to removing carbon from the atmosphere.

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[23] Fajardy et al. (2019), BECCS deployment: a reality check (link).

[24] IPCC Special Report on Climate Change and Land (2020) (link).

2.2.2. Direct air capture

Another option to capture CO_2 is to take it directly from the air, which is called direct air capture (DAC). The main challenge in this process is that the concentration of CO_2 in the ambient air is rather low (around 400ppm). The advantage of direct air capture is that it allows capturing CO_2 when and where there are no point sources.

DAC uses engineering processes relying on chemical capture to remove carbon dioxide (CO_2) directly from the atmosphere into a separating agent that is regenerated with heat, water, or both. The CO_2 is subsequently desorbed from the agent and released as a high purity stream. There are two main methods to capture CO_2 from the air:

- Liquid systems: the air passes through chemical solutions (e.g. a hydroxide solution), which removes the CO_2 and returns the rest of the air to the environment.

- Solid system: the air passes through filters composed of solid sorbents which chemically bind with CO_2.

The process to separate CO_2 from the other components of ambient air is either done through absorption or adsorption. The main disadvantage of these adsorption and absorption processes is that the regeneration of the sorbents requires large amounts of energy and thereby leads to high costs of direct air capture technologies. Further practical barriers include the need for an abundant supply of renewable energy. Even though DAC installations per se do not require a lot of space, the supply of renewable energy translates to around 2,000 km^2 of non-arable land that could be needed to remove 1 Gt of CO_2 net from the atmosphere[25]. Furthermore, the water input to different DAC technologies needs to be considered[26]. Capture technologies that use electrochemical processes to regenerate the sorbent are promising to reduce energy requirements for direct air capture and thereby cost. However, these processes are still nascent and not deployed at industrial scale.

2.3. Recycling carbon

The EU economy will still require carbon for its functioning in 2050 and beyond, for instance for the production of plastics, rubbers, chemicals and other advanced materials requiring carbon as a feedstock. A complete and well-functioning circular economy will minimize the end-of-life impact of these products by promoting their reuse, recycling and energy recovery. The bioeconomy will also have an important role to play in the construction sector by providing substitutes for conventional building materials able to store carbon for long periods of time. Virgin fossil carbon will be replaced by more sustainable streams of recycled carbon from waste, biomass and directly from the atmosphere to supply the organic chemistry processes for the synthesis of sustainable products and fuels. Combined with renewable energy these streams of carbon set the pathway for a climate-neutral economy in 2050.

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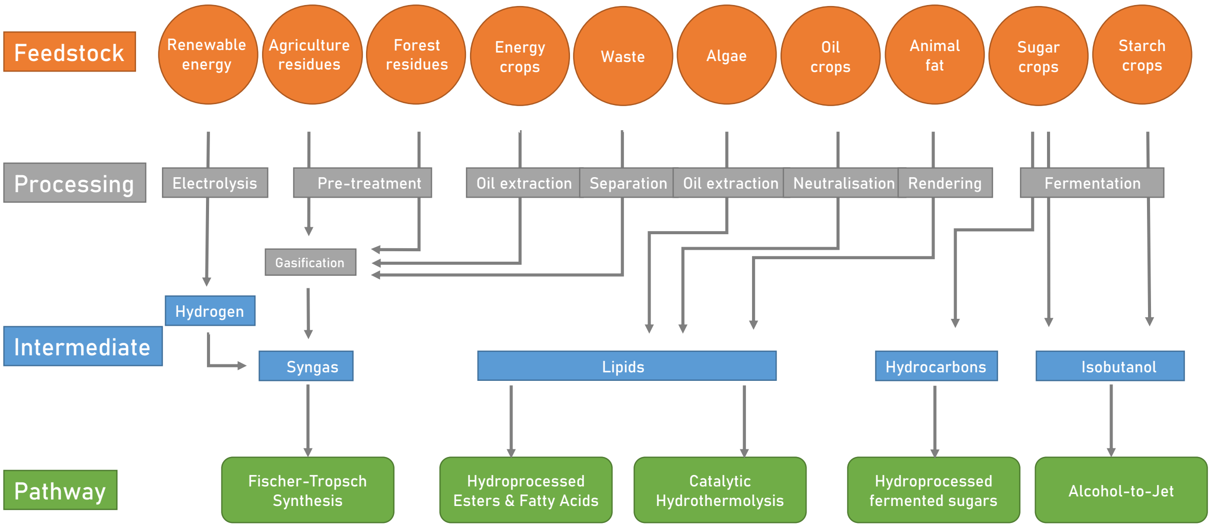
[25] Beuttler C. et al. (2019). The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions 1 (link).

[26] JRC factsheet on Direct Air Capture (link).

2.3.1. Sustainable carbon fuels

In a climate-neutral economy where electrification is the norm, hydrocarbon fuels will play a less important role. However, due to their high energy-density, liquid fuels and compressed gaseous fuels will still be required for some activities such as aviation and shipping. Since CO_2 from fuels in mobile applications is difficult to capture after combustion and to close the carbon cycle, fuels are needed that take up carbon when they are produced. With the phase-out of liquid and gaseous fuels from fossil origin and 1st generation biofuels, the focus will be on advanced biofuels[27], biogas, biomethane and synthetic fuels. See Figure 10 for production pathways of sustainable aviation fuels.



Source: Roland Berger Consulting[28]

Figure 10 Feedstocks and processes for sustainable aviation fuels

The biomass feedstock for these different processes can come from different sources. However, in a climate neutral and circular economy, the focus will lie on using wastes and residues for the production of biogas and biomethane[29]. Advanced biofuels are biofuels produced from feedstock stemming from wastes, residues and non-food crops[30]. These feedstocks are processed in a biorefinery to molecules that are similar to their fossil counterparts. Most of them can be grouped into bioethanol and biodiesel but also sustainable bio-based aviation fuels will play an important role in the future. As the availability of wastes and residues for the production of advanced biofuels is limited, novel feedstocks (e.g. Miscanthus) are being explored. However, the production of advanced biofuels from non-food crops is not yet established at industrial scale.

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[27] advanced biofuels' means biofuels that are produced from the feedstock listed in Part A of Annex IX of Directive 2018/2001 (link).

[28] Sustainable Aviation Fuels key for the future of air travel (link).

[29] see also Annex IX of Directive 2018/2001 (link).

[30] The rationale for using these feedstocks is to avoid direct and indirect land use change.

Synthetic fuels are fuels that do not have a fossil nor a biogenic origin, which is why they are also called renewable fuels of non-biological origin[31] when they are produced with renewable electricity. Synthetic fuels are produced from electricity that is used to convert water into hydrogen and oxygen through water electrolysis. There are different electrolysis technologies that can be distinguished according to the electrolyte used, namely alkaline electrolysis with a liquid electrolyte, proton exchange membrane (PEM) electrolysis with an acidic ionomer, and high-temperature steam electrolysis with a solid oxide as the electrolyte[32]. The main barrier for the uptake of hydrogen production via electrolysis is the relatively high price compared to hydrogen obtained from fossil fuels and the availability of sufficiently cheap renewable electricity. Hydrogen, which is a gas under normal conditions, can be converted into liquid fuels when it is brought into reaction with CO_2 or CO. Therefore, the resulting fuel can also be called a CCU fuel.

2.3.2. Materials and chemicals

In a climate neutral and circular economy, not only fuels but also other carbon-based materials of everyday life need a sustainable carbon source. These include plastics, chemicals, fertilisers, lubricants, pharmaceuticals, cosmetics and many more. The carbon source can either be biological through photosynthesis or technical through carbon capture. Thereby, the carbon cycle of these materials is closed and prevents the exploitation of finite natural resources.

