NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Who should use NETPs?

Managing expectations for NETP demand: Considerations for allocating carbon dioxide removals

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Executive Summary

Negative Emissions Technologies and Practices (NETPs) will be essential to remove and store carbon dioxide (CO_2) permanently and reach net-zero targets. Some sectors may not be able to completely abate all emissions. NETPs will play a crucial role in counterbalancing these so-called “residual emissions”.

Many NETPs are emerging technologies with a range of technological readiness, potential physical limitations, adverse impacts, and co-benefits. Hence, there is large uncertainty as to how much of the theoretical potential for each NETP to remove carbon permanently can be achieved in the next 30 years, and still respect physical limits in the natural environment, sustainable resource use and other planetary boundaries, as well as technological and societal constraints to the large-scale deployment of NETPs.

What is clear is that expectations on how much carbon removal can contribute to achieving net-zero goals needs to be managed. All sectors will need to pursue decarbonisation with maximum effort to minimise their emissions, independent of the rate at which NETP deployment develops. Our analysis of published data indicates that the availability of CDR from NETPs will be insufficient to fully counterbalance even one sector’s level of current emissions, despite rapid scale-up of available technologies. Here we examine the aviation and agriculture sectors as examples for expected CDR demand based on anticipated residual emissions in these sectors. Furthermore, our analysis implies that the supply of removals will certainly be insufficient for the current expected demand.

This raises the question of how to best allocate the scarce resource that CDR is and will remain for the foreseeable future. This report cannot provide a specific answer to the question of “Who should use NETPs?”, however it aims to highlight a range of questions and considerations that should be used to guide such decisions. Behind this question, there are two central components:

Firstly, **who should be responsible for deploying NETPs?** This pertains to the access to limited natural and financial resources needed to remove and store carbon efficiently and permanently using these Negative Emissions Technologies and Practices (NETPs):

- **Carbon Removal Efficiency:** What role should CDR efficiency play in the NETP allocation? Should NETPs be primarily allocated to the countries/regions/ecosystems where they can most effectively, and efficiently remove and store carbon permanently?
- **Sustainable and efficient natural resource utilisation:** Natural resource availability for sustainable biomass production and favourable geological locations make the natural resource use for CDR more efficient in some regions. What role should efficient and sustainable resource allocation play in decisions on NETP deployment? Should this be where sustainable development and planetary boundaries are best respected?
- **Financial resource availability:** To what degree, should the task of NETP deployment lie with those who have the highest ability to finance these?

Secondly, **who should be permitted to use the carbon removed by NETPs to counterbalance their emissions?** Some relevant considerations here for making this decision are:

- **Need:** Not all sectors will be as easy to decarbonise, and some residual emissions are likely to remain for a few sectors. Should these “hard-to-abate” sectors have priority or exclusive use of removals?
- **Moral responsibility:** Numerous countries have large historical GHG emissions compared to other countries. Should entities that have historical emissions foot the bill by paying for expensive CDR and take responsibility for their higher overall climate footprint?

- **Ability to pay:** NETPs that remove carbon permanently are often expensive and require new infrastructure to be built. Market-based principles of allocation risk that wealthy sector demand would outprice other sectors that need removals to reach net-zero targets. How should entities with the ability to pay be allocated NETP use, if at all, without compromising other sectors?
- **Equitably:** Should NETPs be managed as a public good which acknowledges the overall societal benefit of reducing atmospheric CO_2 concentrations?

NETPs will need financing by either public, private funds, or a mix of both, nevertheless, the societal benefit should be clear. Various financial and regulatory mechanisms and instruments have been suggested as approaches to allocate removals and distribute financial benefits and burdens.

This report identifies some risks associated with these approaches that should also be considered in NETP allocation.

- **Market-based approach:** Price-driven outcomes are in principle economically efficient but may not adhere to principles of credible use of NETPs, unless there is at least partial regulation; Permanent removals would be concentrated among wealthy consumers or may favour use of low-quality removals, which may have shorter storage permanence. Rigorous standards for certification will be needed to ensure that minimum requirements for both environmental impacts and robust MRV are set, as well as clear assignment of storage liability.
- **Regulatory compliance:** Excessively lenient or strong targets may lead to economic inefficiencies – striking the right balance will be important. If targets are too high relative to available removals they may prove costly, diverting resources from other activities including emissions reduction. Conversely, weak targets may fail to achieve adequate action. Market based approaches can mitigate these risks. At the same time, regulatory approaches may fail to create adequate mechanisms to incentivise innovation to go beyond current standards. There is a further risk of weak regulatory design being insufficient in enforcing compliance and inadequate sanctions if targets are not met. This may lead to loss of credibility in NETP governance.
- **Partial regulatory compliance with market-based approach:** This option carries both the risks and benefits of both market-based and regulatory compliance allocation mechanisms. There is risk of economic inefficiencies, where fine-grained regulation could lead to poor resource allocation and risk mitigating opportunities. However, decision makers may retain discretion in decision-making and this can enable them to react flexibly for permitting in different sectors. Ultimately, a well-balanced combination of both is likely to be the best outcome.

Irrespective of the approach used to distribute their deployment and use, safeguards are needed to ensure that NETP allocation has a credible, verifiable, and overall reduction in atmospheric GHG concentrations and is understood as a societal benefit, and not an individual actor's responsibility. Here we provide a set of physical and social credibility principles that should be adhered to, to ensure responsible and fair utilisation of NETPs in future.

Key policy relevant messages

- **All sectors of the economy will need to either eliminate or reduce their emissions down to 'residual' levels.** The future availability of removals (~0.3 Gt CO_2 yr^{-1} globally from BECCS and DACCS combined by 2050 as a conservative estimate based on projected upscaling and anticipated technological bottlenecks) is highly unlikely to be enough to fully counterbalance the emissions of any individual sector's current levels of emissions (residual emissions ~3.8-5.9 Gt CO_2 eq yr^{-1}), or even a significant fraction of current fossil CO_2 emissions [1] (~38 Gt CO_2 yr^{-1}). Even with contributions from DACCS and BioCCS totalling 1.0 - 1.2

Gt CO_2 yr^{-1}, which appears to be close to the plausible maximum and would require very strong policy action to achieve, CDR into geological storage would be insufficient to balance the projected remaining emissions of N_2O (2.0-3.0 Gt CO_2 eq yr^{-1}). No single sector or activity should assume that it will not need to radically change and minimise its emissions.

- **NETP deployment will need strategic consideration to ensure efficiency of carbon removal, natural resource use, and economic efficiency. Not all removals are the same.** CDR efficiency will likely vary by location, e.g., due to different climate conditions that impact sink characteristics, varying availability of renewable energy, and reservoirs may saturate over time. As with the deployment of any climate mitigation measure, there will be regional considerations for competing demands on physical resources such as land area, biomass, fresh water, and it will be necessary to minimise the negative impact of these activities on the natural environment. Hence, deployment location, type and size are important considerations and potential barriers to the scale of CDR deployment. NETP deployment should demonstrate highly efficient and permanent CDR and account for both direct and indirect impacts of activities (cradle-to-grave accounting).

- **Mechanisms that allocate the limited availability of NETPs to users must align with principles of physical and social credibility.** It is not yet clear how NETPs will be shared and who will decide on this allocation. Each interested ‘user’ of NETPs will be identified by different needs, capacities, and motivation. We highlight here relevant aspects to contemplate for the deployment of NETPs and how these will be shared amongst users that could include: a need to counterbalance in hard-to-abate sectors, CDR efficiency and sustainable natural resource use, moral responsibility to address historical emissions, ability to pay, and the social equity of benefits and burdens.

- **Use of NETPs should generate a clear benefit to societies by ensuring counterbalancing of emissions is achieved at a system-level, rather than simply at the individual-level.** Mechanisms which expect individual actors to counterbalance their own emissions have a significantly higher risk of deterring achievable emission reductions and outcomes which are not equitable. The counterbalancing of emissions should be achieved by simultaneously minimising emissions and maximising the sustainable deployment of removals at a societal level, designing policy mechanisms with those separate objectives in mind. Deployment of removals should not be at the expense of planetary health, or societal prosperity and allocation to individual actors to counterbalance their emissions should be avoided due to risk of unfair distribution of benefits and burdens. Nevertheless, allocation of responsibility to individual actors may be necessary, for example in the case of inclusion of removals in an ETS.

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Introduction

Introduction to Net-Zero

The Paris Agreement[2] signed in 2015, establishes the political and global ambition to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century". This is more commonly understood as achieving "net-zero emissions".

The concept which underpins "net-zero" is well-established in the academic and scientific communities. The premise is that halting human disturbances of the climate system requires the stabilisation of atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHGs). This requires a balance between the quantity of GHGs being emitted to the atmosphere and the quantity of CO_2 removed from the atmosphere.

The Intergovernmental Panel on Climate Change (IPCC) is clear in saying that active carbon dioxide removal (CDR) is 'unavoidable' if the world seeks to reach net-zero and maintain global temperature increases below 1.5°C or 2°C. CDR will be necessary to accelerate net emission reductions in a first instance, then to counterbalance residual GHG emissions and achieve net-zero, and finally to remove more CO_2 from the atmosphere than GHGs are emitted and thereby drawdown global concentrations of GHGs. The quantity of CDR needed is dependent on the quantity of GHGs that are emitted to the atmosphere in the coming years and decades. However, there is no guarantee that a given 'need' for CDR deployment at large scales can realistically be met. This report seeks to explore how this likely imbalance between the 'demand' for CDR and the 'supply' of CDR can be managed, such that a balance between emissions and removals can be achieved at a global level.

The IPCC's most recent Assessment Report (AR6) elaborates on the necessity to achieve a balance between emissions and removals, specifying that this should be achieved by around 2050 for CO_2, and early in the second half of the century for all GHGs based on economically optimized projections. It has also further explored the topic of 'net-negative' emissions, whereby more CO_2 is removed from the atmosphere than GHGs are added to the atmosphere, implying that 'net-zero' is simply an intermediate target or temporary state of equilibrium to be reached before drawing down global concentrations of CO_2. With the ever-increasing likelihood of a so-called 'overshoot' of average global temperatures increases above 1.5°C or even 2°C compared to preindustrial times, the need for global net-negativity in the long-term becomes clearer.

A critical nuance worth emphasising is the need to counterbalance emissions of CO_2 as well as other greenhouse gases. Man-made CO_2 is the largest contributor to global warming since it represents the largest fraction of greenhouse gases emitted by human activities[3] and accumulates in the atmosphere much faster than it is naturally removed. However, other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) are also significant contributors to global warming[3]. It is expected that even with stringent measures to reduce emissions of those GHGs, a residual amount of non-CO_2 emissions could remain and would therefore need to be counterbalanced by an equivalent quantity of carbon dioxide removal[2].

In 2015, the global community agreed to strive towards the goal of globally reaching net-zero emissions of GHGs. This target is consistent with the climate science findings presented by the academic community. However, some countries have taken it upon themselves to apply this concept of 'net-zero' at the national level, or even at the regional level, such as in the EU's net-zero GHG target by 2050. While the intent is generally present as an image of leadership and ambition, the application of net-zero at a national level is an extrapolation of the global aim to reach net-zero and has at times been questioned by parts of the scientific community[4]. An extension of this is the application of the net-zero label to non-state entities, such as corporations or even products, which further dilutes the original meaning of the term. The French Agency for Sustainable Development (ADEME) argues that non-state entities should not make claims such as 'carbon neutral' or 'net-zero'[5].

Even though 'net-zero' is robustly backed by science as a state at which human interference of the climate system ceases to worsen, it represents only a single point in time as a transition between net positive emissions, and net negative, often decades in the future without offering clarity on the ways in which to achieve net-zero, nor the scales at which emissions are balanced by removals. For this reason, the term has often been identified as problematic or incomplete by virtue of its ambiguity[6]. Here we highlight three significant causes of this (unconstructive) ambiguity[a].

Firstly, the achievement of net-zero is conceptually possible with a large volume of emissions balanced by a corresponding volume of removals[b], just as much as it might be possible with a small volume of emissions balanced by correspondingly small volume of removals. The implication here is that the achievement of net-zero emissions could theoretically be understood as being equally about increasing the volume of removals as about decreasing volumes of emissions. In practice however, it will be significantly more important to reduce the volumes of emissions (currently at nearly 40 $GtCO_2$ yr^{-1} from fossil fuel use and land-use change[1]) since the availability of removals is likely to be substantially below this level (0.3 Gt CO_2 yr^{-1} from BECCS and DACCS combined, Section 2.2.3) and the timeline for the large-scale deployment of Negative Emissions Technologies and Practices (NETPs) to carry out carbon dioxide removal (CDR) is likely to be much slower than for large scale efforts to reduce emissions.

Secondly, in the absence of regular intermediary targets the pathway to reach net-zero can conceptually be met with little-to-no effort in the short- to medium-term, with an enormous ramp up in the years or months immediately preceding the targeted net zero date. At the same time, a net-zero pathway could see immediate mitigation and be just short of net-zero for years or decades before eventually achieving a balance between emissions and removals. Effectively, a net-zero target alone says nothing about the pathway towards that target, which in the context of minimising the impact of a cumulative greenhouse gas, is equally or perhaps even more important. Added to this is the possibility that emitting 1 tonne of CO_2 is likely to have a greater climate effect than removing 1 tonne of CO_2 from the atmosphere would mitigate[7]. Ultimately, the pathway of emission reductions will determine the cumulative emissions and, by extension, the climate impact.

Thirdly, the types of emissions that will be counterbalanced and the types of removals used to counterbalance those emissions is still unclear. As such, 1 Mt of fossil CO_2 emissions could theoretically be counterbalanced by 1 Mt of CO_2 temporarily stored in the land sink or permanently removed and stored geologically, despite these carbon reservoirs having vastly different characteristics, particularly in terms of their storage permanence and vulnerability to climate change itself. Therefore, a country could theoretically meet their net-zero target by balancing fossil long-lived GHG emissions with temporary carbon storage in vulnerable land sinks. Just as it may do so with permanent geological storage, or a combination of the two. At the same time, it is unclear how residual non-CO_2 emissions will be counterbalanced by CO_2 removal, even though these emissions are likely to remain the biggest contributor to continued global warming well into the second half of the century.

Net-zero targets alone demonstrate three critical ambiguities which allow them to be met in many different ways on paper, while ignoring the physical realities and necessities of the climate crisis. An effective net-zero target would need to clarify the pathway towards net-zero, the volumes of removals expected to be required by net-zero and the type of removals and accepted residual emissions which are expected by the target date.

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[a] Note: This does not include the EU's Net-Zero target which applies to the bloc as a whole (i.e., the EU's overall emissions must be matched by equivalent quantities of removals).

[b] Some scientific evidence suggests that 1 tonne of CO_2 emitted has a greater warming impact than the cooling effect of 1 tonne of CO_2 removed [7].

In practice, the extreme scenarios outlined above are somewhat unlikely, yet the ambiguity provided by the term net-zero leaves significant room to manoeuvre for entities who want to signal an intent to reach net-zero, even if they are not seriously committed to the short-term (or long-term) implications of trying to achieve such targets.

