

# Overshoot and Recover? On the Problem of Substitution between Negative Emissions and Emissions Reductions

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## **Abstract**

The remaining global carbon budget is so small that carbon dioxide removal (CDR) measures are very likely to be required to avoid dangerous climate change. Multiple scenarios consistent with a high probability of limiting global warming to well below 2°C include removing hundreds of gigatons of carbon dioxide. At the same time, deep decarbonization pathways show that rapid and drastic emissions reductions can substantially reduce or even avoid the need for CDR. This article discusses one major problem raised by pathways relying on large-scale CDR: by potentially discouraging or at least delaying the implementation of deep decarbonization measures, such pathways might cause a substantial overshoot of the global carbon budget that would lead to severe injustices. More specifically, it highlights the problem of substitution between large-scale CDR and deep emissions reductions by explaining the structure of this problem, stressing the ethical issues it raises, and investigating three conditions under which it is likely to occur.

## **Keywords**

Mitigation, carbon dioxide removal (CDR), negative emissions techniques (NETs), scenarios, decarbonization, justice

## **Introduction**

To avoid dangerous anthropogenic interference with the climate system, our remaining global carbon budget must not be exhausted.<sup>1</sup> Determining what counts as dangerous climate change is a complex matter that involves juggling both empirical and normative considerations (Moellendorf, 2014). Despite this complexity, it has become clear that if we are to comply with the overall goal of the Paris Agreement to limit global warming to ‘well below 2°C’ while ‘pursuing efforts to limit the temperature increase to 1.5°C’ (UNFCCC, 2015, art. 2.1), the remaining budget is small and rapidly shrinking (see e.g., IPCC, 2022a: 10).

What can be done about this planetary predicament? The most obvious response is to reduce global GHG emissions quickly and drastically. But what if we<sup>2</sup> do not do so quickly or drastically enough? This is where the idea of carbon dioxide removal (CDR) comes into play. CDR makes it possible to adjust the initial carbon budget by integrating the removal of excessive carbon dioxide emissions from the atmosphere into climate models through the use of so-called ‘negative emissions’. Unsurprisingly, CDR has become a major topic in scientific, political, and legal debates on climate change over the last decade. As a critical reaction to this, the field of the ethics of CDR has started to emerge over the last few years (see e.g., Lenzi, 2018; Shue, 2021; Lenzi et al., 2023; Mintz-Woo, 2023; Voget-Kleschin et al., 2024; Paiusco, 2025). Although there are currently just a few CDR prototypes and projects, climate models already rely heavily on negative emissions in the order of several tens to several hundreds of GtCO<sub>2</sub> over the 21<sup>st</sup> century (see e.g., IPCC, 2022a: 25).

Large-scale CDR would allow us to expand our very limited global carbon budget, so that the overshoot of the remaining budget during the century would be compatible with achieving stringent warming targets by 2100. Given current emissions trajectories and the limited results of subnational, national and international mitigation policies, it seems like a long-awaited *deus ex machina*. The idea that hundreds of gigatons of negative emissions will be available in the coming decades is, however, problematic: it might encourage to ‘overshoot’ our carbon budget and later ‘recover’ by removing the excessive GHG emissions from the atmosphere, without any guarantee that this will be economically, technologically, politically, or biophysically possible – or, indeed, ethically desirable. The idea of overshooting and using CDR to recover at a later point is now integrated into most scenarios compatible with the Paris Agreement climate goals, without much debate on the ethical aspects of such a construct. This paper argues that there is a risk for negative emissions to be perceived as a substitute for emissions reductions, when they are at best a complement.

The first section defines the key characteristics of CDR that will be useful for the argument developed in the rest of the analysis. The next two sections explain the structure of the substitution problem and highlight why it is a serious ethical issue, based on harm avoidance justice and burden-sharing justice considerations. The following section explores a pathway in which the substitution problem is mitigated. Finally, the last two sections highlight three conditions that make the risk of substitution more likely and respond to two objections related to the third condition. The basic normative claim is that, given the moral challenges and deep uncertainties that come with large-scale CDR, there is a moral imperative to avoid the overshoot, or at least keep it as small as possible, for the sake of young people and future generations. The methods used to support this claim are conceptual analysis and normative argumentation from a political philosophy perspective.

The main objective of the paper is to contribute to the emerging field of the ethics of CDR by focusing on the substitution problem. This is significant for two reasons. First, normative approaches to CDR (whether from an ethical or political theory perspective) remain marginal in academic publications on CDR, especially compared to contributions from natural and agricultural sciences.<sup>3</sup> Second, CDR also remains marginal in the climate ethics literature, especially compared to philosophical contributions on solar radiation management (SRM) (for a review of the literature, see Pamplany et al. (2020)). Normative perspectives on CDR are emerging, and I engage with contributions that are relevant for my argument below, but, to my knowledge, this is the first paper to discuss at length the problem of substitution between emissions reductions and negative emissions from a philosophical perspective.<sup>4</sup> The paper contributes to the literature in the following way: it highlights the ethical problems raised by the substitution problem by drawing on the distinction between harm avoidance justice and burden-sharing justice; it explains why deep decarbonization pathways (DDPs) with limited or no reliance on CDR are ethically superior to pathways that heavily rely on CDR; and it discusses three conditions that increase the likelihood of the risk of substitution.

## **1. Defining CDR**

According to the IPCC (2014: 4), mitigation is ‘a human intervention to reduce the sources or enhance the sinks of greenhouse gases.’ This definition follows the UNFCCC (1992, art. 4.2), which states that each Party shall mitigate climate change ‘by limiting its anthropogenic emissions of greenhouse gases and protecting and enhancing its greenhouse gas sinks and reservoirs.’ There are therefore two components to climate change mitigation: reducing GHG emissions and protecting and enhancing the sinks in which GHGs are stored. The first option directly cuts GHG emissions at their source. Replacing fossil fuels with renewable energies, promoting energy efficiency, and reducing energy use all fit into this category. The second

option is partly based on CDR, that is, on removing CO<sub>2</sub> from the atmosphere to store it in geological, terrestrial, or ocean reservoirs, or in products. CDR relies on three key features: the CO<sub>2</sub> must have been captured from the atmosphere; the storage of CO<sub>2</sub> must be durable; and the removal process must be the result of a human intervention (Smith et al., 2023: 11).