Bio-based products

Increasing carbon stocks in (long-lasting) bio-based products is a way of storing carbon, with additional climate benefits by replacing GHG-intensive materials with bio-based materials. For example, it is estimated that 1 tonne of carbon in wood construction products substituting a non-wood construction product on average displaces emissions of approximately 2.1 tonnes of carbon or roughly 3.9 t CO_2 eq[33]; The carbon pool of bio-based products can act as a temporary reservoir that delays emissions of the renewable biogenic carbon to the atmosphere. The size of the bio-based products' carbon pool depends on the quantity of carbon stored in newly-produced products entering the pool, the duration of storage and their end of life options (landfilling, energy recovery, recycling, re-use).

The substitution effect of bio-based products can be uncertain and depends on a lot of variables such as the type of product being substituted, the energy-mix used in the production of the substituted product and the life cycle emissions of the bio-based material. Besides assessing the climate change mitigation potential through the temporary carbon storage and substitution effect, other environmental impact categories of bio-based products have to be taken into account such as toxicity, eutrophication, biodegradability, water and land use, acidification etc. These can be both positive and negative compared to the fossil- and mineral-based counterparts.

The production of biomass for bio-based products must come from a combination of sustainable sources from agriculture, animal farming, aquaculture and forestry production

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[31] renewable fuels of non-biological origin' means liquid and gaseous fuels the energy content of which is derived from renewable sources other than biomass.

[32] Smolinka T. et al. (2015) Hydrogen Production from Renewable Energies—Electrolyzer Technologies (link).

[33] Sathre R. et al (2010), Meta-analysis of greenhouse gas displacement factors of wood product substitution. (link).

while ensuring the maintenance and the enhancement of natural sink and preserving healthy ecosystems. Pathways that can both reduce greenhouse gas emissions in the short term while not damaging, or even improving, the condition of forest ecosystems include for example collecting fine wood debris within the limits of locally recommended thresholds or afforesting former agricultural land with mixed species plantations or with naturally regenerating forests[34]. Solutions based on circular economy principles applied to bio-based products such as the cascading principle[35] are also beneficial.

The building sector is overall responsible for about 36% of EU greenhouse gas emissions from energy[36], but is also one of the most promising sectors to foster the use of carbon-removing products and materials. Numerous approaches have been identified to store carbon in the built environment[37] and building as a carbon sink has become a key mitigation strategy promoted by several policy initiatives such as the Renovation Wave Strategy[38] and the new European Bauhaus initiative[39]. Using dynamic life-cycle analysis methodologies which allow explicit consideration of the timing of emissions and biogenic carbon uptake[40], climate benefits of wooden building have been estimated to 85 kgCO2e/m2 of gross floor area, in comparison with conventional buildings. While wood is one of the most popular construction materials that removes carbon, many other materials, traditional or innovative, can also contribute with various storage durations[41], e.g. cellulose fibre, cardboard and construction paper, bamboo, hemp, cork, straw, sheep wool, seaweed, herbaceous plants, composites from agriculture residues or from mycelium.

Carbon capture and utilisation products

Carbon Capture and Utilisation (CCU) refers to the use of carbon dioxide or carbon monoxide (e.g. from steel flue gases) in diverse production processes. These processes either directly use CO_2 such as in soft drinks or greenhouses or use it as a working fluid or solvent such as for enhanced hydrocarbon recovery (EHR). Other applications use CO_2 as a feedstock in chemical or biological technologies to convert it into value-added products such as polymers and primary chemicals such as ethylene and methanol, which are building blocks to produce a range of end-use chemicals (Figure 11). Urea production from ammonia and CO_2 is an example for an existing commercial application of CCU.

CO_2 can also be used in the production of building materials as feedstock in its constituents (i.e. cement and construction aggregates) via reaction between CO_2 and minerals or waste streams (e.g. concrete waste) to form carbonates. Another way that CO_2 can be used in building materials consists in adding CO_2 to concrete during curing, CO_2 emissions

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[34] Camia A. et al. (2021), The use of woody biomass for energy purposes in the EU (link)

[35] The cascading principle aims to achieve resource efficiency of biomass use through prioritising biomass material use to energy use wherever possible, increasing thus the amount of biomass available within the system.

[36] These figures refer to the use and operation of buildings, including indirect emissions in the power and heat sector, not their full life cycle. The embodied carbon in construction is estimated to account for about 10% of total yearly greenhouse gas emissions worldwide, see IRP, Resource Efficiency and Climate Change, 2020, and UN Environment Emissions Gap Report 2019.

[37] Churkina G. et al. (2020), Buildings as a global carbon sink (link).

[38] COM (2020) 662, Renovation Wave for Europe - greening our buildings, creating jobs, improving lives (link).

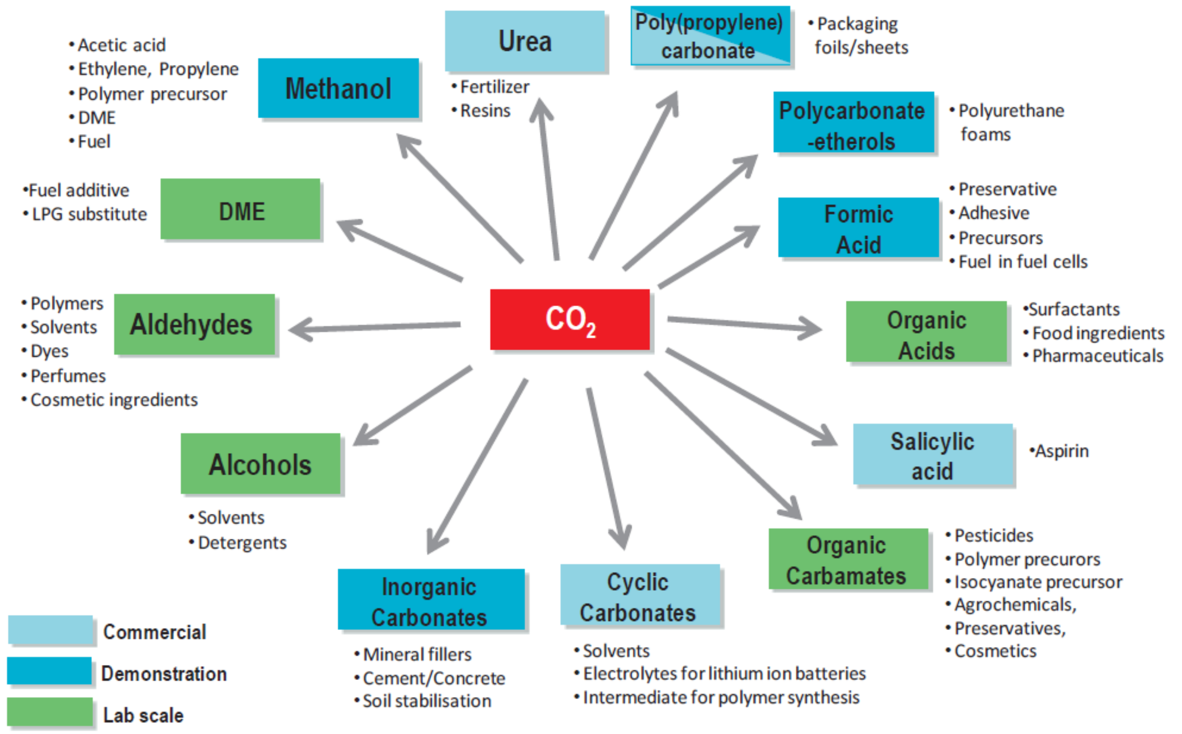
[39] New European Bauhaus (link).