Several key guidelines are outlined in this paper with the above ambiguities in mind. One point is that for net-zero to be effective at achieving its purpose, any GHG emissions should be counterbalanced by a removal activity with an equivalent level of permanence, also known as "geological net-zero". For example, fossil emissions of CO_2 should be counterbalanced by a removal of CO_2 into permanent geological storage. The key difference with the "like-for-like" principle is that it is the storage permanence of the removal should counterbalance the residence time of the GHG in the atmosphere, rather that the origin of the emission. Another point is that emissions must be reduced to a sufficient extent as to be able to match the likely limited quantity of CO_2 being physically removed by the time we reach net-zero. Finally, the pathway to net-zero should also seek to avoid an overshoot of global temperature to the greatest extent possible, by maximising short-term efforts to cut emissions. This is because overshoot scenarios should not be considered interchangeable with non-overshoot scenarios even if they both attain the goal of Net-Zero.

This paper will first explore the ways in which the volume of removals is assumed to contribute, either explicitly or implicitly, to long-term climate mitigation plans. Then, there will be an assessment of the realistic supply of the different NETPs based on anticipated future technology upscaling, pointing to a significant excess in demand that is unlikely to be met. Next, the paper explores different approaches to benefit and burden allocation of a limited quantity of CDR. Finally, the paper concludes with policy recommendations on how to manage expectations on removals and how to design a governance framework which can facilitate the deployment of removals without diluting ambition to cut emissions in the first place.

1 Demand for NETPs

1.1 Drivers of NETP demand to meet net-zero targets

The fundamental physical purpose of NETPs is as atmospheric remediation: to reduce concentrations of atmospheric greenhouse gases so that our planet remains habitable for humans. In this sense, the use of NETPs is a global societal good, or public good — everyone benefits from the decreasing atmospheric greenhouse gases, just as everyone is harmed by their increase.

However, their physical potential is not necessarily the sole motivating factor to NETP deployment. Other aspects of deployment can have private costs and benefits, and these can be the driving factor of their deployment. For example, they may be used as a social-signalling tool (e.g., contribution claims) or as a disbursement of responsibility for climate damage (e.g., compensation claims)

In particular, the use of NETPs as compensation—that is, the assumption that NETPs can be used to balance emissions of greenhouse gases—and who, if anyone, should be allowed to use NETPs in this way, is contentious. This is related to the idea of "residual emissions" whereby one must determine which emitting activities are likely to remain unabated by the targeted net-zero date but are instead balanced with removals. A recent paper by Buck et al. finds that Annex I countries currently expect their residual emissions will remain at around 18% of their current emissions levels by their targeted net-zero date[8]. However, the question of what emissions are allowed to be defined as residual is inherently linked to questions of demand and values, necessity, and possibility[9]; what activities do we—as society or decision-makers—deem important enough not to forego despite the climate damage they cause? What emitting activities do we classify as being so important that we are willing to expend *additional* resources to remove their resulting GHG emissions and enable them to continue by the time we reach net-zero and thereafter?

Much of the media attention - and funding - surrounding CDR involves the use of removals as "carbon credits", or "carbon offsets"; both attention on how actors are trying to improve the quality of offsets available to use as a way to compensate for (mostly fossil) emissions of greenhouse gases, and attention on the failure of many offset schemes to fulfil their stated goals.

At the core of the issue of carbon offsets are two fundamental questions of equivalence:

- Under what conditions - if any - is CDR an equal and opposite climate action to the emission of greenhouse gases? That is, when can removals physically compensate for the climate damage done by emissions?
- Under what conditions - if any - can emissions be allowed to be classified as residual and CDR be used to compensate for them?

Removals as a form of moral compensation for climate damage can take one or more of the following forms:

1. compensation for climate damage done in the past.
2. compensation for ongoing climate damage.
3. compensation for climate damage intended or expected to be done in the future.

While the three forms can exist concurrently, they imply that actors view CDR as having different moral purposes, when taken in context of the actors' other climate action. Use of CDR must always be considered as part of a portfolio of climate action, and therefore the credible use of CDR requires considering CDR in the context of the actor's other actions. In particular, the motivation of the CDR user is revealed in part by whether and how aggressively they are pursuing emission reduction, as well as CDR. Here we define “CDR user” as the entity using removals (CDR) to counterbalance or compensate their past, present, or future emissions.

By using CDR to balance ongoing emissions without concurrent efforts to cut reductions[c], the user reveals:

- that they believe they are entitled to the resources required for the CDR e.g., because of their ability to pay.
- by the permanence of the CDR they choose, how much value they attribute to the well-being of future generations.
- that they believe damage and reparation to be both physically and morally equivalent.

1.1.1 Removals as a “licence to emit” for hard-to-abate sectors

One use of removals is for actors to justify their ongoing (or even growing) emissions of greenhouse gases, viewing removals as a "licence to emit". Essentially this is what has occurred in the absence of appropriate policy, where the majority of CDR on offer is sold on the voluntary carbon markets with very little to no regulation and often dubious claims of permanence and additionality, among other methodological issues[10,11].

Policy currently under development such as the Paris Agreement’s Article 6.4 mechanism and the EU’s Carbon Removal Certification Framework (CRCF), have led to suggestions of directly integrating permanent removals into the EU Emissions Trading Scheme (ETS)[12]. This use of removals implies they accept (at least tacitly) an equivalency between climate damage and climate reparation, even if a physical equivalency remains unclear. That is, by offsetting greenhouse gas emissions with removals, they have fully discharged their responsibility. In essence, this implies that NETPs can directly balance out emissions, despite potential temporal decoupling between the pulse of emissions and the removals, in particular before net-zero is reached. In the absence of

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[c] See more in this article: https://carbonmarketwatch.org/2023/09/27/daccs-evasion-how-green-policies-risk-enabling-fossil-fuel-giants-to-pollute-and-profit/

evidence, or even robust ways of achieving physical equivalence, it is problematic to assume that it is inherently possible to achieve.

Crucially, this stance places equal value on emissions reductions and removals, a stance often reflected in cost-optimised integrated assessment models that have heavy reliance on NETPs and are based on carbon fluxes (not stocks) and disregards differences between deployment timing and type of environmental and climate impacts[13,14]. However, this issue can be addressed in some respects, for example by specifying a renewal period for unit issue, using a multiplier for NETPs, and setting robust minimum standards for environmental co-benefits or minimisation of negative impacts.

1.1.2 Reparation of historical contributions to emissions

Carbon removal is also viewed as a way to remediate emissions from historical activities, whereby actors take responsibility for their past emissions. The focus here lies on reducing the current atmospheric CO_2 concentration by extracting already emitted carbon, rather than balancing the emissions from current or justifying future emitting activities. Hence, NETP use remains distinct from the conversation of reducing emissions. This aligns with separate targets for emissions and removals[15], with a recent example of separate target implementation being the SB308 amendment to the California Carbon Dioxide Removal Market Development Act[d], that includes the obligation to purchase negative emissions as a certain proportion of the greenhouse gas emissions for a given body.

There can be different ways of perceiving historical responsibility via different accounting approaches for national emissions, such as cumulative CO_2 emissions, per capita GHG emissions or consumption-based CO_2 emissions (D6.3, Tanzer et al. 2022[16]). Territorial accounting is the basis of Nationally Determined Contributions, where emissions from all sectors within a country (e.g., industrial, agricultural, forestry, waste and energy production) are calculated indirectly. In this sense, a consistent accounting approach for removals and emissions, thereby emissions reductions, is needed, even if these targets are clearly separated.

However, there is a temporal discrepancy between the time of emission and removal in this case, which has a non-negligible climate impact. What was emitted 50 or 100 years ago, has had a measurable contribution to climate warming and is missing recognition in this approach to allocation.

A question can also be raised as to the value of counterbalancing historical emissions while there are still contemporaneous emissions which require neutralisation.

1.1.3 Negative emissions as a co-benefit

Some activities may extract and store carbon from the atmosphere even if CDR is not the primary goal. These negative emissions happen as an ancillary impact of the activity and are mostly related to the fast carbon cycle, often having a high uncertainty related to the climate benefit of the removal and storage component of the activities.

One example is afforestation and reforestation, which impact the flows of carbon through terrestrial ecosystems and may in some cases also act as a net carbon sink for atmospheric CO_2. There may be other good reasons to conduct this activity, including restoration of biodiversity and soil health, improving soil quality, and enhancing erosion control. Here, CDR can be viewed as a co-benefit of the activity, rather than the increase in ecosystem resilience being a co-benefit to CDR. These terrestrial ecosystems have carbon flows that can be difficult to constrain with an acceptable level of uncertainty so that additional carbon removal and storage can be quantified and verified, that is, additionality can be proven. Carbon in above-ground biomass can be estimated by remote

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[d] For more information see: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202320240SB308

sensing with relatively high confidence, but below-ground carbon is more difficult to measure and has higher uncertainty in the pool quantification. At the same time, even with high confidence of monitoring, it can be particularly challenging to prevent or manage reversal events for short carbon cycle removals. The same issue of uncertainty also applies to Land Use, Land Use Change and Forestry (LULUCF) and thus, it is questionable if these types of activity need to be, or even should be, explicitly recognised and quantified for the purpose of CDR. Engineered and geological CDR storage processes that use e.g., carbon capture and storage (CCS) are not affected in this same way by natural environmental fluctuations.

1.2 Magnitude of expected NETP demand

Global estimates of the quantity of carbon removals necessary to meet net-zero targets are highly uncertain but remain substantial with 12 Gt CO_2 yr^{-1} residual emissions expected even in ambitious decarbonisation scenarios[8]. Even at national and supranational levels, future residual emissions, and by extension demand for removals, is also poorly defined. On evaluating the long-term strategies of the EU alone, we find there is a lack of clear understanding of removals and the role they will play in EU climate neutrality, both at the national and EU levels. The Commission's in-depth analysis[17] supporting the communication "Clean planet for all" - a long term vision for the EU, considers multiple scenarios that are net zero compliant by 2050. These scenarios account for negative carbon flows with unclear disaggregation between synthetic materials, fuels and geological storage of captured CO_2, ranging from 201-307 Mt in 2050. It appears from the modelling that some activities, such as producing synthetic materials with atmospheric/biogenic carbon, are assumed to qualify as removals when there are significant questions as to the permanence of those approaches. Given that most of the emissions stored permanently underground are modelled to be fossil emissions from industry, the Commission relies on short term storage to account for removals, which is not robust. Significant volumes of removals come from LULUCF sector. There is no difference among member states, with some independent long-term strategies (Austria and Cyprus) pointing to CCS and CCU as removals without clarifying the source and sink of carbon[18].

The modelling of the EU in this communication suggests that in 2050, LULUCF alone will account for 317 to 472 Mt of removals along net zero scenarios, representing 6-10% of EU baseline emissions in 1990[17]. Technological removals with geological storage such as Biomass conversion or Direct Air Capture with CCS (i.e. BioCCS and DACCS) on the other hand are projected to account for 80 to 298 Mt of removals, based on a range of scenarios and anticipated technological development. On a member state level, only France (95-115 Mt), Italy (65-85 Mt) and Slovakia (7-14 Mt) have explicit targets set aside for removals to meet climate neutrality. Many other member states look to balance out residual emissions with removals without a clear evaluation. Being able to identify exactly how many GHGs need to be removed should help to form a clear picture of the efforts undertaken thus far and needed from here on out.

The total amount of removals required as estimated by the Commission on an EU level was to be compared to the sum of individual member state estimates. To do so, the long-term strategies of all member states were evaluated and where possible, the estimated removals or residual emissions were summed. For those where the residual emissions were not mentioned, the volume was extrapolated from the emissions reduction target and net zero date (residual emissions would need to be balanced by removals at net zero date). Between these two levels, the cumulative national volume and the Commission estimate on an EU level, there is a difference of 248-320 Mt or around 5-6.5% of EU baseline emissions. Such deviations point to a lack of clarity in defining removals and a lack of robust methods for accounting for future demand for removals. It also points to a well-known issue within Integrated Assessment Models, whereby cost optimisation often results in large volumes of Bio-CCS being deployed as soon as it reaches cost parity with other types of energy generation. Land-based removals will likely be much more restricted for example, due to climate change impacts than projected in these models. To minimise the risk of models relying excessively on CDR to meet temperature targets, it is vital that future modelling efforts seek to disentangle the generation of removals from reductions of anthropogenic greenhouse gas emissions from the atmosphere, such that emissions are reduced to the greatest extent possible.

1.2.1 Total potential demand compared to current emissions

The current ability to deploy NETPs at scale is highly unlikely to be sufficient to counterbalance anything but a small fraction of current emissions. The IEA has recently updated its net-zero scenario[19], which includes a residual amount of fossil fuel use in the energy sector. This is balanced by removals (estimated at 1.7 Gt CO_2 yr^{-1} globally in the IEA net zero scenario). This excludes any residual emissions from agriculture and other land use. Hence, to achieve net-zero will require very large emissions reductions. This will require action across all sectors and activities.

Decarbonisation of all sectors should also remain the priority because it reduces the amount of greenhouse gases that are in the atmosphere compared with a case of no decarbonisation and thereby reduces the overall need for NETPs. On top of this, the deployment of NETPs often requires more use of resources and accompanying infrastructure compared to direct emission reductions. Even for sectors understood as being “hard-to-abate”, such as cement, decarbonisation options are usually cheaper and can utilise at least in part existing infrastructure and technology, such as retrofitting of carbon capture on point source emitters[20] rather than deploying a NETP to counterbalance all of the emissions. The analysis in the next section (Section 2) indicates that NETPs will be scarce, and that removals to permanent geological storage will be particularly scarce. This emphasises the need for emissions reductions to eliminate almost all emissions in almost all sectors.

Approaches to eliminating emissions mainly rely on replacing fossil fuels and the development of fully renewable energy systems and mainly fall into four categories:

- Reduced product demand and increased material efficiency
- Renewable energy deployment, energy efficiency and where possible, electrification with low carbon electricity, especially renewables
- Hydrogen, either as an energy carrier, feedstock or chemical reducing agent
- CCS with high capture rates and low or no upstream emissions

Almost all sectors have options for decarbonisation that will almost completely eliminate emissions. For example, the power sector can be almost entirely decarbonised, while other sectors – such as road transport, home heating, and some industrial activities – can rely on direct or indirect electrification to decarbonise. While in the past road transport had been seen as a challenging sector to decarbonise, electric vehicles now account for 14% of car sales globally[21], from less than 5% in 2020, with mandates to reach 100% in the 2030s in some jurisdictions, notably the EU. Vehicle manufacture will also need to use low carbon materials including low carbon steel to eliminate lifecycle emissions.[22]

There are also options for reducing emissions in iron and steel production, which accounts for about 8-11% of emissions from energy and industry globally, depending on the scope included[23,24]. The majority of these emissions are produced by metallurgical coal needed for the production, sintering iron ore and converting iron ore to iron by combining the oxygen in the iron oxide with carbon in the metallurgical coal to produce CO_2. These emissions can be avoided by, for example, using low-carbon hydrogen as a reducing agent to produce direct reduced iron (DRI) and using electric arc furnaces to produce steel. Even though this method of decarbonising steel is constrained in scale at present due to the limited availability of low-carbon hydrogen and high quality iron ore, some steelmakers have the resources available to switch to DRI steelmaking with hydrogen and produce low-carbon steel. The HYBRIT DRI project in Sweden[e] is an example of such steelmaking and is due to begin producing from 2025.