Back in 1992, the UNFCCC only referred to biological ecosystem sinks and ecosystems. It is however fair to assume that the Paris Agreement, which was written after the publication of the IPCC AR5, also (at least implicitly) includes the idea of artificial or intentional removal of GHGs from the atmosphere. This is especially the case when Parties stress that their objective is to ‘achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century’ (UNFCCC, 2015, art. 4.1). This means that, according to the definition of mitigation given by the IPCC, the UNFCCC, and its legal instruments such as the Paris Agreement, *CDR is a form of mitigation* (Honegger, Burns, et al., 2021: 329).<sup>5</sup>

Importantly, there are different *motivations* for CDR deployment. CDR can be used either preventatively to supplement emissions reductions so as to reach carbon neutrality more rapidly and maintain temperature stability (enhancement CDR), or correctively, if emissions reductions and enhancement CDR have not been ambitious enough and an overshoot in the global carbon budget has occurred and needs to be corrected (remedial CDR) (Shue, 2021: 95–96). As we will see below, both enhancement and remedial CDR can work as substitutes for emissions reductions, even if remedial CDR is more likely to do so by supporting the idea that it is possible to recover from a global carbon budget overshoot.

There are also different *degrees* of CDR, ranging from small-scale to large-scale CDR. The definition of the precise threshold that separates small-scale from large-scale CDR is a challenging empirical matter that remains implicit in much of the scientific literature. There is currently no scientific consensus on the line that would separate small-scale from large-scale CDR. Despite this, it still makes sense to maintain this distinction. It is true that CDR projects, whether in bioenergy with carbon capture and storage (BECCS) or other forms, will always be specific to the region they are deployed and customized to the geophysical context (Malhotra and Schmidt, 2020). Taken individually, CDR measures will always be inextricably local in that sense. However, taken collectively, CDR measures can feature in national, international, and global mitigation policies that rely on the absorption of GHGs from the atmosphere at a much larger scale. This is especially the case for policies that rely on integrated assessment models (IAMs), which calculate negative emissions potentials at a global level (Anderson and Peters, 2016). For instance, in modelled pathways that limit warming to 2°C (>67%), the IPCC projects global cumulative CDR during 2020–2100 from BECCS of up to 780 GtCO<sub>2</sub> (IPCC, 2022a: 25). As Lenzi et al. (2018: 304) stress, “typical 2 °C climate scenario requires the funding, construction and operation of as many as 16,000 plants that combine biomass burning with carbon capture and storage by 2050”. This kind of climate scenario relies on large-scale CDR and bets on the possibility to drastically upscale CDR in the coming decades (Fuss et al., 2014). Both small-scale and large-scale CDR raise risks of substitution with emissions reductions, but we will see below that the risk is higher with large-scale CDR.

## 2. The substitution problem

Even though emissions reductions and CDR can both be categorised as mitigation of climate change, it is important to keep a clear separation between them. The first reason is that although both follow the same objective of avoiding a given (i.e., dangerous) level of atmospheric GHG concentration, they do so by pursuing two different strategies with different levels of effectiveness (Heyward, 2013: 25; Jamieson, 2013: 582). While emissions reductions ensure that GHGs remain sequestered in stable geological formations, enhancing sinks takes place

after those GHGs have already been emitted. Sink enhancement might well prove less effective, due to reversal risks (human actions and natural forces disturbing reservoirs of carbon), and/or irreversible climate impacts that would cause additional warming during the carbon budget overshoot period (such as permafrost thawing, weakening of land and ocean carbon sinks, and Amazon forest dieback) (Dooley and Kartha, 2018: 82–83).

The second reason why emissions reductions need to be distinguished from negative emissions is that the carbon cycle response is asymmetric: ‘an emission of CO<sub>2</sub> into the atmosphere is more effective at raising atmospheric CO<sub>2</sub> than a CO<sub>2</sub> removal is at lowering atmospheric CO<sub>2</sub>’ (Zickfeld et al., 2021: 617). This asymmetry increases with the magnitude of the emission or the removal. This means that additional CO<sub>2</sub> removal is needed to compensate for an emission of a given magnitude to attain the same atmospheric CO<sub>2</sub> concentration.

The third and probably most important reason why the two forms of mitigation need to be kept separate is that, under certain circumstances discussed in detail below (section 5), CDR may start to work as a substitute for emissions reductions. This substitution problem is well known in the literature on SRM, where it has been labelled a ‘moral hazard’. The problem with the moral hazard argument against SRM is that it has been interpreted in so many different ways that it has become both ambiguous and vague, making it ‘a sort of catch-all used to refer to a suite of objections and hazards’ (Hale, 2012: 114). For this reason, alternative terminologies have been proposed in the literature. For instance, Baatz (2016) highlights the risk of a ‘trade-off’ between strong emissions reduction actions and SRM. In the literature on CDR, the moral hazard problem has been discussed under the label of ‘mitigation deterrence’, which has been defined as the ‘prospect of reduced or delayed mitigation resulting from the introduction or consideration of another climate intervention’ (Markusson et al., 2018: 1). I do not use the ‘mitigation deterrence’ terminology because, as stressed above, CDR is not a different form of climate intervention from mitigation; it *is* a form of mitigation. The expression ‘mitigation deterrence’ can contribute to the misperception of CDR as an alternative to climate change mitigation. This is why I shall use the terminology of the ‘substitution problem’ to discuss the problem of moral hazard in the context of CDR.<sup>6</sup>

The general idea behind the substitution problem is the following: if CDR is perceived to mitigate climate change at costs and efforts that seem to be comparatively lower than emissions reduction measures, collective and individual agents might be less motivated to implement deep decarbonization measures. The mere prospect of seemingly low-cost negative emissions techniques (NETs) can make many producers, consumers, innovators, and policymakers less inclined to implement rapid and ambitious emissions reductions measures.<sup>7</sup>

A couple of clarifications are in order here. First, the substitution between negative emissions and emissions reductions can occur even if NETs only *seem* less costly than deep decarbonization. This might turn out to be false, because some NETs will likely be more expensive than emissions reductions measures, and because the costs of more severe and frequent climate impacts during the overshoot period as well as the costs of the side effects of NETs in the recovery period can be substantial. It is true that pathways that limit or even avoid global temperature overshoot are associated with higher upfront investments and near-term mitigation costs. According to Riahi et al. (2021: 1065) these costs would amount to a GDP reduction of 0.5–4.8% in scenarios that keep warming below 1.5°C with no or limited overshoot, and of 0.1–1.6% in scenarios that limit warming to 2°C with no or limited overshoot, compared to end-of-century scenarios with overshoot. These higher costs would however be fully compensated in the second half of the 21<sup>st</sup> century: ‘avoiding overshoot would be associated with economic gains in the long term (even without considering benefits of avoided climate impacts)’ (Riahi et al., 2021: 1067). The mere *prospect* of a cheaper solution may lead to current deep decarbonization opportunities being neglected. For the substitution to occur, it

is not necessary for CDR measures to have already been deployed, or to be deployed in the near future. Even if it eventually proves impossible to scale up the deployment of NETs, the belief that large-scale CDR is possible is sufficient for negative emissions to be considered as substitutes for emissions reductions.