[40] Hoxha E. et al. (2020), Biogenic carbon in buildings: A critical overview of LCA methods (link).

[41] Kuittinen et al. (2021), How can carbon be stored in the built environment? A review of potential options (link).

originating from calcination of carbonate rocks during the manufacture of cement (excl. energy-related emissions) can to a certain extent be taken up in the concrete by carbonation depending on availability of CO_2, moisture factors and exposure surface. This technique also reduces the quantity of cement needed to reach similar product strength requirements.

While CCU offers to close carbon cycles, most CCU technologies require significant amounts of energy[42] (notably the ones to produce hydrocarbon-like molecules similar to fuels). On the other hand there are several other CCU technologies which require less/no additional energy and can still prove useful products to replace fossil counterparts. For example, in the construction sector, replacing gravel and sand in concrete with synthetic aggregate that stores CO_2 could be achieved with very low energy input. Other interesting approaches are for example the production of polyols from CO_2, which is at an advanced TRL and can support the replacement of widely used fossil-based products such as polyurethanes. Other chemicals such as acetic and formic acid can also be produced with low energy requirement. Approaches for the bio-conversion of CO_2 could also support the production of chemicals and material string CO_2 with lower energy requirements.



Source: DECHMA 2017[43]

Figure 11: CO2 utilisation routes and status of deployment

The pyrolysis of organic matter such as biomass can result into biochar, a stable solid form of carbon (like charcoal) that is relatively resistant to decomposition and which can stabilise

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[42] JRC (2019), Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects (link).

[43] DECHMA (2017), Technical study on Low carbon energy and feedstock for the European chemical industry (link)

organic matter when added to soil as amendment. Biochar can improve the physico-chemical properties of soils and combine potentially many advantages with the long-term storage of carbon from biogenic origin in a product that improves the carbon sequestration capacity of soils as well as their water-holding capacities and their resilience to drought. However, the beneficial effect of biochar depends on the feedstock used for its production and on the soil and crop to which it is applied.

Example of projects funded by Horizon

The CATCO2NVERS, CO2SMOS and VIVALDI projects will deliver on advanced chemicals production from biogenic CO_2 from bio-based industries involving many EU countries.

The PyroCO2 project funded under Horizon 2020 will lead to thermophilic microbial conversion of CO_2 and renewable energy derived hydrogen into Acetone.

The ECO2Fuel project will implement a large scale low-temperature electrochemical CO_2 conversion to sustainable liquid fuels.

The Carbon4Pur project funded by Horizon Europe will turn waste gas CO_2 from plants into new products, such as plastics and will reduce the fossil feedstock required for plastic by 20%.

Example of projects funded by Bio-based Industry Joint Undertaking

The CIRCULAR BIOCARBON project turns carbon of complex organic urban waste streams into value-added products.

2.4. Transport and storage of CO_2

2.4.1. Transport of CO_2 and infrastructure requirements

Transport is the stage of carbon capture, utilisation or storage that links CO_2 sources with production or storage sites. There are four basic options for transporting CO_2: pipeline transport, waterborne transport, rail transport, and road transport.

In the context of long-distance movement of large quantities of CO_2, pipeline transport is part of current practice. Pipelines routinely carry large volumes of natural gas, oil, condensate and water over distances of thousands of kilometers, both on land and in the sea. CO_2 pipelines are not new: they extend over hundreds of kilometers worldwide. However, in Europe there are few CO_2 pipelines today. Liquefied natural gas and petroleum gases such as propane and butane are routinely transported by marine tankers on a large scale. CO_2 is transported in the same way, but on a small scale because of limited demand. Finally, liquefied gas can also be carried by rail and road tankers. The transport of CO_2 by ship and with an onshore or offshore pipeline is at TRL 9[44]. In conclusion, the challenges of CO_2 transport don't stem from the envisioned means for transport.

The challenges for a successful deployment are of economic and regulatory nature and often referred to as the chicken-and-egg problem. Due to the limited demand for CO_2 to be stored in geological formations or incorporated into materials and fuels, there is a lack of incentive for CO_2 emitters and potential direct air capture operators to capture CO_2. Consequently, there is also no business case for operators of a potential CO_2 infrastructure.

Integration of CCUS in high emission industrial hubs and clusters is expected to be the most cost-efficient approach. Sharing, eventually across borders, CO_2 transport, use and/or storage infrastructure will help with achieving economies of scale, and improving the business case.

2.4.2. Storage in geological reservoirs

Carbon storage is a technique for trapping carbon dioxide in a suitable storage site where it is injected into the ground. The Directive on the geological storage of CO_2[45] establishes a legal framework for the environmentally safe geological storage of CO_2. There are six basic options for the storage of CO_2:

- depleted oil and gas reservoirs,
- use of CO_2 in enhanced oil recovery,
- deep unused saline water-saturated reservoir rocks,
- deep un-mineable coal seams,
- use of CO_2 in enhanced coal bed methane recovery and
- other options such as oil shales and cavities.

Information and experience gained from the injection and storage of CO_2 from a large number of existing enhanced oil recovery (EOR) and acid gas projects, as well as from the Sleipner, Utgard and Snøhvit in Norway indicate that it is feasible to store CO_2 in geological formations as a climate mitigation option. Appropriately selected and managed geological reservoirs are very likely to retain over 99% of the sequestere CO_2 for longer than 100 years and likely to retain 99% of the sequestered CO_2 for longer than 1000 years[46].

CO_2 storage in depleted oil and gas reservoirs is very promising in some areas, because these structures are well known and significant infrastructures are already in place. Deep saline formations have by far the largest capacity for CO_2 storage and are much more widespread than other options. Early studies estimated a CO_2 storage capacity of nearly 500 $GtCO_{2,}$ even with certain countries excluded due to lack of data (for example Finland and Iceland)[47]. Storage capacity estimates for Europe stipulate that 95 $GtCO_2$ can be stored in deep saline aquifers, 20$GtCO_2$ in depleted hydrocarbon fields and 1 $GtCO_2$ in un-mineable coal beds[48]. Most of Europe's potential offshore CO_2 storage capacity is located in the North Sea.

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[44] Bui M. et al. (2018), Carbon capture and storage (CCS): the way forward (link).

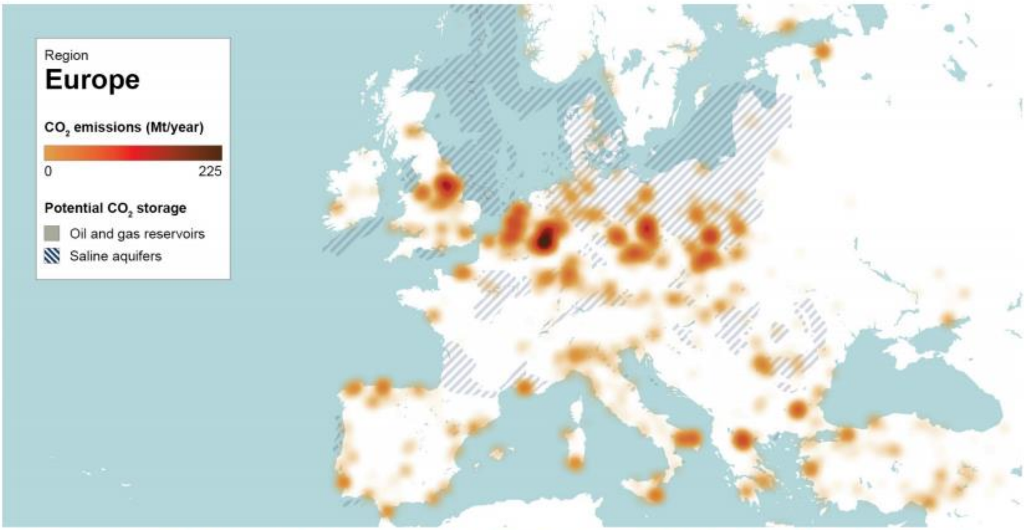
[45] Directive 2009/31/EC on the geological storage of carbon dioxide (link).