Bringing almost all sectors' emissions down to almost zero within the necessary timeline will of course remain a significant endeavour. However, it is important to stress that these efforts must be maximised to increase the chances that the deployment of NETPs can one day be large enough to counterbalance the remaining residual GHG emissions.

1.2.2 Residual emissions and the need for NETPs

Currently there is no collective agreement on when an emission can be considered "residual" as this is primarily a social and political question, rather than determined solely by physics or available technology. Relevant open questions include: What level of emissions will be defined as "residual"? Who gets to define residual emissions and on what basis?

There is a strong need to avoid the moral hazard and mitigation deterrence by pre-emptively labelling any emission as residual. Therefore, decarbonisation options need full exploitation and effort in the coming decades.

Realistically, there will still be requirements for some NETPs to balance remaining emissions that are technically or socially infeasible[9] to fully eliminate. This may be when[25]:

- Emissions are economically justified because abatement is prohibitively expensive.
- The emitting activity has a significant social and political license to operate.
- There are no technically available abatement options.

From this perspective, residual emissions in most sectors are likely to be determined on a case-by-case basis, with two significant (potential) exceptions of the agriculture and aviation sectors. The following sections of this report briefly consider each of these.

1.2.3 Estimated future demand in hard-to-abate sectors: Aviation

The aviation sector poses unique challenges for decarbonisation, because of the limited availability of alternatives to burning liquid hydrocarbon aviation fuels. The sector is consequently expected to be a major source of demand for NETPs, including carbon negative biofuels or biofuels produced with sufficient BioCCS in their manufacture.

Aviation emissions are material and growing. In 2019, CO_2 emissions from aviation were approximately 1 Gt CO_2eq yr^{-1}, around 2.5% of emissions from energy and industry[26]. This total excludes any adjustment to recognise non-CO_2 climate effects, especially NO_x and contrails, which could approximately double the climate effect.

Empirical evidence from the recent COVID-19 pandemic show that emissions from this sector can be reduced rapidly by reducing demand. During the global pandemic, air traffic, and hence emissions, fell sharply to about half 2019 in very short period. However, demand for aviation has since returned to pre-pandemic levels[27,28] and is expected to continue to rise into the long term. This increase in passengers is expected to lead to increasing CO_2 emissions on current trends.

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[e] See https://www.hybritdevelopment.se/en/ for further information

Table 1 shows estimates of future emissions in the absence of action from various sources. It includes estimates based on simple extrapolation of historical trends and allowing for the effect of the COVID-19 pandemic[f].

Table 1 Estimates of business-as-usual emissions from aviation in 2050

	Expected CO_2 emissions from aviation in 2050 in the absence of action to decarbonise (Gt CO_2eq yr^{-1})
Current emissions (2019)	*1.0*
IATA[29]	1.8
McKinsey[30]	2.0
Estimates based on extrapolation of historic rates	1.8

Potential for pricing emissions to reduce demand

The inclusion of an adequate carbon price in aviation could internalise the climate effect and substantially raise the costs of air transport. By 2050, marginal abatement costs in aviation may be set by the cost of removals by DACCS. Carbon prices should reflect these costs to give economically efficient prices. We have estimated cost of in 2050 is expected to be \$350/tCO_2 [g], (€318/tCO_2), about 14% above the central value of €280/ tCO_2 in NEGEM's expert solicitation, but well within the range of uncertainty and variation between projects. Such a price could be realised, for example, under an ETS including aviation or as a tax on jet kerosene.

There is no reliable evidence from past experience to indicate what the effect on demand would be if such relatively large price rises were imposed on a sustained and widespread basis. Responses would depend in part on the availability of substitutes including high speed rail and electronic communications. However, the effect seems likely to be substantial, and could limit the growth of emissions. Indicatively, based on past industry-led studies of price elasticities[31], demand may be reduced by a quarter to a third.

However, large increases in the price of flying appear likely to meet significant opposition. Aviation emissions have been largely unpriced to date. There is no international tax on jet kerosene, and only limited inclusion of aviation in emissions trading systems to date. The current CORSIA offsetting system is ineffective in imposing adequate carbon prices, with prices typically in the range[32,33] \$3-5/tCO_2 and compensates fossil emissions with land removals. Furthermore, the high-altitude impacts would need counterbalancing by CDR even if aviation was only using Sustainable Aviation Fuels. Attempts to extend carbon taxes to international aviation or to include international flights in the EUETS have met with strong resistance. There is also evidence of reluctance of consumers to pay substantially more.

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[f] Our modelling estimates are broadly consistent with the long term historic trend of global aviation emissions growing slightly less rapidly than GDP. The table shows emissions projected to slightly less than double between 2019 and 2050. The OECD forecasts world GDP to double over the same period (2020 to 2050) from \$100 trillion to \$205 trillion (https://data.oecd.org/gdp/real-gdp-long-term-forecast.htm#indicator-chart). This compares with the period 1970 to 2019 when world GDP increased by a factor of just under five, while emissions grew by a factor of slightly less than four. However, in the 2010s aviation emissions grew more rapidly than GDP, and if this trend were to continue then emissions might be correspondingly higher in 2050 than we have projected.

[g] The costs of using power to liquids (e-fuels) would be greater than this, with carbon prices potentially correspondingly higher. For e-fuels to be carbon neutral their production requires DAC or biogenic CO_2 as the source for carbon, as well as minimal or zero emissions associated with the process. In addition to this there are the costs of making low carbon hydrogen, in addition to the costs of synthesising the liquid fuel. Carbon negative biofuels do not require DACCS, but face challenges require CCS for emissions during manufacture, and sustainable and carbon neutral biomass resources are likely to be scarce.

How might the aviation sector be decarbonised?

Different assessments of pathways for reducing emissions from aviation include broadly similar categories of options for decarbonisation, but with different mixes. Studies by IATA and McKinsey[30] illustrate this variation. They both show a substantial role for Sustainable Aviation Fuls (SAFs, including both biofuels and power to liquids), with IATA estimating 65% and McKinsey's prudent scenario 56% of emissions reduction[h]. Use of hydrogen or electric power are smaller in both projections, and very much smaller in a recent assessment by Bain[34][. McKinsey's estimate of 20% reductions from improved efficiency is larger than IATA's and closer to the Bain study. It is unclear how the studies treat the need for DAC to manufacture e-fuels. Under the IEA's updated net-zero scenarios around 80% of this remaining demand is met by biofuels and synthetic kerosene. Again, the sourcing of carbon and the treatment of DAC in the modelling in producing synfuels is unclear, which could potentially question the validity of the decarbonisation pathways identified in these reports.

These projections seem to exclude demand reductions due to carbon pricing, although the IEA's scenario includes behavioural change. However even with demand reductions, any use of aviation will need to be decarbonised, which means that supply side measures will continue to be necessary.

Implications of this analysis

Assessments of mixtures of emissions reductions are inevitably speculative, because they depend on technologies and policies that are not yet in place, as well as on a set of assumptions (e.g. sufficient availability of clean energy) which may not materialise. However, it may be possible (though challenging) to reduce 2050 emissions significantly from the level they would reach under a scenario with no action, using a combination of:

- Incorporation of full carbon costs in ticket prices
- Removal of public subsidies
- Greater use alternative fuels, such as electricity, hydrogen, and Sustainable Aviation Fuels (such as advanced biofuels and e-kerosene)

We estimate indicatively that there may be residual emissions of 0.8 - 1.4 Gt CO_2eq yr^{-1} in 2050. The upper end of this range represents just over a 20% reduction from a business-as-usual scenario. This is assumed to represent a combination of efficiency gains and demand management, with limited use of low carbon fuels. The lower end of this range represents approximately a 56% reduction from business as usual, reflecting further efficiency and demand management and greater use of low carbon fuels (excluding e-fuels).

Abating these remaining emissions would require some combination of DAC, including that to supply any e-fuels (power to liquids) or even greater use of the approaches described above. In allowing a contribution from biofuels it will be important to avoid double counting the available biofuels resource. The same biomass cannot be used both for two applications, for example both to make biofuels and burn to make electricity with CCS. Consequently, it is important to ensure that the total resource is not exceeded.

1.2.4 Estimated future demand in hard-to-abate sectors: Agriculture

The agriculture sector presents major challenges, not only due to the scale of anticipated residual emissions but also because agricultural activities emit other GHGs such as CH_4 and N_2O. These emissions are typically difficult to avoid because the sources such as emissions from ruminant animal digestive systems or storage of farm manure, are difficult to abate without reducing demand on animal and crop production for food supply. Furthermore, the sustainable transformation of the agricultural sector is inextricably linked with food security and is a deeply politically charged discussion, especially at the EU level.

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[h] This figure is adjusted to a total that excludes efficiency improvements on existing trends.

Current emissions of N_2O from agriculture worldwide are large (~2.3 Gt CO_2 eq yr^{-1} in 2020[i]) and have increased steadily since the 1990s[35]. More recently a decrease in emissions has been measured by the European Environmental Agency (EEA). Projections from the EEA[36] estimate agricultural emissions across the EU will decrease modestly by 4-8% of 2005 levels, by 2030, depending on which emissions reductions measures are implemented in the member states.

N_2O is a long-lived gas that has an atmospheric residence time of 109 years[37] and a global warming potential over a time horizon of 100 years 273 times higher than CO_2[38] , so emissions today have long-term consequences. In addition, there are no direct removal options for N_2O, implying that either the source is to be minimised or an equivalent volume of CO_2 needs to be removed instead, which inevitably will result in an imperfect counterbalancing of its climate effects, due to the different residence times and associated radiative forcing. This means that, without a substantial shift towards plant-based diets or other mitigation options, enduring emissions from farming activities are highly likely to remain at gigatonne scales. Changes in land-use will likely remain an infeasible option due to the scale of change required. A recent publication estimated that the equivalent of twice the carbon currently stored in managed grasslands would be needed to be sequestered in soil carbon stocks to be able to offset global emissions of CH_4 and N_2O[39].

There are some measures that can be taken to reducing emissions. Among these, managing fertiliser more effectively is the main way of intervening to reduce N_2O emissions[40], with up to a 95% reduction in CO_2eq emitted possible[41] though other approaches are also relevant, including the use of biochar[42].

One study[43] from 2014 suggests that without action N_2O emissions could increase by 83% above current levels in 2050. Emissions reduction measures could temper the increase to 26% above current levels. Further action could reduce emissions from present levels by 22% in 2050. However, this would still leave around 1.8 Gt CO_2 eq yr^{-1}, while less vigorous action would leave 2.9 Gt CO_2 eq yr^{-1} of emissions. This implies approximately 2-3 Gt CO_2 yr^{-1} of removals may be needed to balance N_2O emission by 2050.

We have estimated other residual energy sector emissions excluding aviation based on the IEA's latest scenarios (see Section 1.2.3). We have excluded residual aviation emissions estimated by the IEA (1.7 Gt CO_2eq yr^{-1}) and allowed for uncertainty to give a non-aviation energy sector total of 1.0-1.5 Gt CO_2 eq yr^{-1} and have restricted our analysis to CO_2 and N_2O as longer lived GHGs.

Table 2 Summary of demand for NETPs from hard-to-abate sectors

Sector	Demand for NETPs (Gt CO_2 eq yr^{-1})	Notes
Aviation	0.8-1.4	Depends on biofuel availability as well as inclusion of non-CO_2 radiative forcers.
N_2O from agriculture	2.0-3.0	Estimates are highly dependent on chosen CO_2 equivalence. Excludes CO_2 and CH_4 emissions[j].
Other sectors (excluding aviation and agriculture)	1.0-1.5	Based on IEA Net-Zero scenarios[44] and is an optimistic estimate.
Total	**3.8-5.9**	**Indicative – equivalent to about 8-12% of current global GHG emissions[k]**

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[i] Source Statista. Other sources appear broadly consistent. Estimates from one study find fertiliser use accounting for 2.4% of global emissions (~1.2 Gt CO_2eq yr^{-1}), mainly as N_2O. This excludes other agricultural sources of N_2O. https://www.iatp.org/new-research-chemical-fertilisers. Our World in Data indicates 2 Gt CO_2eq yr^{-1} in 2016.

[j] CH_4 is short-lived so is not explicitly included in this analysis, even though we recognise the short-term climate forcing this and other aerosols have. We assume that CO_2 emissions can be eliminated otherwise.

[k] For comparison, the IPCC AR6 estimate is 5-11 Gt CO2eq yr-1 for residual non-CO2 emissions at net-zero for a >67% chance of <2°C warming. Source: https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter03.pdf

2 Supply of NETPs

Negative Emissions Technologies and Protocols (NETPs aim to reduce atmospheric greenhouse gas concentrations. Practically, NETPs will probably be entirely centred around removal of CO_2 (CDR) because the concentration of other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) are simply too low (ppb-level concentrations compared to ppm-level concentrations for CO_2) to be easily extracted from the atmosphere.

A robust definition of what qualifies as CDR is critical to ensuring that there is a net reduction in atmospheric CO_2 concentrations and that more carbon is removed than GHGs are produced in the NETP's activity. Four principles set out by Tanzer and Ramirez[18] with further details and examples explored by the Advisory Council of the European Zero Emission Technology and Innovation Platform[45,46] (ETIP ZEP) provide guidelines for what should qualify as CDR:

1. CO_2 is physically extracted from the atmosphere.
2. The extracted atmospheric CO_2 is permanently stored out of the atmosphere.
3. All greenhouse gas emissions associated with the removal and storage processes are comprehensively estimated and included.
4. More atmospheric CO_2 is permanently stored than greenhouse gases are emitted in the removal and storage processes and their complete supply chains.

2.1 Types of NETPs

NETPs can be characterized by how they take the carbon out of the atmosphere, where they store the carbon and how rapidly, how permanent the storage is.