Second, the substitution problem can take place both at the individual and at the collective level. For individuals, CDR projects can provide an excuse to delay or avoid lifestyle changes perceived as uncomfortable or overly demanding. DDPs require major efforts from producers in the energy, agriculture, forestry, and land use sectors, alongside profound changes in consumer habits, including significantly reduced road and air travel, stopping meat and dairy consumption, and having fewer children (see section 4). In contrast, the lack of such implications in CDR projects may discourage producers and consumers from necessary questioning of their habits by suggesting an alternative to the lifestyle changes needed to drastically and quickly reduce individual carbon footprints.

At the collective level, CDR measures can serve as an excuse to delay or avoid the implementation of deep decarbonization policies. Budgeting with CDR could allow politicians to stretch the original carbon budget considerably by circumventing initial constraints on global emissions. As Geden (2016: 794) stresses, ‘the introduction of CDR technologies has mainly had the effect of masking political inaction.’ The mere prospect of unproven large-scale CDR could encourage policymakers to mask the inconsistency between talk and decisions in terms of nationally determined contributions (NDCs), especially regarding national climate targets and actual climate action, particularly the rapid decarbonization of national energy supplies. In short, there is a growing gap between declared intentions and actual results, and CDR projects could contribute to concealing and even further widening this gap. This is especially the case in our context of rapid innovation in CDR, with over \$4 billion of publicly funding research globally, a rise in patents, and investment in new CDR capacity of around \$200 million from 2020 to 2022 (Smith et al., 2023: 11).

Let us address two questions raised by this section before moving on to the next. First, is the substitution problem more likely in the case of enhancement CDR or remedial CDR? As a carbon budget overshoot would be the result of mitigation actions that are too weak and too slow, enhancement CDR might, to a certain extent, help avoiding overshoot by removing some of the excessive emissions; in contrast, remedial CDR seems more closely related to overshoot, as its objective is to help recover after the overshoot has occurred. This is correct, but both types of CDR can actually contribute to overshooting the carbon budget: as long as CDR measures are *anticipated*, there is a risk that individual and collective agents perceive CDR as a substitute for decarbonization measures. Conceiving future CDR measures as a substitute for emissions reductions would indeed allow agents to avoid the discomfort that comes with questioning one’s habits or with facing and publicly acknowledging the inconsistency between declared intentions and the policies that are actually implemented. Whether they are preventive or corrective, anticipated CDR measures can work as substitutes for emissions reductions. This is also why arguments against overshoot in general are also arguments against anticipated CDR in particular: as long as CDR discourages or at least delays rapid and ambitious emissions reductions measures, it contributes to the risk of overshoot. This does not mean that negative emissions should not be used in climate scenarios or climate policies; it rather means that they should be used with the utmost caution to ensure that they are not perceived as substitute for emissions reductions (Figure 1 in the conclusion provides some recommendations in this regard).

Second, is the theoretical problem of substitution discussed here observable in reality? At this early stage of development of CDR techniques and policies that rely on these techniques, it is too soon to say. While a recent large-scale online experiment highlights that there is no observable ‘moral hazard’ in the case of SRM (Schoenegger and Mintz-Woo, 2024), another

recent study stresses that although no clear-cut case of ‘mitigation deterrence’ could be identified in the case of EU climate policy relying on CDR, ‘critical opportunities to prevent mitigation deterrence effects have already been missed’ (Brad and Schneider, 2023: 7). Clearly, this does not imply that there will be a substitution between emissions reductions and negative emissions in future EU climate policy, but this paper, together with other studies (see, e.g., Markusson et al., 2018; McLaren, 2020), clearly indicates that there is a risk of substitution in policies relying on CDR, and that this risk should be taken (more) seriously. This is especially the case for policies that rely on IAMs, as they lead to what Lenzi (2018: 2) calls ‘mitigation obstruction by design’: CDR inevitably displaces some near-term emissions reductions measures in these climate models, since scenarios aim to minimize mitigation costs over the century, and the availability of CDR measures lowers the aggregated costs of mitigation. As Lenzi (2018: 2) explains, ‘The extent of mitigation obstructed by scenario design is potentially very large. In one comparison, near-term mitigation is greater by 9.1 gigatonnes of CO<sub>2</sub> by 2030 when NETs were excluded’. If we wait for climate policies relying on CDR and IAMs to be implemented to see if the problem of substitution actually takes place, it will probably be too late, as we will be much closer to the overshoot. This is why it is crucial to anticipate this ethical problem and already take it into account in the design of climate scenarios and policies.

### 3. Harm avoidance and burden-sharing justice

The substitution problem has already been discussed in the literature on CDR. A substitution between negative emissions and emissions reductions is a serious risk, as CDR is insufficient in itself to avoid dangerous climate change: ‘CDR would be too slow, expensive, and technically uncertain to replace the need for rapid emissions reductions’ (Morrow et al., 2020: 150). There are structural biophysical, technological, and economic limits to negative emissions (Smith et al., 2016): ‘NETs may feature in a policy gamble involving less mitigation now, despite being unproven at scale and despite the social and environmental risks this implies’ (Lenzi, 2018: 4). Such a gamble may culminate in a highly troubling scenario: “if the many reservations increasingly voiced about negative-emission technologies (particularly BECCS) turn out to be valid, the weakening of near-term mitigation and the failure of future negative-emission technologies will be a prelude to rapid temperature rises reminiscent of the 4°C “business as usual” pathway feared before the Paris Agreement.” (Anderson and Peters, 2016: 183)

But why would the substitution problem be an *ethical* problem? This question has not yet been examined in detail in the philosophical literature. The major ethical worry is that by potentially discouraging or at least delaying ambitious emissions reductions measure, CDR can contribute to a large overshoot of the global carbon budget. I see two major normative considerations why a large overshoot would be a dangerous ethical risk: harm avoidance justice and burden-sharing justice.<sup>8</sup> The harm avoidance perspective focuses on the plight of the potential victims of climate change and climate policies and technologies, with the task of avoiding (serious) harm to them, typically in terms of threats to fundamental entitlements such as those based on human rights. In contrast, the burden sharing approach is concerned with ensuring fairness among the individual and collective actors responsible for shouldering the climatic burdens of mitigation, adaptation, and loss and damage. These two normative considerations have already been investigated in the climate justice literature, but they have not yet been brought together in an account of the ethics of CDR focused on the risk of overshoot and the substitution problem.