[46] IPCC (2005), Special Report on CCS by the Intergovernmental Panel on Climate Change (link).

[47] Kapetaki Z. et al. (2018), Technology development report on Carbon Capture Utilisation and Storage (CCUS) (link).

[48] EU GeoCapacity (2006) (link).

Norwegian offshore saline aquifers and depleted oil and gas fields might be able to store as much as 56 $GtCO_2$. Germany has an estimated storage capacity of around 20 Gt and storage capacity in the Netherlands is estimated between 2.7 Gt and 3.2 Gt.[49,50]



Source: CO_2 storage data based on CO2StoP (2020), European CO_2 storage database, CO_2 Storage Potential in Europe (CO2StoP).

Source: illustration from IEA (2020)[35] based on CO2Stop data[51]

Figure 12 Map of CO_2 sources and potential geological storage in Europe

2.4.3. Carbon mineralisation

Carbon mineralisation refers to chemical reactions between CO_2 and certain minerals to form solid carbonates and implies permanent storage of CO2[52]. This reaction occurs naturally during the weathering of rocks, a slow process that removes approximately 300 $MtCO_2$ per year at global level[53]. Research is conducted to accelerate the process at reasonable energy costs, this would give access to a large potential of efficient storage of CO_2 in a solid form, hence with lower risk of CO_2 reversal to the atmosphere.

Three main approaches can be considered to store CO_2 through carbon mineralisation:

- The injection of off-gases from combustion and process emissions with high CO_2 concentration in subsurface formations (e.g. basalts, peridotites or metamorphic rocks). The storage potential is large with however lot of variability in the efficiency of the mineralisation depending of the type of rocks and the local conditions.

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[49] IEA (2020) Energy Technology Perspective (link).

[50] Noordzeeloket, CO2-storage Current use and developments (link).

[51] CO2Stop European CO2 Storage database (link).

[52] Kapetaki Z.(2020), Carbon Capture Utilisation and Storage Technology Development Report (link).

[53] Beaulieu et al. 2012. High sensitivity of the continental-weathering carbon dioxide sink to future climate change (link).

- Carbon mineralisation can also produce materials, for instance synthetic aggregates to replace gravel and sand in concrete. It combines the advantage of producing aggregates with enhanced properties and storing CO_2 for the long-term in a solid form.
- Surficial carbonation through the mining and fine grinding of rocks to increase the reactive surface and enhance weathering. This approach can remove directly CO_2 from the atmosphere or can be applied to enriched fluxes of CO_2. Enhanced Weathering can be low cost when mine tailings or industrial waste are spread over warm and humid lands but the quantities are limited. If specific mining and transportation is necessary, the energy requirements and costs increase significantly. Pulverized silicate or carbonate can also be spread onto the sea surface, it is then referred to Ocean Alkalinity Enhancement. Many uncertainties remain in the assessment of risks and co-benefits related to a large scale deployment of Enhanced Weathering and Ocean Alkalinisation Enhancement approaches.
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<u>Examples of projects financed by the EU ETS Innovation Fund</u>

BECCS@STHLM is a BECCS project at the existing Combined Heat and Power-plant KVV8 at Värtaverket, Stockholm, Sweden. The project will capture and store large quantities of biogenic CO2 with a potential to avoid approximately 7.8 Mt CO2 over the first 10 years of operation.

Silverstone is a full-scale CO2 capture and basalt rock geological storage project at the Hellisheidi power station in Iceland.

Kairos@C will initiate a cross-border CCS value chain and kick-start the Antwerp@C project, which is developing a multi-modal transport infrastructure for CO2 in the port of Antwerp. By capturing and storing CO2 from two hydrogen plants, two ethylene oxide plants and one ammonia plant, the project will mitigate approximately 14.2 Mt CO2 over the first 10 years of operation.

The AGGREGACO2 project is a factory for aggregates based on accelerated carbonation processes fed by carbon captured at a refinery in Spain.

3. CARBON SEQUESTRATION IN EU ECOSYSTEMS

Forests and agroecosystems (cropland and grassland) dominate the 4.1 million km^2 of EU land area and each of them covers approximately 40% of the EU area[54]. Wetlands, heathlands and shrubs, sparsely vegetated lands (beaches, dunes, rocky areas in mountains), rivers and lakes are the other types of terrestrial ecosystems shaping the EU landscape. Marine ecosystems are the EU's most extensive ecosystem type covering about 6 million km^2. Ecosystems are dynamic complexes of plant, animal and microorganism communities and their non-living environment, interacting as a functional unit. They provide a large range of economic, social, environmental, cultural and other services benefiting people such as carbon sequestration and storage but also pollination, the provision of food, timber and clean air, water filtration or nature-based recreation. Climate change affects ecosystems through droughts, flooding and wildfires, while the loss and unsustainable use of ecosystems are in turn drivers of climate change. Global warming and biodiversity loss are two major threats of the 21th century that the European Green Deal aims to address by developing synergies between climate and biodiversity policies and ensuring that action taken on one side does not worsen the situation elsewhere.

3.1. Terrestrial ecosystems

3.1.1. State of play and projections

The carbon fluxes related to terrestrial ecosystems are reported in the LULUCF sector of the EU GHG inventory. They result in net GHG removals of -250 $MtCO_{2eq}$ in 2019, i.e. the amount of carbon sequestered from the atmosphere is larger than the amount of GHG emissions which is released back into the atmosphere. Not all ecosystems contribute equally, only forest ecosystems and the Harvested Wood Products categories that store carbon and delay emission beyond the life time of trees, provide a combined total of -400 MtCO2eq net removals[55]. Agroecosystems are the largest source of emissions (in particular from organic soils), followed by wetlands and artificialized soils through urban expansion. CO_2 emissions due to the combustion of biomass for energy are also captured under the LULUCF sector (when and where the biomass is harvested).

The 2021 EU GHG inventory[56] shows a declining trend in net LULUCF removals over the last decade, largely driven by the situation in forest ecosystems. Between 2013 and 2019, the quantity of CO_2 removed from the atmosphere by forests decreased by 20% from -420 $MtCO_{2eq}$ to -330 $MtCO_{2eq}$ despite a slight increase in EU forest area during these same years (the European forest area is today at its largest for at least the last 400 years after reaching its lowest around the year 1850[57]). This decline in carbon removals is driven by a mix of factors, including an increase in wood demand, an increasing share of forests reaching maturity in terms of production management, and an increase in natural disturbances such as insect infestations, storms, droughts and forest fires. Because of the long lead time of forest processes, the present state of European forests is influenced by management practices that took place decades to centuries ago. For this same reason, swift action is required to invest today in carbon farming with a long term perspective that can benefit ecosystems not only for

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[54] EUROSTAT Land cover overview by NUTS 2 regions (link).

[55] Grassi G. et al. (2021), Brief on the role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution (link).