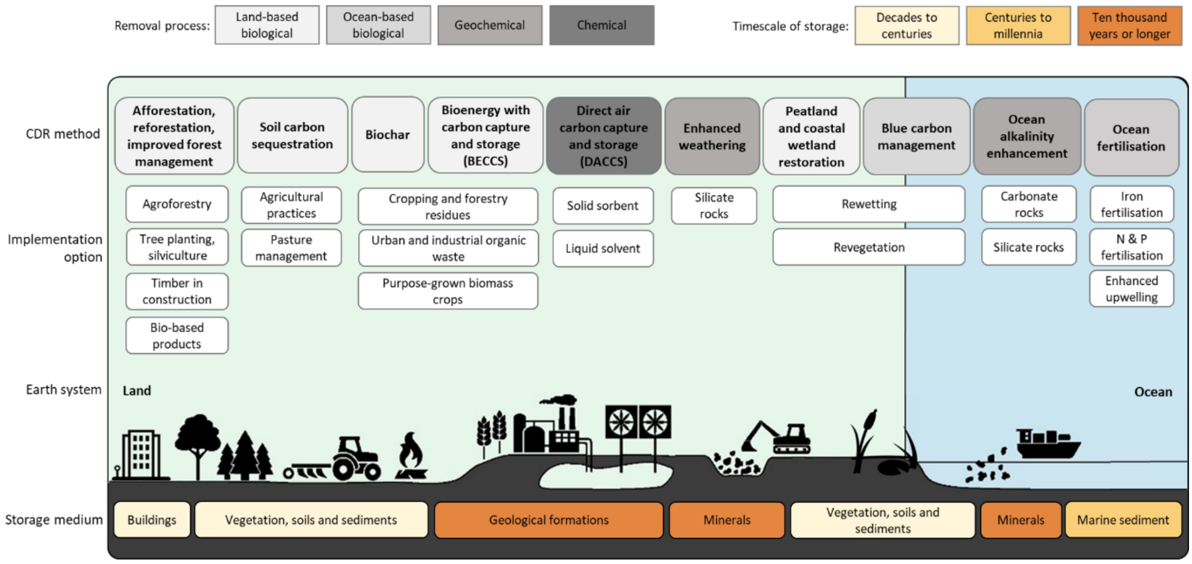

Figure 1. Overview of carbon removal methods, processes, and carbon storage types for a range of NETPs. Source: IPCC AR6 WGIII Chapter 12, Box 8, Fig. 1[47]

The carbon extraction process is the main determinant of resource requirements such as land area, energy and water. Carbon is extracted from the atmosphere by converting dilute carbon dioxide (CO_2) gas into a stable and more concentrated solid or liquid form that can be stored for decades to (preferably) millennia. Transformation into these concentrated reservoirs occurs by both capitalizing on natural processes, such as photosynthesis or enhanced weathering, as well as by artificial processes such as chemical absorption with direct air capture. Technological extraction of carbon is often an energetically costly process with high water footprints[48]. For example, direct air capture (DAC) requires an estimated 1.4 – 4.2 MWh/tCO_2 because of the relatively low concentration of CO_2 present in the atmosphere (just below 420ppm at time of print[l]) and the high temperatures necessary to transform the absorbed carbon into the concentrated liquid form used for storage[49]. In contrast, land-based biological extraction of CO_2 via photosynthesis e.g., BioCCS[m], biochar production, and afforestation captures the carbon in biomass, for which the primary resource constraint is fertile land area. Biomass processing (for e.g., via fermentation, combustion, or pyrolysis into stable and concentrated forms) can often recover large proportions of the energy invested. This thereby reduces the net energy footprint of these NETPs.

Permanent storage of removed carbon is a precondition to CDR. Extracted carbon can be stored in a variety of reservoirs that can generally be separated into terrestrial, such as in vegetation or soils and sediments, and geological carbon stores such as in geological formations or minerals (Figure 1). There are fundamental differences between these storage mediums in terms of reservoir stability, how easy it is to quantify and monitor the stored CO_2, the needed stock management and maintenance effort, as well as the ability to assign liabilities in the event of a reversal of carbon storage.

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[l] https://www.co2.earth/daily-co2

[m] In this report, we use BioCCS to generally refer to any biomass conversion technologies where biomass is used to capture the carbon and is thereafter permanently stored. We use BECCS only where the biomass use is limited to the energy sector i.e. for specific data associated with the BioEnergy Carbon Capture and Storage.

Table 3 NETP Characteristics, adapted from Table 1.1 in "The State of CDR" report[n]

	Re-/Afforestation	BioCCS	DACCS	Enhanced Weathering	Biochar	SCS	Ocean Alkalinity Enhancement/ Ocean Fertilization
Readiness for deployment (TRL)	8-9	5-6	6	3-4	6-7	8-9	1-2
Current and potential scale for 2050 (Gt CO_2eq yr^{-1})	Current[o]: 2000 Mt CO_2 yr^{-1} Future: 0.5 - 10 Future (NEGEM): 1.6 – 4.3 (D3.3, D3.7)	Current[50p]: 2 Mt CO_2 yr^{-1} Future: 0.5 - 11 Future (NEGEM): 1.0 - 14.4 (D3.3, 3.7)	Current: 0.01 Mt CO_2 yr^{-1} Future: 5 - 40	Current: NA Future: 2 - 4	Current: >10 Mt CO_2 yr^{-1} Future: 0.3 - 6.6	Current: NA Future: 0.6 - 9.3	Current: NA Future: 1 - 100 (OAE), 1 - 3 (OF)
Ease and accuracy of MRV (*MRV protocol exists)	Capture: high* Storage: high*	Capture: high* Storage: high*	Capture: very high Storage: high*	Capture: low Storage: low	Capture: high* Storage: medium*	Capture: medium*, Storage: low*	Capture: low Storage: low
Duration of removal[47]	10 - 100 years	>1000 years	>1000 years	>1000 years	> 100 years	10 - 1000 years	OAE: >1000 years OF: >100 years (sediment)
Social impacts[51,52]	Depends on implementation and location: land use conflict, food security/prices, human health (e.g. fine particulate generation, D3.8)	Land competition, food security and prices, land use change[53]	New employment opportunities	Increased crop yields	Indirect land use change (biochar production), increased crop yields, more resilient soils securing income	Increased income/crop yields, indirect land use change and food security/prices, enhanced climate change resilience	Uncertain, potential increase in marine productivity/ regional increase in fish yields[54]
Environmental impacts[51] e.g. biodiversity	Uncertain, implementation dependent[55] (i.e. degraded or natural ecosystem replacement), erosion control, nutrient retention, biodiversity, releasing pressure on planetary boundaries (D3.3/3.7)	Feedstock source dependent: Biodiversity loss (monoculture), water/soil quality, potentially increasing pressure on planetary boundaries (D3.3/3.7)	Water quality, productivity loss, localised CO_2 depletion[49]	Water quality, soil nutrient retention, heavy metal leaching, carcinogenic metal release, air quality (D3.10)	Organic pollutants, soil quality, enhanced water and nutrient holding capacities, soils more resilient to extreme events (D3.10)	Nitrate leaching, water quality, soil quality	Change in food web structure and local ecosystem nutrient status, uncertain impacts in subsurface ecosystems, air quality, heavy metal contamination
Potential constraints	Land, water, sink saturation	Land, water, availability of sustainable biomass or residues (D3.10)	Renewable energy, water, geological storage sites, transport infrastructure	Raw material, land, energy, transport infrastructure, sink saturation	Land, availability of sustainable biomass or residues (D3.10)	Fertiliser use, sink saturation, high reversibility potential	Raw material (iron, N, P, alkaline minerals), permits, social acceptance
Climate feedbacks, non CO_2 GHG emissions	Albedo change (D3.6), soil organic carbon content, evapotranspiration[56]	Water cycle changes[57]			Particulates, SO_2/N_2O, albedo change[58]	N_2O emissions, CH_4 emissions	Nutrient flows, eutrophication, increase in N_2O/CH_4 emissions
Indicative costs at scale (\$/tCO_2)	0 - 240	15 - 400	100 - 300	50 - 200	10 - 345	-45 - 100	OAE: 40 - 260 OF:50 - 500

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[n] All data come from "The State of CDR" report[91] and references therein, unless otherwise indicated.

[o] Estimate is for "conventional CDR on land.

[p] Currently primarily for bioethanol production.

When extracted carbon is stored in appropriately selected geological reservoirs such as retired oil and gas reservoirs or saline aquifers, it is considered permanent because these effectively seal and trap the carbon. The global risk of leakage from mineral and geological reservoirs is also considered to be negligible[59] and the necessary technology to quantify the injected carbon and monitor for potential CO_2 migration or leakage from these subsurface reservoirs already exist. That means that keeping of track of the stored carbon is possible with relatively high accuracy compared to other more diffuse stores of removed carbon (see MRV in Table 3, p.22. However, currently there is little field site data to evaluate leakage risk on time periods of >25 years. Active storage at Sleipner site in the North Sea has run since 1996, with most intensive scientific investigation since 2011.

Other chemical forms of carbon storage, such as mineral carbonation used in enhanced weathering, also have expected storage times of more than 10 000 years (Figure 1) and thereby fulfil the permanent storage criteria with no leakage risk[51]. However, the stored carbon is diluted in the environment, eventually across reservoirs on land, in the ocean and in geological stores[60]. This makes the removed carbon difficult to track over time and verify permanent carbon storage. Hence, these diffuse storage types require higher investment in monitoring to assure storage permanence.

Terrestrial reservoirs such as vegetation, soils and sediments have a shorter storage timeframe of decades to centuries. These storage reservoirs also have a higher risk of CO_2 being returned to the atmosphere because of the higher risk of both natural and human-induced disturbances such as forest fires, drought, floods, and landslides and this vulnerability can increase under global warming. Another feature of these reservoirs is that they are in more direct contact with the atmosphere, hence any leaked carbon can be directly returned to the atmosphere. For example, terrestrial biogenic sinks such as forest vegetation is combustible and may be susceptible to reversal through fires.

A key metric of NETPs will be their carbon dioxide removal efficiency, as a measure of how much carbon is removed (gross) compared with how much is removed and stored (net), including associated emissions and impermanently stored carbon[61]. This metric is an indication of the net carbon removal efficiency because it already takes into account the emissions that result from the supply chain. CDR efficiency should be considered contemporaneously over the expected NETP implementation time scale as it will change over time for a given NETP due to the rate and immediacy of CO_2 removal in each approach[61]. Sinks may become saturated and less efficient over time (e.g. carbon uptake in vegetation). Other approaches may increase in efficiency through decarbonisation of energy sources (e.g. DACCS).

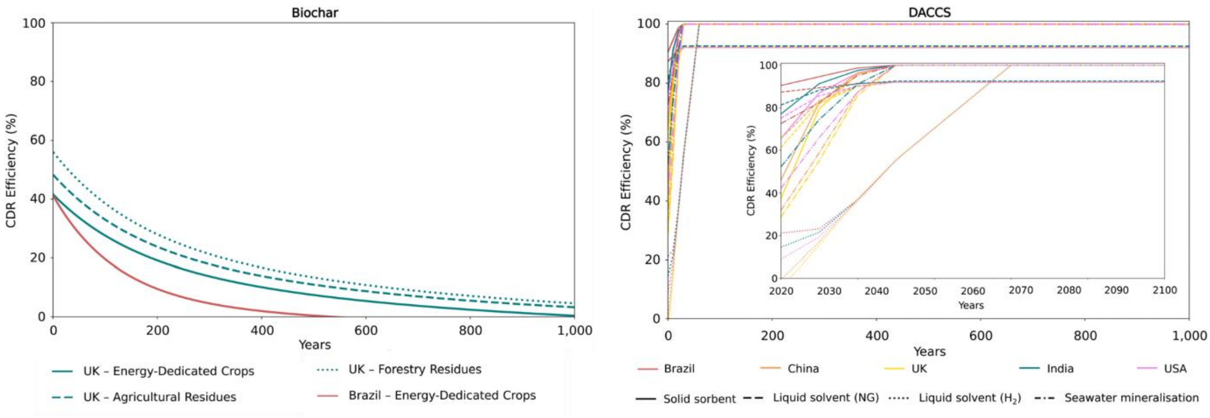

Figure 2. Change in carbon dioxide removal (CDR) efficiency over 1000 years for biochar (left) and DACCS (right). Source: Figures 13 and 14 from Chiquier et al. 2022 [61]*.*

2.2 Estimated potential scale of deployment

Currently commercial availability of novel, and permanent, CDR is < 2 Mt CO_2 yr^{-1} and is dominated by BioCCS, DACCS with other conventional land-based CDR methods such as afforestation contributing around 2000 Mt CO_2 yr^{-1} (Table 3). While these NETPs have the highest technological readiness, the supporting system of transport, energy provision and capital investment are not necessarily at the same level of readiness. Likewise, robust certification frameworks and protocols for MRV are still under development and currently limit confidence in private and public investment.

The development and deployment of DACCS is currently in its early stages. Work by the IEA showed that in 2023 there were 27 DAC plants operating[62]. These were extracting in total less than 0.01 Mt of CO_2 from the atmosphere per year globally[62]. The large majority of them capture CO_2 for utilization, for example for drinks carbonation, with only two plants storing the captured CO_2 in geological formations for CDR. Only a few commercial agreements are in place to sell or store the captured CO_2, while the remaining plants operate for testing and demonstration purposes . Plans for at least 130 DAC facilities are now in various stages of development. One of these is a large-scale DAC plant of 0.5 Mt CO_2 yr^{-1} under construction in the USA and scheduled to be operating by the end of 2025, although there are concerns that these may be used to counterbalance abatable emissions[50]**.** It is understood to have the potential to expand to 1 Mt CO_2 yr^{-1}. The US Department of Energy has recently announced funding for this and a second project of approximately 1 Mt CO_2 yr^{-1} in Louisiana.

BioCCS is similarly at a very early stage of development. There were five commercial scale BioCCS plants in operation in 2019[63], all capturing CO_2 from ethanol production in North America. A further bioethanol project came online last year. The DRAX facility in the UK[q] has a capture capacity of 330 tCO_2 yr^{-1}. There is also a proposed project for CCS on waste incineration[r] near Oslo. However, this has been delayed.

In assessing future scale, we have drawn on a range of evidence on scale-up rates for energy technologies, including:

- CCS

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[q] For more information see: https://www.drax.com/

[r] Note, the capture of the biogenic fraction of waste incineration has the potential to qualify as CDR, while the fossil fraction remains an emission reduction.

- Wind
- Solar
- Nuclear
- LNG
- Biofuels

We have assessed the status of project development for DACCS and BioCCS[s], including the decision by the US Department of Energy to provide financial support two DACCS projects at full scale (0.5-1.0 Mt CO_2 yr^{-1} each). Based on this assessment it seems plausible that under favourable conditions, including strong policy support, there might be up to a total of around 10-12 Mt CO_2 yr^{-1} of CDR into geological storage possible by the end of this decade. This total may include somewhat more BioCCS that DACCS, due to the lower capture costs for BioCCS, and assumes that geological storage space does not limit CCS for CDR. We discuss geological storage capacity as a potential bottleneck later in Section 2.2.2. Looking at other energy related technologies indicates a maximum credible scale-up rate for this technology of about an order of magnitude per decade. Only solar energy production capacity has grown faster than this.[64] On this basis, an ambitious deployment scenario could show DACCS and BioCCS, as the currently most developed NETPs, each growing rapidly to remove about 400 Mt CO_2 yr^{-1} and 600-800 Mt CO_2 yr^{-1}, respectively, by 2050. Cumulatively, total removals over time between now and 2050 would be approximately 2 Gt CO_2 for DACCS and 3-4 $GtCO_2$ for BECCS.

Optimistic estimates from the NEGEM project of total potential CDR capacity by 2050 are ~12 Gt CO_2 yr^{-1} or more (D8.1), with few limitations on the deployment scale or storage permanence of the removals. However, realistically removed carbon will remain a scarce commodity and will need to respect to competition for resources to ensure an overall positive climate outcome and sustainable implementation schemes (D3.10). Characteristics of DACCS and BioCCS mean that this rate of upscaling will nevertheless be challenging and perhaps even impossible, to achieve.