Let us start with *harm avoidance* considerations. A large overshoot of the carbon budget is very likely to be harmful for two main reasons. First, the GHGs that will be emitted after the carbon budget has been exhausted will have some climatic effects for the time that they will

stay in the atmosphere before being potentially removed by CDR. As the IPCC stresses, ‘Risk of severe impacts increase with every additional increment of global warming during overshoot (*high confidence*)’ (IPCC, 2022b: 20). Additional warming caused by an overshoot period above 1.5°C (even more so above 2°C) would result in irreversible impacts on certain ecosystems, with increased risks for infrastructure, low-lying coastal settlements, ecosystem-based adaptation measures, and associated livelihoods. Such severe impacts would lead to avoidable and foreseeable harms, typically by undermining the human rights to health, subsistence, and even life of people disproportionately exposed to these impacts. Less ambitious near-term emissions reductions would cause more harmful climate impacts on vulnerable people and populations, both in present and future generations. Other harms caused by the continued use of fossil fuels include the effects of air pollution on people’s health: more than 10 million premature deaths each year can be attributed to fine particle pollution generated by fossil fuel combustion (Vohra et al., 2021). Harm avoidance justice therefore dictates the immediate implementation of pathways with no or limited overshoot.

A second reason to keep the overshoot as limited as possible can be found in the planetary boundary framework. Earth system scientists stress that once critical tipping points are crossed, there is no coming back (Steffen et al., 2018). If we greatly overshoot the carbon budget, there are significant risks that the planetary threshold of 2°C will be crossed during the century. At this point, the Earth system is likely to follow an ‘essentially irreversible pathway driven by intrinsic biogeophysical feedbacks’ that could lead to a cascade of tipping points pushing the Earth irreversibly into a ‘Hothouse Earth pathway’ (Steffen et al., 2018: 8254). According to Armstrong McKay et al (2022), even within the Paris Agreement range (1.5°C to <2°C), the crossing of six tipping points becomes likely, including the collapse of the Greenland and West Antarctic ice sheets, the die-off of low latitude coral reefs, and widespread and abrupt permafrost thaw. The large overshoot to which the substitution problem could contribute would lead not to temporary, but to irreversible effects in the climate system.

Positive feedback processes may play a more important role than assumed in IPCC scenarios relying on large-scale CDR, ‘limiting the range of potential future trajectories and potentially eliminating the possibility of the intermediate trajectories’ (Steffen et al., 2018: 8253). This means that if the gradually narrowing opportunity to implement ambitious emissions reduction measures is missed, intermediate pathways could also become unachievable as a consequence, leaving room for only for a Hothouse Earth pathway or a scenario involving large-scale SRM and/or CDR. Once we are locked into a large overshoot trajectory, there may be no turning back. Even if large-scale CDR ultimately proves to be biophysically, technologically, and economically feasible, a large overshoot would still impose escalating risks on young people and future generations by committing them either to dangerous climate change, or to endless technological management of the climate system through large-scale SRM and/or CDR. This is a significant ethical problem.

A substitution between CDR and emissions reductions would therefore lead to two different kinds of harm. First, it may increase the probability of foreseeable, avoidable, and irreversible harms to people vulnerable to climate impacts during the large overshoot period. Second, it may harm people by forcing them into situations of moral dilemma, such as having to choose between dangerous climate change and large-scale CDR and/or SRM with potentially catastrophic side effects for themselves and subsequent generations (Ott, 2012). A situation in which one is being forced to make morally bad choices can be considered harmful. As Gardiner stresses, in such cases, ‘we are responsible for putting the first future generation in a position where it must inflict a great harm on the second, and so mar itself’ (Gardiner, 2010: 306). Evils that mar people are particularly problematic because they put innocent individuals in harm’s way and leave a permanent negative mark on the lives of those who brought about the harm by

their agency. While the first kind of harm is best expressed by a violation of human rights, the second corresponds to the imposition of a permanent negative mark on other people's lives.

Turning now to *burden-sharing* considerations, a related argument is that the allocation of mitigation costs would probably be much more unfair in a scenario with a large carbon budget overshoot than in a scenario with a small overshoot or no overshoot. In a large overshoot scenario, a substantial part of mitigation costs is transferred to young people and future generations, who are left with the task to compensate insufficient past mitigation measures with large-scale CDR. By contrast, in a small overshoot scenario or a scenario without any overshoot, the most significant part of mitigation costs is shouldered by members of current generations, as more ambitious emissions reductions measures will be taken in the next few years and decades.

The problem is therefore one of intergenerational costs and risks transfer. A large overshoot would lead to a severely unjust allocation of climate burdens by transferring the costs of the implementation, management, and side effects of CDR to young people and future generations, while avoiding present opportunities to deeply decarbonize our economies. The mitigation measures chosen by present generations will have important implications for how young people and future generations will live. The alternative we are facing today is the following: do we want to bequeath to young people and future generations the 'normal problems' that come with the implementation of a carbon-free energy regime, or the 'extraordinary dangers' that come with a large overshoot and large-scale CDR (Shue, 2021: 114)? This choice can also be summarized the following way (Hansen et al., 2017: 595–596):

If rapid emission reductions are initiated soon, it is still possible that at least a large fraction of required CO<sub>2</sub> extraction can be achieved via relatively natural agricultural and forestry practices with other benefits. On the other hand, if large fossil fuel emissions are allowed to continue, the scale and cost of industrial CO<sub>2</sub> extraction, occurring in conjunction with a deteriorating climate and costly dislocations, may become unmanageable. Simply put, the burden placed on young people and future generations may become too heavy to bear.