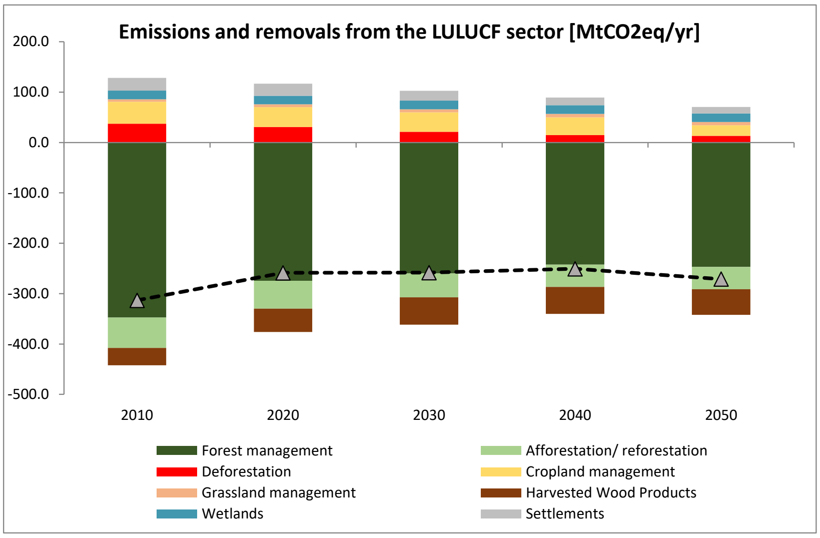
[56] National Inventory Submissions 2021 = UNFCCC (link).

[57] McGrath M. J. et al. (2015). Reconstructing European forest management from 1600 to 2010 (link).

the coming years but also for the coming decades or centuries. More detailed information related to Member States GHG inventories submission of 2021 is provided in annex.

A Forest sink projected to decline without specific action

Modelling analyses conducted on scenarios allowing the EU to be climate neutral by 2050 show that the declining trend of EU forests capacity to remove carbon from the atmosphere will continue in the next decades if no action is taken to revert this trend[58]. Without specific intervention (i.e. management), forest systems move over the long term towards a balanced state, with a likely decrease in increment and an increase in mortality, and an upper limit to the carbon stock present in above ground biomass and a limited carbon sink. The long-term projections from the EU Reference Scenario 2020[59] show the EU Forest sink could continue to decrease by 6% between 2020 and 2050 and only an expansion of forest area and a reduction in agriculture soil emissions would make it possible to maintain the overall LULUCF sink.



Source: GLOBIOM model

Figure 13: Projections of EU LULUCF emissions and removals without specific action taken (2020 EU Reference Scenario)

Enhancing the European natural sink at a level allowing the overall EU economy to be climate-neutral by 2050 would require dedicated actions that go beyond business as usual practices. For forests, it means maintaining or intensifying the forest system imbalance towards net removals through increasing the forest area with reforestation or afforestation of non-forest land, the carbon density per hectare of forest with appropriate tree species, or through stimulating faster increment by optimising harvests and smarter management practices – in practice most likely a combination of all three. For agricultural soils, it means protecting and restoring carbon-rich ecosystems, adopting farming practices that increase the soil carbon pool, improve soil biological activity (including net productivity), decreasing nutrient and organic carbon losses from erosion and leaching, and increasing the humification efficiency.

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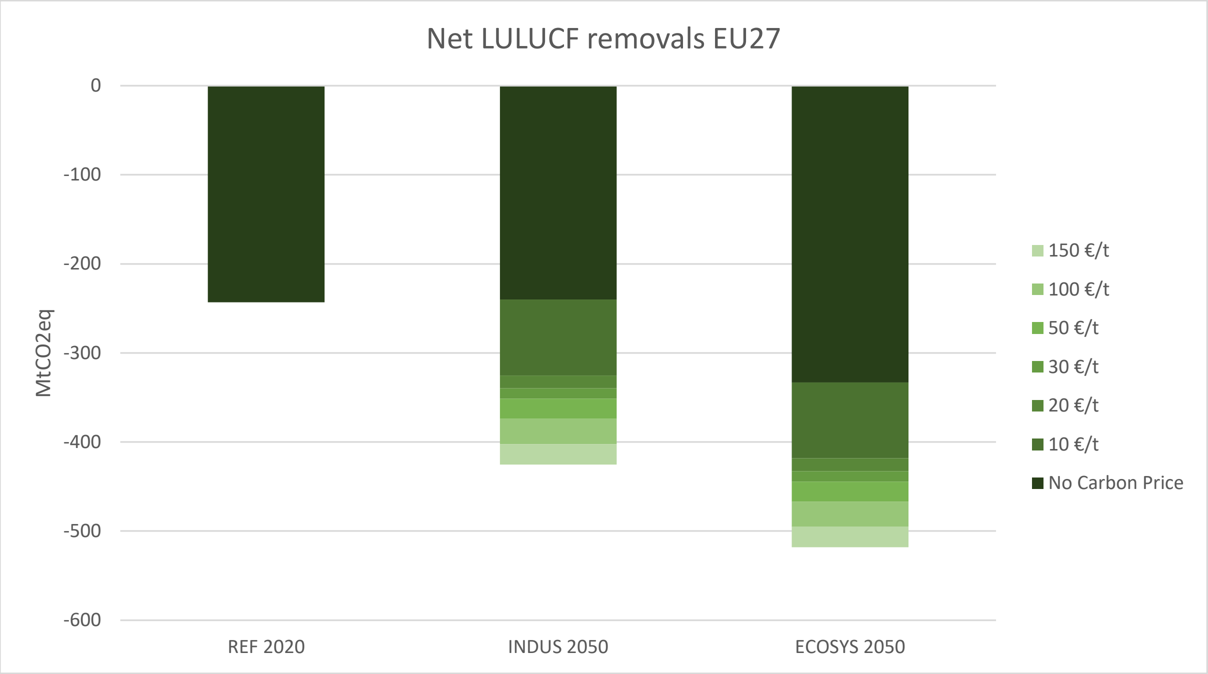
[58] COM (2018 773, A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy (link).

[59] EU Reference Scenario 2020 (link).

Figure 14 presents the LULUCF sink projected for the scenarios INDUS and ECOSYS (presented in section 2.1) at various carbon prices aiming to incentivise action in the sector. The potential at “No carbon price” corresponds to the level of net removals with no specific measures deployed to support the enhancement of carbon removals in ecosystems.

The “No carbon price” level of LULUCF sink for the scenario INDUS is lower than the removals projected in the EU Reference scenario 2020 due to the greater use of bioenergy. On the contrary, in ECOSYS the LULUCF sink benefits from a lower demand in bioenergy and from the release to natural vegetation of agriculture land driven by changes in the food consumption pattern of this demand driven scenario.

If appropriate supporting action is taken, the land-use modelling suggests a potential to increase the net removals of the LULUCF sector by about 185 Mt of additional CO_2 sequestration towards 2050 at a maximum marginal cost of EUR 150/tCO_2e. But the starting point matters, and removal potential can be higher or lower depending on lifestyle changes and bio-energy requirements impacting land use requirements.