In the following subsections, we explore many of the likely constraints on NETP deployment scale-up in some depth, recognising that there are considerable expectations being placed on what each individual novel technology, and the sum of their contributions, will deliver. Our aim is to provide some context around our estimates of potentially highly constrained NETP supply in the foreseeable future to set this against the high expected demand for removals. This novel field has many uncertainties in cost, resource availability and allocation, amongst other factors that need to be considered in realistic long-term planning for climate change mitigation. Responsible implementation and deployment of NETPs should consider the CDR efficiency in relation to environmental, social, economic and engineering limitations and the storage durability, with some examples described here.

2.2.1 Natural resource constraints

Evaluating the pressure an NETP exerts on resource demand or other impacts requires a metric that can be applied to fairly assess the CDR efficiency of the diverse range of NETPs against this pressure. One tool utilised in the NEGEM project (WP3, D3.8) was a comparative sustainability assessment between NETPs on a per tonne CO_2 removed basis using a life cycle assessment (LCA, D3.8 and D3.10). This compared how human health, ecosystem quality and resource scarcity may be influenced by large scale deployment by 24 different NETPs. However, comprehensive evaluation of the NETPs and wider environmental impacts and co-benefits[65] is in most

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[s] See for example: https://www.iea.org/reports/direct-air-capture, https://www.globalccsinstitute.com/wp-content/uploads/2019/03/BECCS-Perspective_FINAL_18-March.pdf, https://www.negemproject.eu/wp-content/uploads/2023/08/NEGEM_D5.4-Expert-elicitation.pdf

cases not yet possible due to the currently limited scale of deployment and ability to validate findings. The scale of impact may also change with the scale of deployment for resources such as biomass and energy that become more scarce when the NETP is deployed at a very large scale.

- Biomass availability: Biomass-dependent NETPs scale-up rates will be limited by the rate at which vegetation can grow and capture the carbon, both before and after maturation. Alternatively, the diversion of suitable dry biomass waste streams (forestry residues, solid pellets, municipal waste) may enable NETPs to scale more quickly and enhance resource utilisation efficiency, but waste streams are also an inelastic source of biogenic material and are dependent on the primary activities that they result from. An estimate by WP3 in NEGEM indicated an upper total CDR potential of 1.7-7.0 $GtCO_2eq\ yr^{-1}$ (D3.3, D3.7) could be acquired from residual biomass and organic waste streams. However, the quantity of these waste streams and residues may be insufficient for upper estimates of CDR potential. In addition, the quantity of the waste streams may vary depending on the scale and development of the primary activity over time (e.g., forestry residues depending on the scale and sustainability of logging practices). Nevertheless, relying on waste streams sourced from unsustainable practices could lead to perverse incentives, whereby the unsustainable activities from which the waste streams originate may be incentivised to continue or expand.
- Available land area: Additional area will be permanently required for feedstock production for biomass-dependent approaches (Bio-CCS, afforestation, biochar). This presents a potential conflict between food and CDR feedstock production, as well as space to accommodate growing populations and/or urbanisation. The healthy functioning of other key Earth subsystems could also be weakened if further semi-natural vegetation is replaced by less biodiverse plantations (D3.3, D3.7). Dedicated vegetation for Bio-CCS may have negative environmental impact as usually implies rapid growing monoculture , that are less resilient to pests and invasive species due to lower biodiversity and could compete with reforestation efforts to reach biodiversity targets[66]. To alleviate this pressure, substantial additional land area could be made available by a transition to the Lancet EAT planetary health diet, or other low-impact diets (D3.3, D3.7). Utilisation of marine biomass as feedstock would circumvent at least in part this potential land-use conflict, but would still have the potential to affect biodiversity amongst other environmental impacts.
- Raw materials: Large amounts of alkaline rock powder will be required for enhanced weather and ocean alkalinity enhancement applications. Waste streams from industrial processes or mine tailings could provide this and reduce, or even eliminate, the need for new materials to be mined or produced. Once again, relying on waste streams sourced from unsustainable practices could lead to perverse incentives.
- Fresh water availability: Some estimates suggest the water demand of CCS technologies (Bio-CCS, DACCS) to meet 1.5° targets could lead to a doubling of the anthropogenic water footprint[48]. Degradation of amines used in carbon capture process in DACCS may leak into freshwater systems and threaten freshwater quality (D3.10), if wastewater treatment is poorly managed. Dedicated vegetation for biomass-based NETPs may also require irrigation with fresh water.
- Sink saturation: Primarily a limitation for ecosystem-based CDR that enhance natural sinks. This is accounted for in CDR efficiency metric but may overburden the most efficient biomes.

2.2.2 Physical resource constraints (Permanent geological CO_2 storage and renewable energy constraints)

What will be accepted politically and socially, as a strong and convincing evidence base of permanence, is not yet clearly defined for NETPs. However, the storage of carbon arising from direct air capture and biomass conversion is primarily constrained to permanent geological reservoirs and is considered permanent. DACCS and BioCCS projects are complex, with multiple elements that require dedicated infrastructural support, including energy supply, the capture units, and CO_2 transport and storage.

- Low carbon energy demand: Availability of low carbon energy sources and capital investment and operating expenses present the largest barriers to realising the CDR potential of DACCS. The rate at which grid capacity and renewable electricity generation can firstly decarbonise the grid and then expand to accommodate demand from a variety of other sectors (industrial processing, zero emissions transport, green hydrogen production, grinding of rock for enhanced weathering, electrolysis for some direct ocean carbon capture technologies) will continue to be an important limiting factor for DACCS capacity. 1 Gt of CO_2 removals via DACCS would require around 1,400-4,200 TWh of additional low carbon energy annually. This compares with total global energy generation in 2022 of just under 1,300 TWh of solar photovoltaics and just over 2,100 TWh of wind[67]. Total U.S. utility-scale electricity generation in 2022 was about 4,240 TWh[68]. 1 Gt of CO_2 removals via DACCS will also require more than 20 times the current global installed base of CO_2 transport and storage for CCS[t].

- <u>CO_2 transport and storage infrastructure:</u> There is growing demand for CCS for point source emitters in addition to transport and storage for BioCCS and DACCS. Additional capacity in geological stores and in transportation to the storage sites will be needed for NETPs as most CCS storage capacity in planning only accounts for industrial emissions on land. This ancillary infrastructure such as pipelines for CO_2 transport to storage sites, typically have slow learning rates and possibly present a greater barrier to deployment than the CO_2 capture process itself.
- <u>Scale of material handling:</u> Material stores for biomass dependent NETPs will also require large-scale storage in dedicated buildings, which border on completely impractical. As an example, for enhanced rock weathering, substantial volumes of material must be mined, crushed, and then transported to the eventual application site, possibly undermining the net value of the overall undertaking.
- <u>Ability to accurately monitor and account for removed carbon:</u> Uncertainty in how much carbon is stored and for how long. MRV protocols are being co-developed along with each technology but there is a lack in standardised reporting requirements or agreement on what accurate measurement of each individual carbon flux or store will entail. BioECCS and DACCS have a higher certainty that the carbon removed is stored permanently with a low risk of reversal. There is also little certainty in biochar decomposition rates outside laboratory conditions, where biological and chemical processes can enhance degradation. However, present methods used to quantify biochar durability in soils rely on extrapolating short-term decomposition patterns observed in laboratory settings and do not account for the underlying processes that could elucidate its persistence over millennia. More dispersed carbon storage e.g in EW and ocean based NETPs are more difficult to quantify accurately and will have a higher inherent uncertainty in MRV as well as co-benefits and environmental impacts. This may impose on social acceptance of NETP implementation and limit the degree of deployment.

We here highlight a particular bottleneck for the scale-up for any NETP that requires CCS because these will entail substantial increases in transport and storage of CO_2 from current levels. The current CO_2 storage capacity is only about 44 Mt CO_2 yr^{-1} globally[50] (excluding discontinued In Salah project[69]) and has increased steadily over the last few decades. The Sleipner project, the first large-scale CCS project to inject captured CO_2 into a saline aquifer, began in the late 1990s. There have been enhanced oil recovery (EOR) projects since 1972 and before Sleipner (also included on Figure 1Figure 3), but these were not built with the intention of storing CO_2 permanently. Recent rates of deployment have been faster in absolute terms, with approximately an average of 2.5 Mt CO_2 yr^{-1} of capacity added between 2009 and 2019. Figure 3 assumes that all projects can operate at full capacity, which has not been the case for some projects to date, notably the Gorgon project in Australia.

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[t] This comparison excludes transport of naturally occurring CO_2.

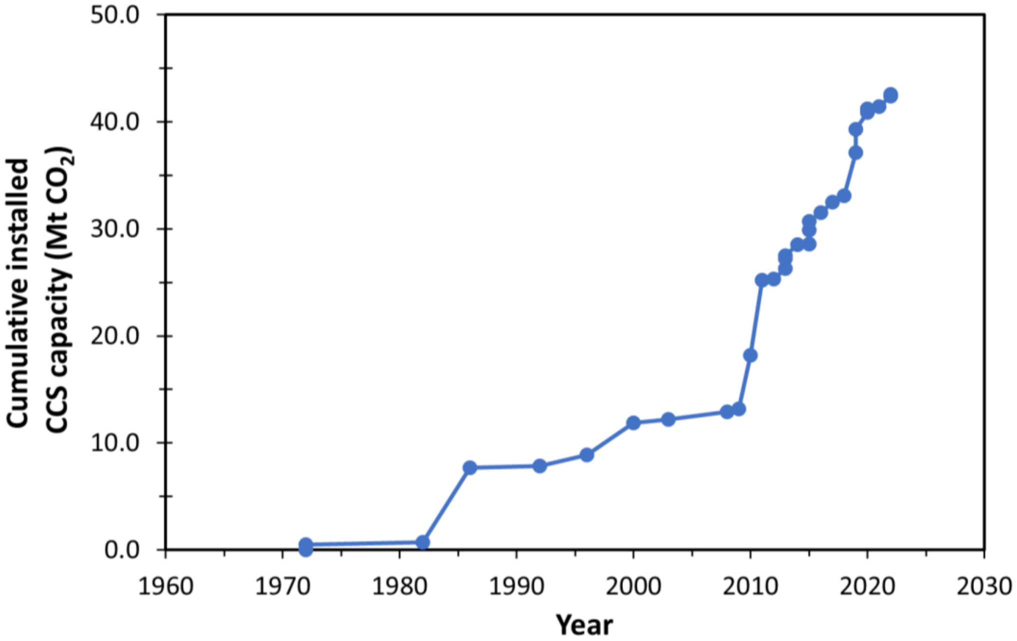

Figure 3. Global deployment of CCS capacity over time [3]. Data from GCCSI[69]

Substantial growth in capacity is required because geological storage capacity for CDR will need to be in addition to the transport and storage of industrial CO_2, as CCS is an essential tool in decarbonisation strategies of some industries. This implies that only a fraction of CO_2 transport and storage will be available for BioCCS and DACCS.

There are indications that the rate of deployment of CCS is likely to increase significantly in future. Governments and project developers in a range of locations in North America, Europe and the Middle East are looking at hubs storing CO_2 from multiple projects. There are now over 200 projects in various stages of planning and development worldwide with a potential total future capacity of about 250 Mt CO_2 yr^{-1}, six times the currently installed base[69]. However, it is too early to say how many of these projects, or any additional projects that may yet be developed, will be completed, or when this additional storage capacity may available.

2.2.3 Financial and permitting barriers

In addition to the constraints on sustainable biomass availability, CDR growth is constrained by current financial incentives to encourage long-term investment in costly infrastructure for both CO_2 transport and storage, or energy provision for CO_2 extraction. Finance for each BioCCS or DACCS project will need to be large scale (into the billions of dollars investment per project for plants with capacity of a million tonnes p.a. or more). There will be significant lead times for planning, permitting and construction in many cases. Hence, momentum will need to be sustained over multiple decades, which to date only appears to have been achieved by renewables.

Funding mechanisms have been directed primarily towards innovation (e.g., Horizon Europe Research and Innovations actions (RIA) or EU Innovation Fund for the Stockholm Exergi BECCS project) up to demonstration level with the potential to scale. Hence, despite public and private interest the spectrum of CDR technologies is not yet removing and storing carbon at a meaningful scale to contribute to lowering atmospheric CO_2 concentrations, leaving considerable risk for interested (customers) surrounding uncertain potential costs and future availability. As is the case for many novel technologies, DACCS is currently in the early stages of deployment and uncertainties on future deployment costs are correspondingly large. Removals from early full-scale plants coming online by 2030 are currently estimated to be likely to cost \$400-1000 per tonne of net CO_2 removed from the atmosphere. Recent NEGEM analysis (D5.4) that costs for DACCS may fall to around \$200-400/tCO_2 by 2060 if large scale deployment is successful. However, costs towards \$200/tCO_2 only appear achievable if costs of early projects are towards the bottom of the expected range and there is large scale roll-out of DACCS. Aspirational goals of DACCS costs of \$100/tCO_2 seem unlikely to be achieved even in the longer term.

A cost of \$300-400/tCO_2 is used in this report as a reference point for DACCS costs in 2050. However, costs will continue to vary with location and other factors such as availability and cost of renewable energy. This is in line with expert views collected by NEGEM[u]. These show the experts' best estimates suggest that, by mid-century, costs will fall to an average value of €280/tCO_2 for DACCS and €153/tCO_2 for BioCCS (current cost assumptions are €581/tCO_2 for DACCS and €172/tCO_2 for BioCCS). However, these 'averages' hide a wide divergence in views among experts, particularly for DACCS.

Costs of DACCS may nevertheless be below the costs of abatement in some applications. For example, it seems likely that there would be continuing demand for aviation at a carbon price of \$300-400/tCO_2, although at a reduced level. This compares with the situation for cars where until recently there was no alternative to internal combustion engine vehicles and there was continuing demand for transport despite taxes equivalent to a carbon price of the order of \$200-500 t$CO_{2.}$

BioCCS will tend to have the advantage compared with DACCS that it captures a more concentrated CO_2 stream, because growing the biomass has already concentrated the carbon from the air. This may make projects more tractable and cheaper. Furthermore, unlike DACCS, BioCCS projects produce a valuable product – useful energy or low carbon products – in addition to climate benefits.

However, the costs of BioCCS projects will depend on cost and availability of sustainable biomass feedstocks. Some BioCCS projects are likely to be able to make use of existing biogenic feedstocks, such as the biogenic element of municipal waste. These projects may be lower cost than DACCS, likely within the range of costs industrial CCS projects. However, as noted elsewhere in this report, total bio-energy resources are likely to be significantly constrained. This may increase costs or make projects infeasible within sustainable boundaries.

The financial costs of BioCCS will also depend on when removals occur. Projects are likely to depend on revenue from removals, for example from sales of removals units. A removals unit should be issued when a net physical outflow from the atmosphere occurs. However, it should not be issued before a net outflow occurs. Correspondingly, 'front-loading' of removals – the practice of certifying expected total removals over project lifetime early in that lifetime to create units – should not be allowed. For example, BioCCS projects which harvest and then replant dedicated vegetation should only generate units over time, as vegetation regrows. This may be short duration in many cases. However, in other cases it may be over decades. If removals are not credited until the distant future their commercial value may be–reduced[v]. Some existing best practice already follows this approach of recognising removals when they occur. For example, the UK Woodland Carbon Guarantee issues credits corresponding to verified removals by new woodland every 5-10 years. Payments are under a contract, with the price set by auction[70].