Dealing with a small overshoot could be achieved via 'relatively natural agricultural and forestry practices with other benefits' (Hansen et al., 2017: 595). For instance, in addition to storing carbon, the re-establishment of forests can contribute to other sustainable development goals (SDGs) reliant on land, such as SDG 2 ('zero hunger') and SDG 15 ('life on land'). Reforestation using mixed native species in carefully chosen sites can increase biodiversity and restore waterways; likewise, reforestation programs in which local communities play a key role can help secure livelihoods and reduce conflicts (Dooley and Kartha, 2018: 90). In addition to this, 'relatively natural agricultural and forestry practices' can substantially contribute to global mitigation efforts. According to the IPCC AR6, the cumulative mitigation potential of afforestation and reforestation, soil carbon sequestration in croplands and grasslands, agroforestry, peatland and coastal wetland restoration, and improved forest management ranges from 2 to 32.9 GtCO<sub>2</sub> per year, which is considerable (Babiker et al., 2022: 1275–1276; see also Smith et al., 2023: 18–19).

In contrast, dealing with a large overshoot would involve using more problematic options. For instance, trade-offs can arise between BECCS and SDGs, especially when bioenergy production raises food prices, competes with food production for land, and causes food shortages along with water stress, thereby undermining SDG 2 and SDG 15 (Dooley and Kartha, 2018: 91; Honegger, Michaelowa, et al., 2021: 682–684; Shue, 2021: 98–103). In this case, 'the burden placed on young people and future generations may become too heavy to bear' (Hansen et al., 2017: 596). The best strategy would therefore be to develop 'portfolios of multiple NETs, each deployed at modest scales' (Minx et al., 2018: 1), rather than relying on the large-scale deployment of a single technique. The main reason for this, as Shue (2021: 97)

stresses, is that ‘Small-scale CDR using any of several techniques can on balance be helpful, and the worst problems emerge only when one technology for CDR becomes large scale – if, for example, it requires extensive land, water, or energy more urgently needed to grow food instead’. To avoid or at least mitigate the substitution problem here, portfolios of mitigation measures must clearly separate negative emissions measures from emissions reduction measures, and frame the former exclusively as a complement to the latter – CDR should only be conceived as a technical addition to extract unavoidable carbon emissions (see Figure 1 in the conclusion).

Another way of framing this problem of intergenerational risk transfer is to conceive it as a new form of what Gardiner (2011: 148–160) calls ‘intergenerational buck-passing’. Intergenerational buck-passing takes place when current generations engage in actions, such as those associated with fossil-fuel-based consumption, whose benefits accrue largely to them but many of whose costs will be borne by members of future generations. This takes place especially when current generations fail to invest in ‘back-loaded goods’, which refer to efforts such as ambitious emissions reductions measures whose benefits accrue in large part to future generations but whose costs are borne mostly by present generations. Very much like continuing to rely mostly on fossil fuels in the global energy mix, planning to rely on large-scale CDR to recover from a substantial overshoot of the carbon budget can contribute to intergenerational buck-passing by delaying investments in back-loaded goods such as ambitious emissions reductions measures and encouraging measures that benefit present generations at the expense of future generations.

If the argument above is correct, this section has led to two important findings. First, both harm avoidance justice and burden-sharing justice dictate that the carbon budget overshoot should be avoided, or at least kept as small as possible. Second, while context-sensitive agricultural and forestry practices with small-scale BECCS and DACCS represent an acceptable portfolio of NETs, large-scale projects involving thousands of BECCS initiatives should be avoided. The major reason for this is that large-scale CDR is more likely to create trade-offs with SDGs related to hunger and land-based activities. These represent two major reasons for seeing the substitution problem as a serious ethical problem: not only can it contribute to a substantial overshoot of the carbon budget that can lead to severe injustices, but it also encourages large-scale CDR to try to recover from this overshoot, which can threaten SDGs.

#### **4. Deep decarbonisation**

If there is a duty to avoid or keep the overshoot as small as possible, then it should be possible for individual and collective agents to comply with it. As the ‘ought implies can’ principle dictates, agents should not have a duty to do something that is not in their power.

This leads to the following question: is it still possible for a portfolio of mitigation measures to limit global warming to well below 2°C and contribute to efforts to limit the temperature increase to 1.5°C without having to rely on large-scale CDR? Many empirical studies highlight that it is still possible to reply positively to this question (see e.g., Falk et al., 2019: 106; Hansen et al., 2017: 595–596; Rockström et al., 2017: 1271; Strefler et al., 2018: 2–3). There is still a safe operating space for humanity that would substantially limit our reliance on CDR; it would however require radical social, political, and economic reforms, and substantial changes in our lifestyles, behaviours, and habits. Pathways that limit or even avoid global temperature overshoot are still in reach, but, as we saw above, they are associated with higher upfront investment and near-term mitigation costs.

DDPs represent a good illustration of what is required to maintain global temperature rise well below 2°C and contribute to efforts to limit the temperature increase to 1.5°C without

having to rely on large-scale CDR. They rely on three major scenarios focusing on three emissions reduction measures (van Vuuren et al., 2018; Voget-Kleschin et al., 2024). The lifestyle change scenario relies on radical shifts towards more environmentally friendly behaviours such as plant-based diets, changes in transport habits, and reductions of heating and cooling levels. The renewable electricity scenario relies on the substantial expansion of solar and wind technologies, based on their encouraging progress over the last few years. The low-population scenario is based on population policies that would reduce birth rates around the world. None of these scenarios could on its own maintain temperatures well below 2°C or below 1.5°C. However, together, and alongside relevant adaptation and compensation policies, they would substantially reduce the need for CDR.

DDPs also raise important ethical issues. For example, when it comes to the renewable electricity scenario, special attention needs to be paid to energy justice considerations, to ensure that the energy transition does not lead to new distributive, procedural, recognitional or gender injustices (Feenstra and Özerol, 2021). As Voget-Kleschin et al. (2024) stress, however, the vast majority of emissions reductions measures in the three scenarios discussed above are not intrinsically problematic; everything depends on how they are implemented. To take another example, if the low-population scenario is implemented by choice-enhancing population policies that lead to a voluntary reduction of fertility as well as incentives for smaller families that protect prospective parents' autonomy, DDPs can not only promote climate justice by contributing to ambitious mitigation measures, but can also promote social and global justice goals by securing universal access to contraception and promoting equal rights and opportunity for women (Bourban, 2025). In short: while pathways relying on large-scale CDR raise major ethical issues such as those discussed in the previous section, DDPs do not raise similar ethical issues and could even contribute to climate justice, social justice, and global justice goals if properly implemented.