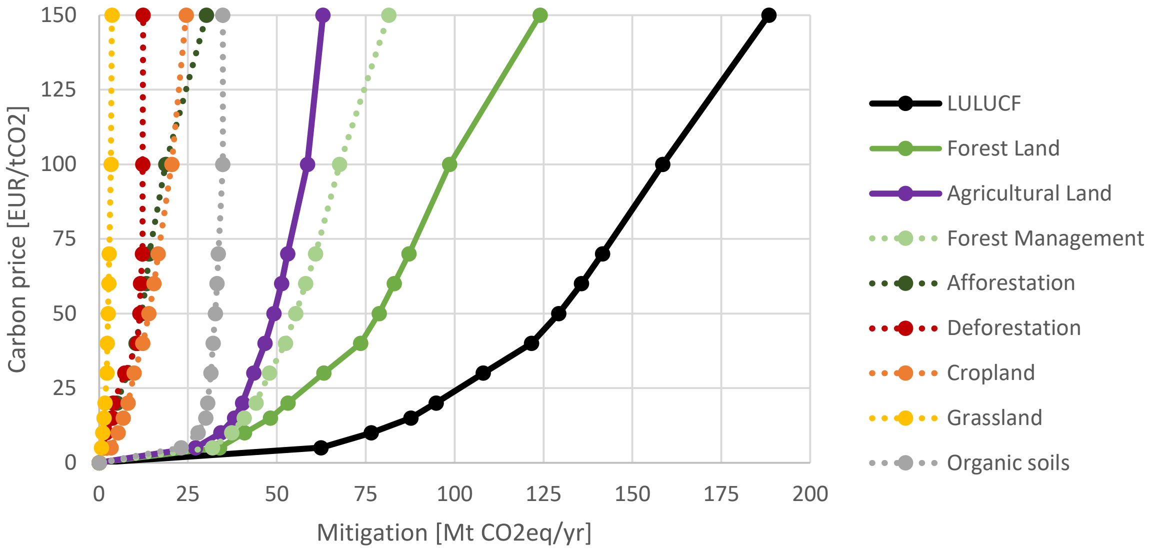
Source: GLOBIOM, CAPRI models

Figure 14: Potential for EU LULUCF sink enhancement at various carbon prices.

The marginal abatement cost curves by type of ecosystems from Figure 10 show that forest lands and agricultural lands have similar potentials when a carbon price is introduced to stimulate additional climate action. This underlines the importance of mitigation action and their significant potential on all major land uses. These estimates are rather conservative and focus on simpler and cheaper mitigation measures, not all land uses and mitigation actions were explicitly modelled.

Measures on Forest Management, such as change of rotation length, thinning and harvest intensity, have the highest mitigation impact for Forest Land; yet, maximum potentials around 40 MtCO_2eq are reached with carbon prices as low as 15 EUR/tCO_2. This is mainly because the carbon price only needs to compensate for the opportunity costs, e.g. foregone income due to a longer rotation length.

Restoring organic soils and, hence, preventing them from releasing large quantities of carbon into the atmosphere is among the most efficient solutions to reduce emissions in agriculture. Organic soils need to be drained to be used for crop production, and this drainage leads to aeration and subsequent decomposition of the peat, which results in a substantial release of CO_2 and N_2O emissions. Fallowing organic soils currently used for agriculture or as grasslands hold the same mitigation potential as measures for improved Forest Management. Very high mitigation levels at low carbon prices (e.g. 23 $MtCO_2eq$ for 5 EUR/tCO_2) soon reach a limit of 35 $MtCO_2eq$ because all land has been set aside.



Source: GLOBIOM, CAPRI models

Figure 15: Marginal abatement costs in the LULUCF sector for 2050 from the Reference scenario.

3.1.2. Carbon farming solutions to enhance ecosystems removals

The potential of carbon removals or emission reductions varies according to bioclimatic conditions and, furthermore, strongly depends on site conditions such as topography, soil type, and past and current land use practices. Although very site-dependent in application, the following carbon farming practices are the most effective examples of improved land management practices resulting in the increase of carbon sequestration in living biomass, dead organic matter and soils by enhancing carbon capture and/or reducing the release of carbon to the atmosphere:

- Afforestation, reforestation and improved forestry management: the planting of new trees, the restoration of degraded forests remove CO_2 from the atmosphere over many decades and possibly centuries, at the same time providing ecosystem services and enhancement of biodiversity. Changes in the management practices of existing forests have lower mitigation potentials for the same land area. However, implementing a change in forest management over large areas could result in a significant total additional mitigation potential;

- Agroforestry: land use management systems in which woody vegetation (trees or shrubs) are deliberately grown in combination with crop and/or animal production systems on the same land. Agroforestry has an important role in carbon sequestration, combining significant mitigation effects with co-benefits for ecosystems and biodiversity;
- Use of catch crops and cover crops: protecting soils, and enhancing soil organic carbon on degraded arable land;
- Targeted conversion of cropland to fallow or set-aside areas to permanent grassland;
- Restoration of peatlands and wetlands: raising the water table of drained peatlands or wetlands not only restores the hydrological balance of soils but also reduces oxidation of the existing carbon stock and increases the potential for carbon sequestration[60].

Carbon farming can have important co-benefits for biodiversity and the provision of ecosystem services with regard to air and water quality, it can ensure food security, and serve adaptation to climate change. An illustrative example is the rewetting of peatlands: stopping the agricultural use of drained peatlands and raising the water table of such lands has multiple benefits as it contributes to stabilise the carbon stocks in the soil, reduce CO_2 emissions and possibly achieve small CO_2 removals, improve biodiversity conservation, provide ecosystem services linked to water purification and help flood control. Trade-offs resulting from the loss of agricultural land can additionally be addressed through possible cropping under wet conditions (paludiculture) which is also beneficial for the provision of bio-feedstock. Table 1 qualitatively assesses the above mentioned mitigation actions against its area demands or availability, mitigation potential per unit area, total mitigation and short and long term mitigation benefits.

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[60] There is a balance between CO_2 removals and CH_4 emissions which is closely linked to the water table that needs to be regulated.

Table 1: Action on land, mitigation and benefits (XXX: High, XX: moderate, X: small)

Mitigation action	Mitigation per land unit	Benefits over 10 years	Benefits over 50+ years	Emission Reduction / Enhanced Removal
Afforestation/ Reforestation	XXX	X	XXX	Removal
Forest Management	X	XX	XX	Removal
Agroforestry	X	X	XX	Reduction and Removal
Mineral soils under agriculture land	X	X(X)	X	Reduction and Removal
Organic soils including peatland	XXX	XXX	XX	Reduction and Removal

A multitude of modelling studies exist to assess mitigation potentials. Careful analysis is needed to distinguish between technical potentials, e.g. maximum biophysical potential of a certain mitigation action, cost efficiency that is commonly linked to carbon prices, and societal acceptance of the actions. An additional caveat in many studies is the analysis of certain land uses or mitigation actions in isolation, i.e. disregarding or making specific assumptions on land competition and trade with regions outside the geographical domain.

Afforestation

Afforestation and Reforestation are among the most prominent land mitigation actions and imply a long-term land use change. In Europe, afforestation takes place mainly on marginal land or land that may not be used anymore for crop production. On the other hand, valuable arable land and peatlands, biodiverse grasslands, should not be afforested. Forests on organic soils hold a much lower mitigation potential, in some cases are even net GHG emitters due to continued drainage, and may hold lower value for biodiversity than it its original state.

Modelling[61] shows that trees planted in the period 2020-2030 would remove 4.5 tCO_2 ha^{-1} after 10 years and 7.8 t CO_2 ha^{-1} after 20 years of planting, which is broadly in line with the average EU mitigation potential of 5.8 tCO_2 ha^{-1} reported in the GHG inventory for land converted to forest land within the first 20 years. The total mitigation potential by afforestation is limited by the availability of land.

Most of afforestation in the EU takes place through natural or spontaneous forest growth. This however requires that land managers allow for trees to spread and grow, hence require a land management strategy of no action. Once a dense low story forest has developed land managers may intervene by pruning, thinning and species selection, assisting the development of taller trees with high value for the bioeconomy. In other cases, nature may develop forests through all successional stages.