There remain many emissions reductions that will cost much less than DACCS or Bio-CCS per tonne CO_2 and governments may prioritise these for the use of scarce funds. They may also prefer removals to biogenic sinks on grounds of availability and cost, as well as their contribution to nature restoration targets, even though these are at greater risk of reversal.

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[u] Estimated costs in the NEGEM assessment are in Euros (€) as this is a European research project.

[v] However projects may have more immediate value because they convert storage in a biogenic sink to storage in a geological sink, which increases permanence and thus value.

In light of these obstacles, scenarios showing 400 Mt CO_2 yr^{-1} for DACCS and 600-800 Mt CO_2 yr^{-1} of BioCCS are the likely maximum potential capacity available in 2050, although they may grow further in the second half of the century. This is in line with the upper end of the range of estimates collected by NEGEM (D5.4), which show a maximum of 1 Gt CO_2 yr^{-1} by 2050 for DACCS and BioCCS combined. Speculation of much larger quantities, including 50-60 Mt CO_2 yr^{-1} by 2030 and 2-3 Gt by 2050, do not seem to be supported by evidence. Indeed, we would suggest that much lower capacities will be available by 2050 due to both the aforementioned factors for BioCCS and DACCS, or other factors such a supply of geological storage for removals. We have limited the scope of our estimates to these two novel technologies as these both have a high storage permanence in geological reservoirs and have deployed pilot-scale projects. We have adopted a lower-case scenario of 0.2 Gt CO_2 yr^{-1} of BioCCS and 0.1 Gt CO_2 yr^{-1} DACCS by 2050, however lower availability than this is still possibility. This estimate for 2050 is much more conservative than other economically based estimates as we include a high likelihood of slower technological and energy infrastructure advances that will constrain BioCCS and DACCS deployment at scale.

3 Matching supply with demand: considerations for NETP allocation

Following our analysis on NETP demand (Section 1) and estimates NETP supply (Section 2), two key points are clear. Firstly, carbon removals will remain a scarce commodity. This is illustrated by Figure 4, which compares emissions by sector[71] with removals likely to be available in 2050. Even if available removals were to be around 1.5-3.8 Gt CO_2 yr^{-1} by 2050 (with the addition of managed land), this is approximately 3-8 % of current global emissions[72]. The majority of this will be due to more vulnerable carbon storage in the LULUCF sector (D3.2), followed by smaller contributions from DACCS and Bio-CCS (see also previous section). This implies that all different sectors will need to reduce their emissions by an average of 93-97 % to achieve net zero, with most eliminating GHG emissions altogether.

Secondly, not all sectors will be able to decarbonise to the same degree. Within this average, two sectors, aviation and agriculture, produce emissions which are currently understood as being particularly challenging to reduce with residual emissions likely to remain around 3.8-5.9 Gt CO_2eq yr^{-1} (see Section 1.2). This implies these sectors may require removals that are a greater proportion of current emissions than the average across all sectors, relative to their current emissions. This in turn implies that other sectors will need to reduce emissions more. Indeed, most sectors will need to eliminate emissions almost completely if net-zero targets are to be achieved.

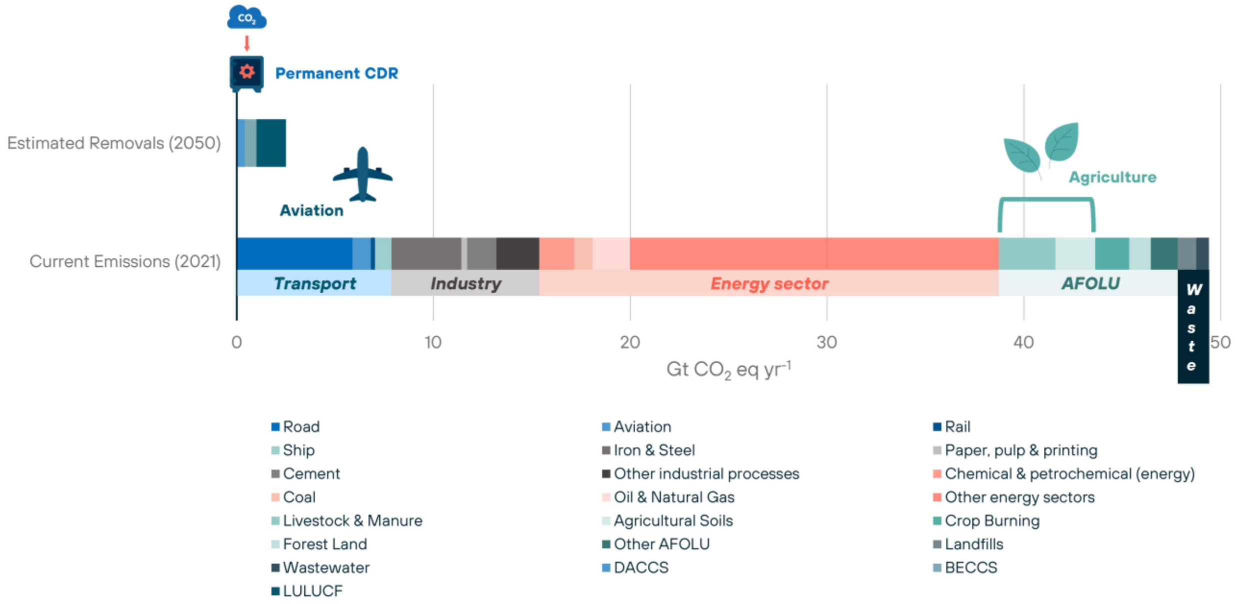

Figure 4. Comparison of current emissions with potential for CDR

A further point illustrated in Figure 4, is that the available capacity in permanent carbon stores will be restricted. Removals to geological storage are likely to at most about 1-1.2 Gt CO_2eq yr^{-1} total by 2050, and perhaps much less (~0.3 Gt CO_2eq yr^{-1}, see Section 2.2.3). This implies there will be an even greater scarcity of NETPs able to counterbalance emissions of fossil carbon to 2050, although there may be greater potential beyond that. Removals to biogenic sinks are not sufficiently permanent to balance emissions of fossil carbon (see Section 2.1). This implies a further challenge to achieving long-term climate targets even if there are large amounts of biogenic sinks.

3.1 Principles for NETP use

Since demand will be immense for this limited supply of NETPs, the integrity of usage of carbon removals needs to be safeguarded by a set of physical credibility principles, and by a set of social credibility principles to ensure a fair distribution of the benefits and burdens.

3.1.1 Principles for physically credible use

Any NETP to be used for counterbalancing of emissions should lead to a net physical and permanent removal of carbon that can be accurately quantified, and monitored, and the deployment should not create any significant harm to the natural environment.

More specifically, this means that the NETP deployment:

- **Demonstrates permanent CDR that meets minimum acceptable CDR efficiencies (see also D6.3).**
- **Avoids false fungibility between carbon sinks.** A tonne of CO_2 sequestered in biogenic stores (i.e. the fast carbon cycle), is not equivalent to the removal of one tonne of CO_2 removed by a technological process (such as DACCS) and stored in a stable geological reservoir i.e. the slow carbon cycle[73].
- **Provides a clear system description of how carbon is emitted, extracted and stored and assigns liability for storage reversal.**
- **Quantifies the physical flows of carbon to determine how much carbon will be removed and the associated uncertainty and demonstrates an overall climate benefit**. This quantification uses cradle-to-grave system

boundaries that incorporates all resources utilised in the carbon extraction and storage, as well as also wider Earth system impacts including, land-use change, energy source impacts from cradle-to-grave. Potential climate impacts for the presence of a GHG between emission and removal are also considered. Ideally this aligns with monitoring, verification, and reporting for the NETP.

- **Scale of implementation respects resource limitation locally, regionally and globally**, **and does not exert additional pressure on planetary boundaries and ideally reducing pressure on those already transgressed.** Deployment utilises underlying resources with maximum efficiency and adheres to strict sustainability criteria (D6.3, 3.2, 3.7, 3.8).

This also means that the use of the carbon removed via the NETP:

- **Acknowledges differences between different GHGs** as these have different climate impact strength[74], atmospheric residence times and different roles in the carbon cycle. Note: CO_2 will be the removed GHG source because it is technically easier to remove than other GHGs, irrespective of the relative climate impacts.
- **Avoids false fungibility between a removal and a reduction.** Furthermore, one tonne of removal CO_2 is not the same as one tonne of reduced emissions.
- **Counterbalances GHG residence time and matches sink storage permanence**. Where CO_2 has been emitted to the atmosphere with a residence time of thousands to millions of years, it should be returned to a sink with an equivalent stability of storage.

3.1.2 Principles for socially credible use

Beyond being physically credible, it is also important for the use of NETPs to be socially credible if it is to reliably contribute towards achieving the aims of the Paris Agreement. With CDR having been long understood as a controversial subject within climate mitigation conversations, it will be important to ensure that NETPs are used in a manner which is consistent with the global and socially disparate nature of the climate crisis.

- **Does not deter or get in the way of action to reduce emissions.** Any use of CDR should follow the IPCC's recommendations, namely that CDR should first serve to accelerate net reductions of global emissions (i.e., be additional to the reduction of emissions); second serve to counterbalance only residual emissions of CO_2 and other GHGs; and third to remove more CO_2 than are emitted GHGs at the global level.
- **Does not remove any responsibility to minimise emissions in the first place.** The deployment and use of NETPs should not allow an emitting entity to absolve themselves of the harm caused by the GHGs they are emitting (or have emitted). Any emissions must be clearly reported and highlighted as problematic.
- **Ensures that counterbalancing of emissions is achieved at a system-level, rather than simply at the individual-level.** One entity which is empowered to counterbalance its emissions with removals is unlikely to be conscious of the needs of other entities within the system. As such, it is possible that one entity's ability to reach net-zero, via reliance on removals, could compromise another entity's ability to do so as well. Leaving such decisions to individual entities is likely to produce unjust outcomes compared to a more centrally managed or coordinated approach. The ability to pay should also not enable one to be absolved of responsibility. NETP use should not endanger other societal targets such as the Sustainable Development Goals for poverty elimination, zero hunger, affordable and clean energy, and reduced inequality.
- **Avoids imposing further burden on other entities**. Using NETPs to counterbalance emissions which could otherwise have been abated and have a lesser social license is likely to result in a shortage of NETPs available to counterbalance emissions which cannot be abated and have a higher social license. This could lead to some activities being curtailed on the basis that there aren't enough removals to counterbalance the emissions associated with those activities, even if those activities have a significant societal value.
- **Assigns clear liability to minimise and make good on any reversal of carbon storage**. An entity which reports that it has generated and sold a carbon removal should also be responsible for any potential liabilities emerging from the reversal of carbon storage.

3.2 NETP allocation mechanisms and implications for credible use

In answering the question of who should use NETPs, follows the question of how the limited amount of NETPs should be used in any allocation, if they should be used at all. Here we consider a range of approaches that could be used to govern their allocation. These mechanisms can be broadly categorised by their underlying principles, such as market-driven regulation, obligation for compliance, or commitments by governments. Voluntary approaches may have some value in the short term in stimulating early-stage deployment and innovation of NETPs. Some large companies have already bought NETPs[w]. These initial buyers are often in sectors such as software, which have the highest financial return on CO_2 emissions (\$profit per tCO_2 emitted)[75]. However, these voluntary approaches are unlikely to generate the volumes of removals needed to meet climate goals, or meet the large costs involved in creating permanent removals at scale. For these reasons we focus on compliance obligations on emitters, and commitments by governments that retain the ambition to contribute to net-zero targets.

Three types of approaches considered here are:

1. Allocation based on a market, for example an emissions trading scheme that includes removals.
2. Allocation based on regulatory compliance at sector or sub-sectoral level with decentralised/market-based removal purchases.
3. Allocation based on regulatory compliance obligations at sector or sub-sectoral level with centralised removal purchases (a Carbon Bank). Under some variants of this, the Government acts as the sole buyer for units, with no explicit matching to remaining emissions, and with no obligation on emitters to buy units, although they may be required to pay a tax or levy which is used to fund removals.

There are inevitably overlaps between these options. For example, an ETS could apply to some sectors only, with sectoral requirements on others. The Central Bank may be responsible for all units or may complement bilateral trading of certified removals in markets.

There are also many variants of each option. For example, there may be different degrees of matching between sectoral obligations on emitters and purchases by the Carbon Bank. A market-based system may feature separate markets for emissions and removals, perhaps with linkages to each other.

In the following sections, we briefly describe each approach. We also link these back to some identified drivers of demand in Section 1.1 (e.g., “Limited licence to emit”, “Reparations to balance historical climate damage”) to understand the implications and risks to the credible use of NETPs if this allocation approach is implemented.

Regulatory aspects

- What can emitters purchase? E.g. type of removal, quality of removal
- How much can one emitter purchase? (max limit)
- How much should one emitter purchase? (min limit)

3.2.1 Allocation based on user demand

Using market-based mechanisms, each interested entity competes against the others for their share of the market. For a CDR market, this approach would already define the total allowed amount of net emissions

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[w] See for example https://www.reuters.com/business/environment/amazon-makes-first-investment-direct-air-capture-climate-technology-2023-09-12/

(emissions minus removals) permitted, for example a cap under an emissions trading system. Emitters would be required to surrender removals units to match their emissions, or allowances, if caps are not set to zero. Eventually, caps under emissions trading systems will need to be set to zero to be consistent with net zero commitments. No emissions allowances (or very few emissions allowances) would be issued. The ETS would in practice become mainly an obligation on remaining emitters in hard to abate sectors to buy removals. In the long term, caps may be negative, although that would greatly alter the operation of the system).

This means there is full fungibility across unit buyers and sellers and that the mix of removals and emissions is set by the market. If removals are relatively cheap compared to abatement, then there will be a higher level of emissions and removals than if removals are expensive and abatement is relatively cheap. This approach assumes that cost is the only limitation to the overall supply of removals, which is not consistent with the current understanding of NETP supply, as is mentioned throughout this report. The cost of removals could be influenced by factors such as technological availability and quality of the removal (including social and environmental sustainability). For any market-based approach to be physically credible, the quality of removals which can be included would need to be high enough to be confident about the ability to counterbalance the global warming effect of an emission of fossil GHGs.

This market-based approach also offers flexibility in pricing that could recognise uncertainties and risks, and differences in between a removal and an emission. For example, an exchange rate could be introduced between an emission and a removal. This would mean that more than one tonne of removals is required to balance a tonne of emissions.

Another possibility would be for governments to act as intermediaries, rather than emitters and owners of removal certificates trading directly. Governments could filter or select which removals could be surrendered for different parts of the market. The idea of this type of compliance-based regulation will be discussed in the following section.