DDPs currently represent an alternative to pathways modelled in IAMs. IAMs typically have limited capacity to integrate new behavioral changes or social structures that affect energy demand. In contrast, low energy demand scenarios integrated into DDPs rely on structural changes such as transportation modal shift to public transport, lower demand for emission intensive materials such as cement, and lower heat demand in building through behavior change and efficiency (Gaur et al., 2022). There are three main options moving forward: keep developing DDPs and IAMs in parallel; start integrating DDPs into IAMs (Sang et al., 2026); or stop relying on IAMs (Anderson and Jewell, 2019).

The upshot is that scenarios focusing primarily on emissions reductions with a good chance of limiting global warming to well below 2°C with no or limited use of CDR are still possible. This is significant, as it shows that large-scale CDR can still be avoided, and that the risk of substitution between emissions reductions and negative emissions can therefore be mitigated.<sup>9</sup>

## **5. Three conditions**

The substitution between emissions reductions and large-scale CDR is not automatic; for the problem to occur, specific conditions need to be met. In this section, I discuss three of those conditions: they are not sufficient to cause a substitution between CDR and emissions reductions, but, taken together, they increase the likelihood of the problem occurring. The three conditions are the following ones:

- (1) Psychological mechanisms must encourage consumers, producers, and policymakers to seek alternatives to deep decarbonization measures.
- (2) Technological solutions must be generally perceived as something positive or desirable.

- (3) The quantity of negative emissions envisioned in influential scenarios must be significant enough to drive people to rely more on technological innovation than on institutional, structural, and behavioural changes.

Regarding condition (1), a major psychological mechanism causing resistance to lifestyle changes is conformity (Gibert, 2015; Joy, 2010). It is a tendency to be conservative, dislike change, and have difficulty questioning one's habits. Members of current generations who grew up in industrial societies have been used to enjoying the benefits of abundant fossil fuels and animal-based products on a daily basis. There is a tendency to find it normal, natural, and necessary to travel by car and plane, use fossil fuel generated electricity, and eat meat and dairy products. The profound questioning this necessitates is psychologically uncomfortable. Other mechanisms behind people's reluctance to change their behaviour include denial, advantageous comparison, diffusion of responsibility, and displacement of responsibility (Peeters et al., 2019). The idea that large-scale CDR can contribute to substantially expanding the global carbon budget may encourage psychological mechanisms of resistance by providing a new excuse not to implement deep and immediate emissions reduction measures at the individual and collective levels.<sup>10</sup>

Let us turn now to condition (2). Industrialized and industrializing societies are characterized by a pro-innovation bias and an ideology of technological optimism. We now live in so-called 'innovation societies' in which technological innovation plays a fundamental role. Both in the literature and in public perception, there is a prevalent pro-innovation bias: the mainstream view conceives technological innovation as something inherently good (Blok and Lemmens, 2015: 31). This bias is partly based on technological optimism, which makes policymakers confident about the efficiency and effectiveness of technological solutions to social, political, and environmental problems. The belief that cheap 'techno-fixes' will help solve climate change without much effort from individuals is ubiquitous. The pro-innovation bias could lead many policymakers to see pathways with large-scale CDR as desirable and as relevant alternatives to DDPs.

This pro-innovation bias is clearly illustrated by the national climate plans of many developed countries, such as the US and the UK (Brisbois, 2022). These plans focus on trendy technological innovations whose effectiveness in terms of mitigating emissions remains unproven, such as hydrogen fuel, new nuclear technology, and CCS, and neglect less glamorous but more effective solutions, such as improved home insulation, free public transport, new cycle lanes, and animal-free proteins. Demand-side mitigation strategies also have co-benefits in terms of well-being: cycling and walking, efficient buildings, and prosumer choices of renewables all have beneficial effects on well-being (Creutzig et al., 2022; Prinzing, 2023). Likewise, vegetarian and vegan diets are generally healthier than alternative diets (Craig and Mangels, 2009). Despite this, new, high-tech innovations continue to be at the forefront of mitigation policies. Some high-tech solutions are of course also needed, but the priority should be to scale up emissions reduction measures that have already proved their mitigation effect, instead of always favouring the newest and most innovative option.

Turning finally to condition (3), it is important to stress that, in the scientific literature, most scenarios that keep global warming well below 2°C and aim for a temperature increase of no more than 1.5°C imply a substantial carbon budget overshoot compensated by hundreds of gigatons of negative emissions over the second half of the century (Riahi et al., 2021: 1063). In large overshoot scenarios, the probability of CDR contributing to undermining ambitious GHG reduction efforts is higher, because it becomes more tempting to rely on NETs rather than institutional, structural, and behavioural changes. Planning to rely heavily on CDR can therefore significantly affect the lifestyle changes we choose (not) to adopt and the policies we choose (not) to implement.

IPCC scenarios play an important role in shaping what is considered as feasible or infeasible in terms of individual and collective climate action over the next few decades. IPCC reports are policy-relevant and policy-neutral, which means that they are not policy-prescriptive (Mahony, 2022). Still, when IPCC authors agreed include speculative NETs in their authoritative mitigation scenarios, they inevitably made value-laden assumptions in projecting different policy pathways: ‘the IPCC included negative emissions technologies in its ‘default’ technology mix, even though some of these solutions might never be viably scaled up.’ (Lenzi et al 2018: 304). This can have an influence on policymakers’ expectations. For instance, in IPCC scenarios with CDR, GHG emissions from fossil fuels and industry can remain as high as 32 GtCO<sub>2</sub> in 2030; in contrast, in scenarios without CDR, emissions must be reduced to 23 GtCO<sub>2</sub> by 2030. In short, the sociotechnical dimensions that are more emphasised and those that are less emphasised play an important role in the choices made by policymakers.