Assisted afforestation by tree planting is currently rather limited but it ensures higher survival rates per seedlings and is therefore a useful means to complement natural forest growth. Afforestation by tree planting requires comparatively high initial investments. Soil preparation, seedling costs, cleaning, thinning and maintenance over the first 15 to 20 years range between 1,600 and 3,500 EUR/ha. Under specific circumstances such as for water scarcity investments may be even above 10,000 EUR/ha[62].

Forest management

Carbon friendly changes to management practices of existing forests are a powerful means to achieve additional mitigation. They do not result in any visual changes of the landscape (no land use change) but can have significant consequences for biodiversity, the environment and the socio-economy. Changes in the land management may imply additional actions, and hence operational costs that would commonly be attributed to forest maintenance budgets – or no actions with cost-savings; both resulting in possibly significant long term consequences.

For example, forest thinning is the main management practice influencing tree growth[63]. The action affects the growth and health of the forest, influences the prevalence of species and impact wood production and wood value. In an even-aged forestry system, it is carried out several times during the rotation cycle of a production forest. The thinning type (the method), intensity (how much is thinned) and frequency depends on the forest management objective, with the general rule of longer intervals as the forest grows older. More intensive thinning generally results in straight trunks of high diameter class and thus higher values of the timber once sold on the market. The extracted biomass is generally used as fuel wood or feedstock for bioenergy; medium yield classes could be used in the wood processing industry. Intensive

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[61] SWD(2021) 651 final. The 3 Billion Tree Planting Pledge For 2030 accompanying the New EU Forest Strategy for 2030 (link)

[62] Alliance Environment EEIG (2017), Evaluation study of the forestry measures under rural development (link)

[63] Ker G; et al. (2011), Thinning Practice A Silvicultural Guide (link)

thinning, may have adverse effects on biodiversity due to species selection, especially in even-aged silvicultural systems, and on soil disturbance due to the use of machinery. On the contrary, less thinning intensity or frequency – or in extreme cases no thinning – hold significant benefits for biodiversity and the environment in general, but often implies a low economic value of the wood when harvested. Thinning can also be a means to achieve socio-economic and environmental benefits at the same time. So called final crop thinning can transform even-aged production forest into continuous cover forests with two or more layers, thus an age-class distributions of multiple modes. This approach may be paired with planting multiple species that over time transform monoculture production systems into complex multispecies and multiage forest systems with significant co-benefits and resilience against climate change.

Protection of forests, especially of those of particular ecological value, is another strategy of increasing long-term carbon storage in forest ecosystems. Even though the sink function of old unmanaged forests tends towards zero as they mature and reach an equilibrium[64], forest protection offers short- to medium-term carbon sink benefits until the saturation point is reached, while providing high biodiversity value and increased forest resilience as the forest develops old-growth attributes[65,66].

The optimization of the rotation length to environmental and market conditions holds a significant potential for additional mitigation, while at the same time biomass demands for the bioeconomy need to be met. Such adjustments are comparatively cheap, addressing only the income foregone, significant mitigations can be achieved at low costs ranges (e.g. 15 EUR t-1 CO2). Additional mitigation by forest management is limited by the need to satisfy wood demand and hence increased carbon prices are in competition with local wood prices.

Changes in forest management have rather small mitigation benefits per hectare. On the other hand, a significant roll out can be expected due to the overall low cost for action, the need to adapt to changing climatic conditions, or long-term revenues and co-benefits with the environment. This combination results in the highest total mitigation benefit from changes in the practices for forest management compared to all other actions on land use as modelled in the LULUCF Impact Assessment[67].

Agroforestry

Agroforestry is the prime example of integrated land management and likely the mitigation action with benefits in all policy fields. At the same parcel and time Agroforestry delivers on:

- biodiversity and wider environmental agenda by increasing species richness, better water retention, reduced erosion and natural nutrient management

- climate mitigation and adaptation by increased CO_2 removals, better potentials to retain the stored carbon, nitrogen fixation, and lower risks for disturbances

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[64] Grassi G. et al. (2021), Brief on the role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution (link).

[65] O'Brien L. et al. (2021), Protecting old-growth forests in Europe A review of scientific evidence to inform policy implementation (link).

[66] Albrich K. et al. (2021) The long way back: Development of Central European mountain forests towards old-growth conditions after cessation of management (link).

[67] SWD (2021) 609, Impact Assessment revision LULUCF regulation (link).

- bioeconomy by providing biomass and fiber which may be converted in long-lasting bio-based products

- food sector by providing crops from arable land, ground for grazing or animal feed from grasslands and high value marketable products from fruit and nut trees

- energy by providing feedstock from low value biomass

There is a multitude of forms of agroforestry and a wide variety of its implementation across the world. Of relevance in the EU and at scale are silvoarable systems, i.e. the mix between trees and crops (frequently planted in alleys), and silvopasture systems, that is the mix between trees and permanent pasture that may be grazed or mowed for hay or silage. Other forms such as forest gardening, forest farming tree rows or hedges for property separation or windbreaks or riparian buffer strips are of less importance for carbon but high value of biodiversity and the environment. Agroforestry systems, once established or restored, will last for a long time. Maintenance will in most cases not require substantial management actions, hence operating costs are low.

The mitigation potential per hectare by agroforestry can be approximated from the mitigation by afforestation as reported in Member States greenhouse gas inventories. By assuming a 20% tree cover density on agriculture land, the additional mitigation potential of agroforestry practices ranges from 0.86 t CO2/ha to 1.4 t CO2/ha in the EU-27, depending on the carbon pools considered and the type of land (cropland or grassland). These estimates are broadly in line with other studies[68].

The total EU mitigation potential of agroforestry largely depends on the roll out of the mitigation action on a portion of the technically available land, requiring a deep transformation of today's cropland and grassland management and ecosystems. Beyond cost-effectiveness, land transformation could be restrained by biophysical barriers. For instance, agricultural land on organic soils should not be converted into Agroforestry systems which require to some extent machinery or foraging animals that could lead to soil disturbance and erosion. Instead, the water table should be increased to reduce decay of organic material, which eventually would affect the potential of tree growth and their health.

On the other hand, marginal land or land taken out of crop production, estimated to be up to 4.8 Mio ha between 2015 and 2030 in the EU[69], hold significant potential for low density tree planting. This tree planting could also increase the economic and environmental value of this land compared to its current state.

Mineral soils under Cropland and Grassland

In the EU, almost 99% of all croplands and 96% of all grasslands are located on mineral soils. Yet, while mineral soil carbon stock changes report emissions of 10 Mt CO_2 for cropland, grasslands on mineral soils remove 35 Mt CO_2 from the atmosphere[70]. This indicates that land use and land management practices highly influence the role of mineral soils as sources of net emissions or sinks of CO_2.

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[68] Roe et al (2021). Land-based measures to mitigate climate change: Potential and feasibility by country (link).

[69] Perpiña Castillo et al. (2021) Modelling agricultural land abandonment in a fine spatial resolution multi-level land-use model: An application for the EU (link).

[70] National Inventory Submissions 2021 UNFCCC (link)

There is a wealth of potential practices to increase soil organic carbon in mineral soils under agricultural use, including the conversion to permanent grassland, or rotation between cropland and grassland, crop residue management, planting cover crops to reduce erosion and fix nitrogen, crop rotations, reduced or no tillage, etc. While the conversion of cropland to grassland or forests holds the highest mitigation potential, it also implies a permanent conversion of the land use and implicitly a loss of its value for the land manager. Other changes in the practices maintain the cropland land use and can be applied in parallel or rotation. Yet, they require some extensification by reducing the soil disturbance or by temporally planting other crops.