The principles underlying a market-based approach are illustrated in Figure 5. The demand for removals is set to willingness to pay for continuing emissions, which will in turn be set by emitters' marginal abatement costs. At net zero the remaining emissions must be balanced by removals. The supply of removals increases with price. The volume of emissions and removals is set by the market, in principle where the cost of removals is equal to the marginal emitter's willingness to pay. The emitters with the highest willingness to pay will continue to emit. Those with willingness to pay below the marginal cost of removals will cease emitting. Nevertheless, emitters with the highest ability to pay are not necessarily those with the hardest-to-abate emissions and could price out emitters with a lower ability to pay but with fewer or no alternative mitigation options. In a mature market the price and volume of removals should, in principle, then be driven by demand from hard to abate sectors, with removals preferred where they are cheaper than abatement.

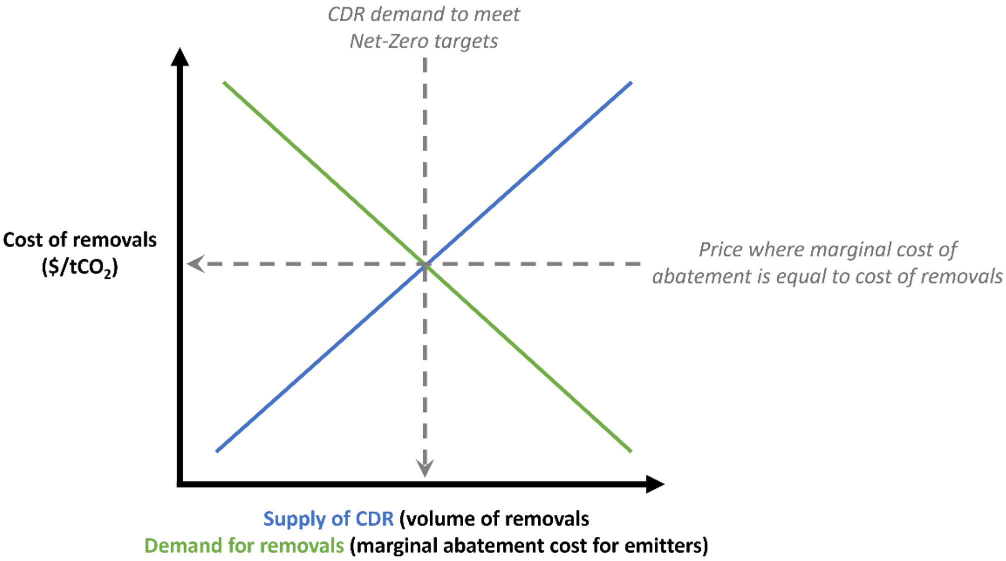

Figure 5. Supply-demand curve for carbon removals, indicating the relative impact on the profitability and number of CDR projects available (blue line i.e supply) and the willingness of the user to pay for removals compared to continued emissions (green line i.e. demand).

The situation is similar before net zero is reached. However, there is a supply of allowances available from the remaining cap, and the supply of removals may be smaller as the industry will have had less time to grow.

Market-based mechanisms have the potential to create economically efficient outcomes, in that removals will be used where they have highest commercial value. For removals, this high value market is likely to be aviation, especially medium and long-haul flights, which currently have few alternatives other than demand-side management and biofuels, and some niche high value applications in industry and power generation.

However, this economic efficiency brings with it considerable risks to the credible use of NETPs, unless there are clear standards for the types of removals included in such markets. These emitters that place high commercial value and are able to pay for removals would ideally like to continue to have a "Limited licence to emit", to counterbalance their residual emissions in these emitters, at the expense of other emitters who have less ability to pay but a greater need for removals. This approach is therefore likely to produce outcomes which are not physically credible, should the inclusion of CDR be poorly handled, nor socially credible, should 'willingness-to-pay' remain the way to allocate NETP use.

The need for rigorous quality standards for inclusion in markets

Markets are not considered good governance tools for natural resource allocation without some set of quality and environmental impact standards. Specifically, there should be robust monitoring, verification, and reporting standards for any removals to ensure accurate quantification of removed carbon and ensure liability is assigned for the permanent removal. This is likely to restrict market inclusion only to removals where the risk of reversal is extremely low and monitoring technology exists, which at the moment only applies to geological storage. Based on our rough estimate of aviation demand (0.8-1.4 Gt CO_2 yr^{-1}, Section 1.2.3) the estimated availability of removals to geological storage in 2050 as 0.3-1.0 Gt CO_2 yr^{-1} will likely be completely exhausted by this sector alone, in the absence of additional efforts. Very limited availability of removals to geological storage will be left to balance other emissions unless the sector switches almost entirely to carbon neutral (bio)fuels. This would certainly increase demand for high quality removals, and with it the price that users are prepared to pay for a removal.

In some respects, tying the carbon price in an ETS to the cost of removals to geological storage (DACCS and BioCCS) may encourage emissions reductions. The costs of DACCS are likely to remain high (\$300-400/tCO_2, NEGEM D5.4) even when the technology is mature. BioCCS is likely to be cheaper, but supply is likely to be constrained by availability of sustainable feedstock, in particular where there is high demand for biofuels to reduce emissions. Enabling early DACCS and BioCCS projects should help make the actual costs clear. The market will consequently likely send a strong signal that further emissions reductions are necessary, including those often considered to be high cost. This may enable other mitigation which is high-cost relative to current prices but low cost relative to DACCS.

Other issues that need to be addressed

Hence, market-based allocation would likely concentrate permanent removals among wealthy consumers, for example business class air travellers, who are most able to pay. These price-driven outcomes may fail to meet other economic or social or environmental objectives, for example wider economic development, or may be inequitable. Other sectors may be priced out of the permanent removals markets, or the use of cheaper temporary removals may be incentivised if their use is not regulated. A prime example is agriculture and food production, where individual farmers would not be able to pay the high price of wealthy consumers to counterbalance residual emissions, with unfavourable implications for food prices and food security highly likely. The high cost may act as a disincentive to entities wanting to acquire removals as reparations for historical emissions.

In practice, these problems can be mitigated to some extent by via regulation, or at least partial regulation. For example, emissions and removals from land use may be kept separate from those in industry and transport, thereby limiting the fungibility between the fast and slow carbon cycles.

One example of an ETS that includes removals is the New Zealand ETS. Owners of forests that meet (specified requirements can earn New Zealand Units (NZUs) by carrying out recognised removals activities. Owners of forests that meet the requirements of the system, for example a certain size, height, and crown cover can earn NZUs by carrying out a recognised "Removal Activity". Eligible removal activities include, among others, embedding GHG in a product, storing CO_2 after capture, or exporting or destroying bulk synthetic GHG such as hydrofluorocarbon (HFC) and perfluoro- carbon (PFC) gases. Removal units for forestry and industrial activities are not bound by the overall limit and add to overall market supply (NEGEM D6.1). However, many of these activities are not removals as defined here.

Other governments are also considering market-based allocation systems. For example, the UK government has recently concluded that the UK Emissions Trading System (UK ETS) is an appropriate long-term market for greenhouse gas removals (GGRs). It intends to include engineered GGRs in the UK ETS, subject to further consultation, a robust MRV regime being in place, and management of wider impacts. Incorporation of removals in the EU Emissions Trading System is also being discussed, with the European Commission tasked with examining the viability of doing so in a report due to be published in 2026. However, adoption of such measures in the EU appears likely only in the longer term, perhaps in the mid-to-late 2030s or beyond, if at all. This in part reflects concerns about the effects of early inclusion of removals in the EUETS, in particular that they may weaken incentives for emissions reductions (mitigation deterrence) as well as a reflection of the concerns raised in this section as to whether ETS inclusion is a credible way of allocating the use of NETPs.

3.2.2 Allocation based on regulatory compliance at sectoral level with market-based purchase

Jurisdictions may adopt arrangements where remaining emitters are obliged to balance any emissions with removals. Conceptually this is similar to a one-sided ETS where removals are purchased but does not consider removals and emissions to be fungible within the same market. Regulation would permit certain categories and quantities of emission that may be distinguished by GHG and activity. For example, governments may require emitters or emitting sectors to buy a specified quantity of certified removals, or to buy units to balance emissions at the sector or subsector level. The purchase price may be set by multiple markets corresponding to different sectors, or may be regulated, for example because prices are set by a central carbon bank (see below).

Requirements to purchase removals units may then be allocated within each sector based on specified rules. It may be achieved in some cases simply by excluding them from the scope of other regulations, for example mandates or an ETS. Governments would still have the obligation to ensure that overall limits on net emissions were respected. Hence, both the economic viability and climate benefits are considered in regulation, therefore some emissions may be permitted for longer to enable a just transition with higher overall societal benefits.

Certificates may be fungible within limits, and secondary markets may emerge. However, there would be no formal structure of tradable allowances, allowance surrender requirements and centralised auctions of the type found in an ETS. In the longer term there may be additional demand for removals from governments or other entities with obligations to achieve net negative emissions. This could, for example, be in the form of tenders for defined quantities of removals.

Sectoral requirements are nevertheless consistent with market-based mechanisms such as an ETS. Indeed, as ETS are likely only to be applicable in some sectors due to MRV requirements and other factors it will be necessary to define approaches where they are not applicable.

This approach gives more control over allocation of different units to sectors. However, it will correspondingly require close management of MRV at the sectoral levels.

This approach may allow more flexibility than a market-based approach in treatment of different sectors that may extend to both the level of targets and the design of compliance. This may enable equity issues associated with exclusive reliance on markets to be addressed. It could address inequality issues between sectors due to their different purchasing powers in a purely market-determined allocation approach. It would also allow the separation, and management, of international aviation and shipping emissions from national emissions.

Furthermore, in regulating which type of removals are considered valid, the principle of matching GHG atmosphere residence time and removal storage permanence type must be adhered to. Sectors emitting fossil carbon may require permanent removals to geological storage, while emissions from land use change may be balanced by removals to biological stores that are more temporary.

Imposing requirements on sectors can help accommodate differences in characteristics of both removals and emissions. For example, it seems unlikely that N_2O from agriculture would be able to meet requirements by using only geological storage, as emissions are too large. Instead, a requirement for N_2O in agriculture could be set that specifies:

- reductions in N_2O emissions and limits to the quantity of removals that can be used,
- the validity of certain types of removals,
- the exchange rate for N_2O emissions relative to CO_2 removals, and
- any buffer stock that may be required in view of N_2O's long lifetime in the atmosphere (approximately 109 years[37]).

Risks of economic inefficiencies

Unduly fine-grained disaggregation of sectors, for example within the industrial sector, could lead to inefficiencies. There would inevitably be risks of large mismatches between required and available volumes of removals. This could lead to unexpectedly high or low demand or supply in some sectors, with correspondingly much higher or lower prices in different markets for similar products. This would in turn lead to a misallocation of resources to less high value activity. Highly disaggregated markets would allow with fewer opportunities to mitigate these risks by allowing fungibility across sectors than under a comprehensive ETS.

The potential for greater discretion in decision making

A variant of this approach that mixes regulation with partial market-based allocation allows for more flexible implementation than a fully rules-driven allocation. There would still be regulatory permitting in each sector with emissions only allowed where they have the necessary approvals. However, under this variant there would be more discretion in application. There would be guidance, around which emissions may continue, but with decisions made on a case-by-case basis. For example, certain emitters may be allowed to continue operating because they are deemed important enough by the local community or regional economy to qualify as residual emissions.

3.2.3 Allocation based on compliance at sectoral level with centralised purchases

Allocation could be managed by a single entity, a “CDR bank” or “Carbon Bank” or “Carbon Central Bank” with risks managed centrally. The CDR bank would buy removals and (potentially) sell removals units to emitters. Emitters would buy from a pool, or (more likely) from a set of pools of different types of certificates. This could replace emitters trading directly with projects, or it could complement direct trading between emitters and projects, with emitters pursuing a mixture of direct purchase from removals projects and purchases from the Carbon Bank. Under some variants of this option the Carbon Bank could act as a single buyer for removals, at least for some types of removal.

A CDR bank would enable the aggregate risks to be centrally managed. The bank would likely need to be state owned, or regulated, to be able to manage risks as required. It seems unlikely that private sector entities alone could manage or accept all the risks across all types of removal. We note, in line with other commentators, that the functions of a Carbon Bank are separate from those of formal removal certification. The Bank would manage the risk of removals and purchase of units but the actual certification process could be carried out by a third party. For example, previous proposals[76] have suggested three new institutions, a European Carbon Central Bank, a Carbon Removal Certification Authority and a Green Leap Innovation Authority. Under some variants of this option the Carbon Bank could act as a single buyer for removals, at least for some categories of removals.

This approach has several advantages. It could aid market liquidity by taking on risks around CDR units, increasing total supply, including by de-risking removals that would otherwise be too risky. However, it would, correspondingly, require risks to be managed by the bank, which would in turn placing risks on government. Furthermore, rules governing allocation and sale of units could help distribute units to where they are most useful for meeting policy objectives. An additional advantage could be the possibility for the bank to finance activities which do not necessarily generate units or credits, such as pilot deployment, underlying infrastructure, riskier and less quantifiable CDR approaches, should it be empowered to provide activity-based finance. This would be a more managed approach to making use of scarce resources.

There are also variants in which governments would act as the only buyer of removal units. Correspondingly, there would be no obligation on emitters to buy removals. Instead, governments could take responsibility for balancing national GHG accounts by buying removal units. Removals would be procured, for example, by tender or reverse auction. Procurement could draw on lessons from the UK woodland trust, which buys removals from forestry through contracts bought at auction.

There would nevertheless usually be an expectation that emitters generate the funding required to finance the purchase of removals under the Polluter Pays Principle (PPP). Funding could come from a levy on emitters, for example by a carbon tax. The method of funding could allow for different distributions of costs among emitters and sectors, for example by varying the level of the tax or levy between sectors.

Purchases by governments may be separate for different types of removals. This could take the form of separate auctions for separate forms of CDR, analogous to those for different types of renewable electricity. This would likely lead to different prices for different types of removals.

There would thus, under this approach, be considerable flexibility in the allocation of both volumes of removals and costs. This potentially allows for greater alignment with wider objectives, including climate targets, than a purely ETS based approach or even a sectoral obligations-based approach. However, there are risks compared to a more fully market-based approach:

- In the absence of markets for removals, good projects may struggle to find funding. This suggests that procurement of removals needs to be competitive, for example with reverse auctions for Contracts for Differences (CfDs).
- There will be a risk of curtailing high value economic activity by allocating insufficient removals to those activities. For example, if a sectoral cap or net zero requirement were put in place and few CDR credits were issued to that sector, then there would be the possibility of too few to removals to allow valuable activity to take place. For example, allocating too few CDR credits to aviation may lead to the number of flights may be unduly constrained. Addressing this issue may require trading or other mitigating actions.

However, this centralised approach is much better suited to handling the issue of over- or under-allocating CDR in a physically and socially credible manner which is likely to result in a system-wide balancing of emissions with removals within the given system (e.g., global, national, sectoral), rather than with an individual entity.