Most IPCC scenarios are characterized by three biases (Kuhnenn et al., 2020: 11): they neglect mitigation opportunities through reductions in economic activity; they rely more on technological solutions than on societal change; and they rely on large-scale CDR. There is a bias towards economic growth and technology fixes in most IPCC scenarios: they tend to underestimate potential changes in economies, societies, and lifestyles and to rely on CDR techniques to avoid dangerous climate change.<sup>11</sup> While the inclusion of large-scale CDR in IPCC scenarios does not represent a prescription by IPCC authors, this controversial choice has the potential of becoming a self-fulfilling prophecy (Mahony, 2022). This is mainly due to the performativity of climate scenarios, which shape our choices by working as a ‘sociotechnical imaginary’ (Parson and Buck, 2020: 74). Such scenarios represent a set of hypothetical measures that are not yet realized but that already influence current policy debate and individual lifestyle choices through the claim of CDR’s ability to remove hundreds of gigatons of carbon dioxide from the atmosphere in the coming decades. As Beck and Oomen (2021) stress, in its role of mapmaker, the IPCC also functions as a corridor-maker: by relying on NETs that can pass the economic tests of IAMs, it left out of the table mitigation measures included in DDPs. This is why it is crucial that future IPCC reports ‘broaden the solution space in a way which goes beyond those solutions deemed feasible within economic models designed to tend towards global economic optimisation’ (Mahony, 2022: 203).

## 6. Two objections

Different objections can be made to this analysis of the problem of substitution. I focus here on two possible objections to condition (3).

The first objection is that IPCC authors, like most scientists discussing CDR, stress that negative emissions should not be conceived as alternatives to emissions reductions. This objection is correct, but given the high risk of substitution between the two mitigation measures, this is not sufficient. At least two additional steps should be taken to properly address the problem of substitution. First, this problem needs to be explicitly recognized in scenarios involving CDR, especially those that rely on large-scale CDR. All the relevant aspects of this problem should be discussed, including its ethical component. This would not go against the policy-neutrality principle of the IPCC, as these ethical issues and limits are discussed in the scientific literature and would not be presented under the form of prescriptions or recommendations, but under the form of information to further clarify the respective risks raised by the different mitigation pathways at hand (this includes of course the risks raised by DDPs).

The second step is that, given the problems raised by CDR, greater emphasis should be put on measures that radically reduce GHG emissions. This applies especially to scenarios that involve small-scale or no CDR. Certainly, climate scientists must inform policymakers about the full scope of possible scenarios, including those relying on large-scale CDR. The inclusion

of CDR in IPCC scenarios was originally meant to keep the possible ‘solution space’ as open as possible for policymakers (Mahony, 2022). However, given the ethical issues raised by such scenarios, as well as the biophysical, technological, and economic limits to NETs, DDPs should occupy a more prominent place among the possible scenarios and should be presented as alternatives to scenarios relying on large-scale CDR. Again, this would not contradict the principle of policy neutrality, as the risks of scenarios relying on large-scale CDR and the advantages of DDPs are well recognised in the scientific literature.

The second objection is that the IPCC AR6 actually already emphasizes deep decarbonization options. For instance, the AR6 WGIII SPM is full of references to emissions reduction measures. The second part of the SPM (‘B’) focuses mostly on ‘low emissions technologies,’ ‘low-GHG technologies,’ and ‘innovation policy packages,’ which seems to indicate that the report remains stuck in pro-innovation bias (IPCC, 2022a: 10–20). However, the third part (‘C’) also includes lifestyle changes that rely on low-tech and non-tech options to reduce emissions, such as ‘balanced, sustainable healthy diets,’ ‘adaptive heating and cooling choices,’ and ‘shifts to walking, cycling, shared pooled and public transit,’ as well as ‘sustainable consumption’ (IPCC, 2022a: 38). The last part of the report (‘D’) also links these demand-side mitigation options with co-benefits in terms of health, employment, energy security, and equity (IPCC, 2022a: 44).

The second objection is therefore sustained. This does not mean that the risk of substitution is sufficiently mitigated; it simply means that one of the exacerbating factors that make this risk more likely is weakening. This strong focus on low-emissions technologies and lifestyle changes in a very influential scientific report – one that discusses modelled global emissions pathways relying on negative emissions of hundreds of GtCO<sub>2</sub> – could contribute to reducing the likelihood of the risk of substitution. We can only hope that future scientific publications will go in the same direction as the AR6 WGIII SPM.

### **Conclusion: five recommendations**

To keep global temperatures well below 2°C and pursue efforts to limit the temperature increase to 1.5°C, it is still possible to rely only on deep decarbonization scenarios that do not involve large-scale CDR. The objective of this article was not to claim that reliance on CDR is unethical; it was rather to explicitly address one major ethical issue raised by large-scale CDR and to explain why DDPs are ethically preferable to pathways relying on large-scale CDR.

Given past and current global emissions trajectories, it is increasingly likely that we will need to resort to some form of CDR measure. But to avoid the ethical risks raised by CDR, the research, development, and deployment of CDR should be subject to strict requirements. Based on the analysis above, the list of requirements summarized in figure 1 can serve to reduce the risk of substitution between negative emissions and emission reductions, focusing both on climate scenarios in scientific research and climate policies designed and implemented by policymakers.

<b>Recognizing and addressing the substitution problem</b>	Climate scenarios that rely on large-scale CDR (on the order of hundreds of gigatons of carbon dioxide) should explicitly acknowledge the substitution problem, clarify its empirical and ethical dimensions, and articulate strategies to avoid or mitigate it.
<b>More emphasis on emissions reductions</b>	Climate scenarios that rely little or not at all on CDR should feature more prominently in scientific assessment reports, including those of the IPCC, to highlight the existence and relevance of mitigation strategies that rely (quasi-)exclusively on emissions reductions, such as deep decarbonization scenarios.
<b>Strict separation between emissions reductions and negative emissions</b>	In climate policies, emissions reductions and negative emissions should be strictly separated, especially when formulating national and international climate targets. NDCs should treat emissions reductions and CDR as separate categories.
<b>Conceiving CDR as a complement</b>	In climate policies, CDR should mainly be used as a complement to emissions reductions in order to reach carbon neutrality more quickly. CDR is primarily a technical addition to extract unavoidable carbon emissions. Conceived, designed, and deployed as a complement, CDR measures are less likely to work as a substitute for emissions reductions measures.
<b>Using CDR on a small scale</b>	In climate policies, CDR measures should be deployed on the smallest possible scale. The larger the scale of deployment, the greater the temptation to see negative emissions as a substitute for emissions reductions (keeping in mind that it is difficult to make a clear distinction between small and large scale).

**Figure 1 - List of Requirements to Reduce the Risk of Substitution**

Importantly, this list is non-exhaustive: additional requirements will be needed to fully address the problem of substitution. It is also important to stress that these considerations are only meant to address one ethical problem raised by CDR: to face other issues, additional requirements will also be needed. These limitations indicate two major areas for future research into the ethics of CDR.