In most Member States grassland systems sequester more CO_2 in mineral soils than they emit. Often, such systems also require significant management action with implications on carbon storage. Mowing and removals of biomass for hay making or silage, soil compaction by the use of heavy machinery or shallow tillage may reduce storage capacities. On the other hand, these practices are needed to maintain grassland landscapes and allow for limited economic benefits from this land. In many cases grazing animals may be preferred, but inadequate management can cause damages e.g. by soil compaction, overgrazing or erosion when roaming on steeper slopes.

A change in the land management practices requires a holistic view. Specific land use practices such as nitrogen fixing catch crops may bring about significant short term benefits for CO_2 removals while, if not properly controlled, N_2O emissions could also increase, resulting in net greenhouse gas emissions after a few decades[71]. While soils hold a significant carbon stock which can be increased, sequestration capacities will reach limits after a few decades, with the long-term challenge of ensuring permanence. Yet, today’s main challenge is the considerable roll out of actions that would be needed to achieve significant additional removals from mineral soils.

Organic soils including fallowing, peatland restoration and rewetting

Across all land uses organic soils represent approximately 5% of EU land area but the organic soil carbon pool reports emissions of just above 100 Mt CO_2, with hardly any changes in the period 1990-2019. Mitigation strategies will predominantly focus on carbon emission reduction from decaying organic material, in most cases due to drainage and intensive land use. The decrease or stop of emissions from carbon predominantly links to the level of anaerobic conditions in the organic soil layer, which is controlled by the water table. To allow more intensive land use practices, the water table has been lowered by drainage. Therefore, mitigation practices such as fallowing of organic soils under cropland and grassland aim at changing the land management practices to a no use scenario, thus avoiding the reason for drainage. Rewetting will accelerate the process of rising water tables, but in some cases requires technical deployment of measures which may be costly and invasive to the ecosystem. A decision on the most appropriate mitigation action and intensity thereof needs to me made on a case by case basis.

However, carbon benefits should not been assessed in isolation; instead it requires an assessment of the greenhouse gas balance, also taking into account emissions of CH_4 and N_2O. Increasing the water table will gradually lower emissions and eventually sequester carbon – in the end this is the mechanism how thick organic layers formed in the first place.

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[71] Lugato, E. et al. (2018), A. Mitigation potential of soil carbon management overestimated by neglecting N_2O emissions (link).

This net CO_2 removal from the atmosphere, however is countered by emissions from CH_4 and N_2O due to the anaerobic conditions in the soil. An optimal Total net greenhouse gas gas emissions can be minimised through a careful control of the optimal water table which can be achieved by various technical controls.

Besides carbon benefits and the greenhouse gas balance, action on organic soils needs a holistic view on co-benefits with the biodiversity and environment and potential economic implications. Most mitigation actions will require an extensification or stop of today’s land use practices. In many cases this will be beneficial for biodiversity, although some species from today’s land uses will not be able to cope with the new, generally wetter conditions. There are also co-benefits for water filtration and retention capacity and air quality. Yet, in a number of cases limited water availability could lead to short-term competition between rewetting and other uses. Economic losses by income foregone may be at least mitigated by opportunities for paludiculture or very extensive seasonal grazing land which can be paired with new business opportunities such as the marketing of carbon credits gained from reduced emissions and increased removals, bio-products from paludiculture or tourism.

3.2. Marine ecosystems

Carbon sequestration in European seas

The absorption of atmospheric carbon by marine phytoplankton is a precious ecosystem service. Although it is not possible to know the exact amount of carbon sequestered in EU waters, the amount of carbon sequestered can be approximated by estimating the primary production rates (PPR), i.e. the production of marine phytoplankton that captures atmospheric carbon when it grows.

Carbon sequestration varies substantially between the European Seas. The Marine Modelling Framework[72] estimate the annual amount of carbon uptake by phytoplankton in the Greater North Sea as well as in the Mediterranean Sea. Both seas differ substantially with respect to the amount of carbon captured per square meter, with the North Sea one being substantially higher due to the stronger growth of phytoplankton. Also within the regional seas, different gradients exist. For example, carbon sequestrations is stronger in the German and Danish waters compared to other parts of the North Sea. In the Mediterranean Sea, a West to East gradient occurs with highest primary production values in French and Spanish waters.

On the basis of carbon sequestration rates analysed in EU waters, the extrapolated total quantity of carbon absorbed in each exclusive economic zone (EEZ) in the Greater North Sea and jurisdictional water in the Mediterranean Sea (i.e. about 2.1 million km^2) amounts to 172.7 Mt/year, with 38.2 Mt/year (22.1%) coming from Italian waters. A wider extrapolation to the almost 6.1 million km^2 of EU waters suggests that EU-27 waters could be sequestering nearly 500 Mt per year. However, carbon sequestration varies significantly by sea and gradient and further work is required to obtain more accurate estimates.

Blue carbon farming

Blue carbon refers to carbon dioxide removed from the atmosphere by the world's ocean ecosystems, mostly phytoplankton, algae, macroalgae, mangroves, seagrasses meadows, and

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[72] Stips A. et al. (2015), Towards an integrated water modelling toolbox (link).

tidal marshes, through plant growth and the accumulation and burial of organic matter in the soil and sediment. In the oceans, carbon could be sequestered in the natural environments[73] or as a result of the micro- or macroalgae aquaculture or in the marine permaculture[74].

Of particular importance are coastal biogenic habitats, or blue carbon habitats (seagrass, mangrove, tidal marshes) with high intensity of biogenic carbon sequestration. It should be noted that other biogenic species are storing carbon not only organically but also through biomineralisation in shells and squelettons (coral, oysters reef, Honeycomb worm reefs).

Development of blue carbon strategies, initiatives, projects will lead to multiple co-benefits, like carbon fixing and storage, ocean health improvement (removal of excess nutrients causing eutrophication), improvement of ecosystem services (bringing back marine life), development of environmental services by creating new, green local jobs etc. Development of regenerative seaweed aquaculture in addition to the above, will bring to the market healthy food alternatives and low-carbon feed and other algae-origin products.

The main challenge is the degradation of blue carbon ecosystems leading to release of stored carbon into the atmosphere (could be up to 2% of global emissions) and due to reduced carbon fixing and storage capacity. For instance, decline in seagrass meadow area has been widespread and substantial over the last century with 19% of globally surveyed meadows lost since 1880. Whilst natural events, including outbreaks of disease and eruptions of grazing urchins enhanced by pollution and overfishing, can result in significant local seagrass decline, the major drivers of seagrass loss are anthropogenic: eutrophication, coastal development, land erosion (leading to enhanced sedimentation), mechanical damage due to dredging, seining, boat mooring, and anchoring.

It needs to be highlighted that the largest ecosystems by far acting as “biological carbon pump” sequestering carbon organically or in minerals are open seas: phytoplankton’s primary production, oceanic living biomass they feed and sedimentation of their shells. Worldwide, this transfers about 10 gigatonnes of carbon from the atmosphere to the deep ocean each year. Even small changes in the growth of phytoplankton may affect atmospheric carbon dioxide concentrations, which would feed back to global surface temperatures.

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[73] Globally macroalgae can sequester 0,17 Gt C yr^{-1} (2% of global emissions), 90% of which is transported to the deep ocean (link)

[74] Marine Permaculture is a form of mariculture that reflects the principles of permaculture by recreating seaweed forest habitat and other ecosystems in nearshore and offshore ocean environments