3.2.4 Allocation based on use case type (EU CRCF)

Robust regulation of carbon removals and the associated certification frameworks is not currently in place to provide potential suppliers of removals with confidence to invest in expensive technology, provide potential consumer/buyers with certainty in their contributions, assign liability in the case of storage reversal, and to provide societies with safeguards on environmental and social implications of this novel field. The EU is currently developing a framework for the certification of carbon removals (CRCF) although the units of carbon removal and how these will be used for each NETP is still unclear. At time of press, the European Parliament, European Council, and the Commission are negotiating on the final contents of the legislative proposal prior to adoption. It is possible that the final agreement will expand the scope from removals and will distinguish between carbon removals, carbon farming (both reductions in emissions and increase in sequestration), and carbon storage in products. This distinction is founded in differences in the physical climate impact each activity has, i.e., the range of storage permanence and uncertainty of storage durability, as well as potential co-benefits. These characteristics, detailed already in Section 2.1, are all relevant for how the units arising from the carbon capture and storage activity could be used in each category.

This certification framework is intended to be considered as an example of best practice using transparent and standardised methodologies to incentivise activities, determine investment priorities and resource allocation, and distribute benefits in different and responsible ways, however its broader scope than just removals makes it challenging to rely on as a tool for CDR at this stage. For example, the framework also intends to provide an incentive to reduce net emissions profiles in agriculture. In many cases these expand on current natural carbon sinks, current infrastructure, and often have co-benefits that reduce non-GHG sources.

Nevertheless, it may be possible to use the framework to incentivise the procurement of products that enhance carbon storage in their materials or in agricultural soils, as this could extend the storage lifetime of carbon.

However, these activities do not meet the definitional requirements of NETPs (see Section 2), especially because of their impermanence, and should there not be used to counterbalance residual emissions.

The criteria requiring high certainty in storage permanence and quantification could provide confidence for investment in novel transport, storage, and energy infrastructure for high quality carbon removals and units with a demonstrable impact in reducing atmospheric CO_2 concentrations. These permanent carbon removal certificates, once they can be generated by the certification framework, could be used as the underlying basis for the approaches discussed in previous sections of this report. However, the certification framework itself is not fit for purpose in planning for the allocation of removals in a physically and socially credible way, instead failing to insert guardrails on how certificates should be used at all.

As such, the EU's Carbon Removal Certification Framework, and the EU more generally, should address the potential mismatch between the demand and supply of NETPs by establishing separate targets (for emission reductions, removals in the land sink, and removals in the geological sink) in the near future and internalising the concerns surrounding the credible use of removals raised in this report.

3.3 Other potential risks in NETP allocation

3.3.1 Efficient and sustainable use of natural resources

This analysis has so far discussed sectoral interests and demand for NETPs, while omitting an important part of the discussion in NETP allocation. Each NETP has different natural and physical resource requirements and environmental[77] and social impacts (see also Section 2, also D3.10 and Chiquier et al.[78], Qiu et al.[77]. The technology used by Carbfix[x] to mineralise carbon is a simple example of this as it can only be used in areas where the Earth's crust is primarily basaltic and has a favourable chemical composition[79]. Additional considerations are financial resources and technical know-how to deploy NETPs at scale. Broadly speaking, historical polluting countries or regions have a higher capacity to finance rapid scaling of NETPs than emerging economies. However, it would be problematic for this to translate into historical polluters being able to lay claim to all of the CDR they are financing.

Hence the most efficient and rapid way to remove and permanently store carbon will not equally distribute CDR capacity among countries[78], nor necessarily align with expected demand to meet domestic net-zero targets[80]. Yet net-zero remains a global climate objective to be reached that should arise from the cumulative contributions of each country. Some countries argue that historical polluters should foot the bill for their prior activities by reaching Net Zero earlier than other countries. Should countries, or sectors, with the higher capacity to remove and store carbon in a physically credible manner, be obliged to maximise CDR for the benefit of humankind? Morally, this would be the right pathway to pursue but difficult in reality to incentivise on the basis of goodwill alone. These political and diplomatic conversations on how to achieve Net Zero on a global level and acknowledge how common but differentiated responsibilities on NETPs may look, need to happen.

3.3.2 Risk of mitigation deterrence

A common objection to the use of NETPs, and specifically their inclusion in Emissions Trading Systems, is that they will deter reduction of emissions because they allow the alternative of removals (NEGEM D6.1). The perception that there will be an alternative to mitigation (emissions reduction) may deter reductions, even if those removals do not exist, because investors perceive that they may to exist in future. The existence of future action may deter investment in emission reductions now, but this delay in emissions reductions may also disproportionately increase the burden to remove the fair-share of carbon in future[81].

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[x] See also: https://www.carbfix.com/how-it-works

However, to the extent that it remains a concern the following actions can reduce the risk:

- Implement separate targets for emission reductions, removals in the short-term biosphere sink and permanent carbon removals.
- Clarification of the types of removal that may be allowed, especially in an ETS. This will clarify the likely status of removals into geological storage, and their likely scarcity. It will also highlight the limitations of removals to biogenic sinks.

Furthermore, in some case visibility of the scarcity and high costs of removals may in some cases encourage emissions reductions.

We note that parallel problems arise with assumptions of widespread availability of biofuels. Although biofuels have an important role to play, there are limits on how much can in practice be produced without unacceptable impacts on biodiversity, and some biofuels may not be carbon neutral on a lifecycle basis. Supply may consequently be less than assumed.

3.3.3 Inequity in distribution of benefits and burdens

NETPs produce a public good – a safer and more stable climate. However, the creation of NETPs and accompanying carbon removal units, involves many private benefits and costs, and the allocation of these raises significant equity issues, which will require careful attention.

Equity issues arise in several contexts.

Within countries: There may be tensions for example between land-owners and tenants on the sharing of rewards, with the risk of elite capture. More broadly, there may be tensions between industrial and agricultural interest groups which may not produce equitable outcomes.

Between countries: Richer countries (including North America, Europe, China, other prosperous Asian Economies, and the Gulf Cooperation Council countries) may be able to buy removals from poorer countries, which may in turn restrict the options open to poorer countries. This risk to climate justice may be an especially difficult problem if high value uses such as aviation are concentrated in richer countries and they use land-based NETPs from poorer countries, in effect buying up their territory[82]. At worst this could become a sort of “carbon neo-colonialism” where richer buyers control important aspects of the development of poorer countries and outsources the burdens associated with NETP deployment[83]. This may extend to a variant of the “resource” curse where natural resources, in this case the availability of sinks, harms wider development.

Between generations: Land use removals will need to be maintained indefinitely. This places a burden on future generations, who will need to bear the costs of maintaining the carbon in place (e.g. as a forest), replacing it with a similar sink, or placing it in geological storage and the associated MRV. In contrast, a tonne of CO_2 not emitted now (i.e. an avoided tonne of emissions) will impose no costs on future generations. This is among the reasons why short-term land-based removals can never be equivalent to reducing emissions. An analogy has been drawn with the Sisyphus pushing a boulder to the top of a hill only to have to do so again the next day[84], with the additional difficulty of having to moving an ever-larger boulder (or a growing volume of land-based NETPs) up an ever-steeper slope (or growing risk of reversal from natural and man-made disturbances due to climate change).

3.3.4 Risk of false equivalency and carbon “tunnel vision”

There is a risk that NETPs are viewed as equal and opposite to reductions in emissions, although their climate impact is not the same. Removals mean that the GHG is first emitted and then later extracted from the atmosphere, potentially decades later. During that period between emission and removal the GHG has a physical impact on the climate and contributes to warming that would be neglected. Furthermore, this gambles on the scale up of NETPs to retrieve this emitted carbon in the future. This temporal discrepancy is also crucial because the Earth system has many tipping points like ice sheet melt, rainforest destabilisation, changes in ocean and atmospheric circulation patterns[85–87] or even a reversal in natural sinks to CO_2 sources[60]. The Earth's climate system exhibits multiple examples of hysteresis[88] , so while the amount of carbon removed may equal the amount of fossil carbon initially extracted, the Earth's climate system may never return to its original state.

This temporal discrepancy is also relevant for the emission of GHGs other than CO_2 that contribute to warming. As previously mentioned, NETPs only remove carbon dioxide because the technologies cannot effectively remove other more dilute GHGs. Hence, there is a risk of a false equivalency arising between i) the impact of emissions reduction of all GHGs, and ii) the impact of the removal of CO_2 although different GHGs with different residence times and climate forcing capacity that may be emitted (CO_2, CH_4, N_2O). This would increase the relative contribution of non-CO_2 GHGs to the future climate risks.

NETPs also run the risk of "carbon tunnel vision" highlighting only carbon-related climate impacts while neglecting other planetary boundaries that are being transgressed[89] and where other Earth subsystems such as global sea levels may continue to change long after CO_2 concentrations have stabilised[90]. Assessing NETPs under this myopic carbon lens risks a fair evaluation of the holistic impacts, trade-offs or benefits, on our Earth system as a whole. The overall imprint of NETPs should be positive with clear benefits to climate and society.

4 Conclusions and further steps

Expectations surrounding what role NETPs will play in achieving net-zero targets need to be carefully managed because the amount of permanent carbon removals is and will remain a scarce resource. Previous work from the NEGEM consortium and other scientific literature reviewed in Section 2 has highlighted how NETP availability is low thus currently has limited capacity to remove and permanently store carbon. Future growth in CDR capacity is unknown and the scale-up rate will depend on many factors – financial, physical, social - but will certainly remain well below the magnitude of current GHG emissions *and* anticipated demand from residual emissions. Work from the NEGEM consortium and our own estimates indicate that the costs of permanent removals are high and are subject to large uncertainties but will likely remain over \$300/tCO_2 for DACCS in the 2050s while the scale of availability for DACCS and BioCCS will highly likely be less than about 1.0-1.2 Gt CO_2 yr^{-1} by 2050, and probably much less . There are large uncertainties on the availability of BioCCS. Costs appear likely to be lower in at least some cases, but with the additional uncertainties around the scale of the biomass resource.

All sectors will need to undergo drastic decarbonisation, with most sectors requiring full decarbonisation. We anticipate emissions reductions of more than 90% of current emissions will be needed to meet net-zero targets with many sectors close to 100%. No single sector or activity should assume that it will not need to radically change and eliminate as many emissions as possible. Almost all sectors have options to abate fossil fuel emissions or to shift away from fossil fuels altogether. Even for sectors understood as being particularly challenging, such as aviation and agriculture, a swathe of measures can and should be applied to significantly cut emissions.

The best use of physical, financial, and social resources is to reduce atmospheric concentrations of GHGs by reducing emissions in the first place. Minimising the amount of GHGs that enter the atmosphere from anthropogenic activities will not only minimise changes to our climate systems, but also reduce the dependence on future CDR capacity to meet climate targets. More carbon of fossil origin above ground means more CDR will be needed to return it to stable reservoirs. Many NETPs are energy intensive and will inevitably entail larger shifts in novel infrastructure and in resource allocation to accommodate it. To rely on projections of future CDR capacity based on our current understanding of the Earth system and its feedback cycles is a gamble. Higher projections of CDR capacity in models cannot fully capture the uncertainty and nuance of CDR because they often utilise idealised representations with reduced complexity (e.g., cost-optimised integrated assessment models) based on our current understanding of physical and social systems and interactions. This is a limitation of these projections, and we should therefore understand these models as indications of a highly uncertain upper bound on potential CDR capacity, costs and impacts rather than as harbingers of what will happen.

While capacity may be limited, CDR will be essential to reach net-zero targets to counterbalance what is designated as residual GHG emissions. Some sectors and activities will continue to emit some GHGs that cannot be fully abated. It is not yet clear which emissions will be classified as "residual emissions" in future, nor who will have the authority to determine this, but it is likely to include GHGs other than CO_2. Every emission, also "residual" emissions, could be abated and instead the question is, *which emissions do we consider socially or politically necessary that we are willing to pay for the damage they incur?* Nevertheless, whatever we do class as residual emissions will need to be low enough to be matched by the available volume of CO_2 removal.

Although the initial question posed was "Who should use NETPs?", we identified two key underlying aspects: 1) the deployment of NETPs i.e., who should use the natural resources to remove and store carbon, and 2) the utilisation of the negative emissions generated by these activities i.e., who should use the NETPs to counterbalance their emissions? Responsible implementation and expansion of NETPs should be strategic and consider the efficient use of limited natural, engineering, and economic resources, the CDR efficiency and storage permanence.

Instruments and mechanisms must ensure that the NETP allocation has a credible and verifiable impact that aligns with sustainable resource use and sustainable development goals and does not exert additional pressure on planetary boundaries. A recurring question arising in this report reflects current discourse surrounding net-zero ambitions[25]: What will be defined socially or politically, as infeasible to fully abate? This question itself underpins the justification for any sector being permitted to rely on CDR more heavily than other sectors, which is ultimately a political and social question which cannot be answered in this paper. However, a general point can be made that remaining emissions to be counterbalanced by removals should have the greatest societal benefit as possible, potentially discounting the value of counterbalancing emissions from aviation, a sector typically associated with a relatively small and affluent part of society. Overall, the use of allocated NETPs should be seen as a public good, where all sectors of society benefit from their use and are not unfairly burdened. Leaving such decisions to individual entities is likely to produce unjust outcomes compared to a more centrally managed or coordinated approach.

Use of NETPs should generate a clear benefit to societies by ensuring counterbalancing of emissions is achieved at a system-level, rather than simply at the individual-level. It is not yet clear how NETPs will be shared and who will decide on this allocation. Each interested 'user' of NETPs will be identified by different needs, capacities, and motivation. We have highlighted relevant aspects to contemplate for the deployment of NETPs and how these will be shared amongst users that include: need to counterbalance in hard-to-abate sectors, CDR efficiency and sustainable natural resource use, moral responsibility to address historical emissions, ability to pay, social equity of benefits and burdens. With these aspects in mind, mechanisms which expect individual actors to counterbalance their own emissions have a significantly higher risk of deterring achievable emission reductions and producing outcomes which are not equitable. The counterbalancing of emissions should be achieved by simultaneously minimising emissions and maximising the sustainable deployment of removals at a societal level, designing policy mechanisms with those separate objectives in mind. Deployment of removals should not be at the expense of planetary health, or societal prosperity and allocation to individual actors should be avoided due to risk of unfair distribution of benefits and burdens.

For preparing this report, the following deliverable/s have been taken into consideration:

D#	Deliverable title	Lead Beneficiary	Type	Dissemination level	Due date (in MM)
D3.2	Report on global NETP biogeochemical potential and impact analysis constrained by interacting planetary boundaries	PIK	R	PU	24
D3.3	Report on global assessment of NETP impacts utilising concepts of biosphere integrity	PIK	R	PU	24
D3.7	Report on global impacts of NETP potentials on food security and freshwater availability, scenario analysis of options and management choices	PIK	R	PU	36
D3.8	Report on the comparative life-cycle sustainability assessment of NETPs for impacts on human health, ecological functions and resources	ETH	R	PU	24
D3.10	Report on synoptic assessment of global theoretical NETP potentials	PIK	R	PU	36
D5.4	Final Report on Expert Elicitation for NETPs	UCAM	R	PU	36
D6.1	Publication “How do NETPs fit in existing climate frameworks?”	CMW	R	PU	36
D6.2	Publication “Principles for carbon negative accounting”	CMW	R	PU	18
D6.3	Publication “Global governance of NETPs – global supply chains and coherent accounting”	BELLONA	R	PU	30
D8.1	Report on “Stocktaking of scenarios with negative emission technologies and practices – Documentation of the vision making process and initial NEGEM vision	VTT	R	PU	8

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