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## Notes

<sup>1</sup> The estimated size of the global carbon budget depends on several considerations (Knutti and Rogelj, 2015: 366): we can take into account only carbon dioxide emissions, or we can include other GHGs; we can choose a higher or lower probability of compliance with the chosen temperature limit; and we can choose a lower or higher temperature limit. Each time we change one variable, we end up with a different carbon budget. For example, choosing a 66% rather than a 50% probability of remaining below 2°C, or aiming for a 1.5°C limit instead, or counting methane as well as carbon dioxide reduces the remaining carbon budget.

<sup>2</sup> In this article, the pronoun ‘we’ refers first and foremost to the policymakers (both citizens and politicians) having a say in framing and implementing mitigation policies. The main reason for this is that policymakers are responsible for developing the appropriate legislative and political framework that would enable individuals and other collective agents, such as cities and corporations, to substantially reduce their carbon footprint. However, ‘we’ can also refer to consumers and producers who have a reasonable range of options to reduce their individual emissions, even if they do not have full control over their carbon footprint. As illustrated below with deep decarbonization pathways, individual lifestyle choices, for example in terms of diets, can substantially reduce the need for CDR.

<sup>3</sup> As Smith et al. (2023: 21) observe, “The scientific literature on CDR is mainly published in natural science (49%), agricultural science (25%) and engineering and technology journals (23%). Only 3% is published in social science journals, and a handful in the humanities.”

<sup>4</sup> In an article published during the last round of revisions to this article, Fulvi and Mintz-Woo (2025) also address the moral hazard argument from a philosophical perspective, but they do so only in the final section; the rest of the analysis focuses on the contribution of a transitional justice approach to the topic of the just transition. In the final section, they take a non-ideal approach to climate justice, arguing that “CDRs can be conducive to a just transition, in light of the gravity of the climate crisis and of the subsequent non-ideal circumstances in which justice is to be achieved”, and that “opposing CDRs because they appear as a moral hazard to less risky and more desirable mitigation alternatives is at odds with a just transition” (Fulvi and Mintz-Woo, 2025: 11–12). Despite their critical appraisal of the moral hazard argument, their approach is not necessarily antithetical to the one I am developing here: while they focus on the conditions that would make CDR permissible, I am more interested in the conditions that make CDR ethically problematic in light of the substitution problem. There is no systematic opposition between my approach and theirs, as I do not support a “notional opposition to CDRs” (Fulvi and Mintz-Woo, 2025: 8); I merely highlight a major risk raised by scenarios and policies relying on large-scale CDR. The idea is not that CDR is inherently ethically problematic, but rather to examine one of the main ethical issues raised by CDR.

<sup>5</sup> CDR can also be categorized as a geoengineering measure, that is, a ‘deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change’ (John Shepherd et al., 2009: 1). This partial overlap between mitigation and geoengineering created confusion around CDR by suggesting two parallel conceptualizing discourses: CDR as a geoengineering method and CDR as a mitigation measure. To avoid this confusion, as well as other issues raised by the term ‘geoengineering’ (see Heyward, 2013), this paper does not categorize CDR as geoengineering.

<sup>6</sup> Note that the expression ‘mitigation deterrence’ would still be relevant in the context of SRM as an alternative to ‘moral hazard’, as SRM methods do not represent mitigation measures. This semantic shift from ‘mitigation deterrence’ to ‘substitution problem’ adds a new expression to a complex problem that has already been discussed in the literature on CDR, but conceptual precision matters, and for the reason pointed out above, ‘substitution problem’ is more relevant and precise than ‘mitigation deterrence’. It is to be expected that terminology replacement will lead to different new expressions, and since the whole point of finding an alternative to ‘moral hazard’ is to improve conceptual clarity, I prefer using ‘substitution problem’, even if this makes it more difficult to track and compare the literature on the topic. Another reason why I think it makes sense to propose an alternative

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to ‘mitigation deterrence’ is that this expression has not been adopted in the literature as the most relevant, as illustrated by the proposal to use ‘mitigation deferral’ instead (see e.g., Lenzi, 2018; Minx et al., 2018; Peacock, 2022) – an expression that runs up against the same limitation since it also reduces mitigation to emissions reductions.

<sup>7</sup> Anderson and Peters (2016: 183) characterized the problem in very similar terms in their early critical analysis of NETs: ‘The promise of future and cost-optimal negative-emission technologies is more politically appealing than the prospect of developing policies to deliver rapid and deep mitigation now’.

<sup>8</sup> For an analysis of these two kinds of justice in the context of climate change, see Caney (2014).

<sup>9</sup> In an early contribution to the ethics of CDR, Morrow and Svoboda explain that a scenario involving ‘aggressive mitigation with a relatively modest CDR program’ is both technically and politically feasible, keeping in mind the large uncertainties that surround CDR techniques (Morrow and Svoboda, 2016: 89). However, they also consider that another kind of scenario would be permissible and feasible, one that involves ‘overshooting wisely’ to enable developing countries to use more fossil fuel for their economic development (Morrow and Svoboda, 2016: 90). Although this second scenario is based on the moral imperative to combat global poverty, it is problematic for several reasons. First, it does not take into account the effects of overshooting the carbon budget on the global poor, which could be, as explained above, very severe. Second, it does not take into account the substitution problem that is more likely to arise once large-scale CDR is being contemplated, as well as the injustices that would be caused by a substitution between emissions reductions and negative emissions. Third, it relies on dubious judgements of technical feasibility of upscaling CDR (it remains unclear whether large-scale implementation of CDR is feasible) and political feasibility of CDR measures (claims about what is politically feasible or infeasible may be disguised statements of willingness or unwillingness to implement certain climate policies: see e.g., Lenzi et al. (2023: 5)).

<sup>10</sup> This idea that the carbon budget can be substantially extended thanks to CDR is especially encouraged by the influence of IAMs on policymaking. As Geden (2016: 793 – emphasis original) explains, ‘Negative emissions allow economists to considerably extend the carbon budget originally set by natural scientists. Both types of budgets work with the same net amount, but the economists’ gross carbon budgets often effectively double the remaining emissions quota, establishing a kind of *carbon debt* to be paid back later in the century’.

<sup>11</sup> This is mostly due to the fact that IPCC scenarios are largely based on IAMs, which assume ongoing global economic growth of 1 to 2.8% over the 21<sup>st</sup> century (Kuhnhehn et al., 2020).