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On economic modeling of carbon dioxide removal: values, bias, and norms for good policy-advising modeling

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Non-technical summary. Integrated assessment models (IAMs) are important scientific tools for advising policymakers and the public on climate mitigation. Recent results of modeling exercises relied upon large amounts of techniques that can capture carbon dioxide from the atmosphere, undoing current and past emissions. I argue that the reliance on such techniques unduly shifts risk to future generations and away from current high emitting countries. From an ethical point of view, this is problematic. IAM studies need to be more explicit about the value positions that evidence of mitigation pathways depends upon and should represent a wider array of plausible value positions.

Technical summary. This paper analyzes the nonepistemic value judgments involved in modeling Carbon Dioxide Removal (CDR) techniques. The comparably high uncertainty of these techniques gives rise to epistemic risk when large-scale CDR is relied upon in most scenario evidence. Technological assumptions on CDR are thus entangled with nonepistemic value judgments. In particular, the reliance on large-scale CDR implies shifting risk to future generations and thereby gives a one-sided answer to questions of intergenerational justice. This bias in integrated assessment modeling is problematic given the policy-advising role of integrated modeling. Modeling climate mitigation should focus on transforming these implicit value positions into explicit scenario parameters and should aim to provide scenario evidence on the complete array of value-laden mitigation strategies.

Social media summary. The ethics of mitigation pathways, for example in relation to CDR, must be made transparent and plural.

1. Introduction

The steady increase of carbon dioxide in the atmosphere is heating up the planet, thereby creating a more dangerous world. At the time of writing, atmospheric CO_2 concentrations stand at 415 ppm, higher than at any point in at least 800,000 years. Concentrations would be even higher if it wasn't for the existence of natural sinks, which have taken up more than half of all the anthropogenic carbon emitted (IPCC, 2013, p. 51). According to scenarios from Integrated Assessment Models (IAMs), these natural sinks need to be accommodated with enormous artificial sinks utilizing *Carbon Dioxide Removal* (CDR) techniques. The appearance of large amounts of CDR in mitigation pathways has, however, come under intense criticism, provoking some fierce objections.[1] The problem is that successfully deploying CDR on large scale is far from proven to work in the real world and is thus often described as a high-risk gamble. However, first facilities exist and thus including such novel techniques into scenarios is seen by modelers rather as an act of neutrality and impartiality, not letting personal values predetermine modeling results (Low & Schäfer, 2020). What is to make of this dispute?

While there are many questions involved in the criticism of CDR, the focus of the present paper is epistemic in asking how CDR should be modeled to serve as a good scientific basis for policy advice. This question arises in the context of a general value-dependence of IAMs. Several contributions have by now highlighted that IAM pathways depend on implicit value judgments, some of which are more entangled than the well-known example of the discount rate.[2] To contribute to this discussion, this paper will show how technological assumptions on CDR are intertwined with value questions and standardly relying on CDR makes modeling results implicitly dependent on a particular normative position. This is problematic because good policy-advising science should be explicit about the normative positions involved and

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[1] Cf. for example Fuss et al. (2014), Geden (2015), Anderson and Peters (2016), Peters (2016), Shue (2017), Beck and Mahony (2018), Lenzi (2018), Anderson (2019). The latest, in line with many previous articles, came in a recent widely recognized blog post by James Dyke and colleagues, calling out the 'ever growing absurdity of the required planetary-scale carbon dioxide removal' (Dyke et al., 2021).

[2] For discussions on value judgments in IAMs, cf. Stanton et al. (2009), Schienke et al. (2011), Gardiner (2011), Frisch (2013), Adler (2016), Kowarsch (2016), Weyant (2017), Frank (2019), Mintz-Woo (2021a). While much of the debate focuses on Cost-Benefit-IAMs, many analyses also apply to Dynamic-Process-IAMs, which are the focus of this paper. DP-IAMs take temperature goals as an explicit input and explore feasible and cost-effective pathways for meeting them.

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aim to provide a pluralistic array of scientific knowledge based on different value positions. Future modeling should aim to be more explicit about the value assumptions in different mitigation scenarios and broaden the value positions represented in them.

The paper will proceed as follows. The second section introduces the apparent mismatch between widespread reliance on CDR and the high uncertainty involved in these techniques (section 2). The high uncertainty gives rise to an analysis of the inclusion of CDR as a case of epistemic risk (section 3). Epistemic risk occurs when there is (for the time being) unresolvable uncertainty in scientific reasoning. In such cases, scientists must evaluate the respective consequences of being wrong. Bringing in common principles from climate ethics, section 4 argues that the epistemic risk analysis would, in this case, suggest being cautious in relying on CDR and setting the required evidence for its feasibility relatively high. This is in stark contrast to the recent practice, in which CDR is a standard feature of most scenarios despite doubts concerning its feasibility. Section 5 argues that the reliance on CDR goes back to a bias at work in integrated modeling. The paper concludes by making a few suggestions on how to improve scenario modeling to fulfill its policy-advising role better (section 6).

2. 'The World's Biggest Gamble'

Carbon Dioxide Removal, or in short CDR, can be defined as the 'intentional human efforts to remove CO_2 emissions from the atmosphere' (Minx et al., 2018, p. 3). The most prominent types of CDR in mitigation pathways are afforestation and bioenergy with carbon capture and storage, in short, 'BECCS'.[3] What unifies different techniques under the label CDR is that they aim to provide 'negative emissions'. Negative emissions promise to compensate for emissions in sectors that are hard to mitigate and allow shifting mitigation requirements into the further future (cf. Fuss et al., 2018, p. 3). Including CDR in IAMs leads to more flexibility in meeting stringent climate targets, which gives rise to CDR's high economic value in the models.

IAMs are computer models, which scientists use to explore how to meet ambitious temperature goals based on scenario assumptions. IAMs aim to simulate the climate system and the socio-economic system in an integrated way to give an overarching perspective on climate change mitigation. The models provide valuable insight into the comparative feasibility and desirability of different climate mitigation strategies.[4] IAMs are one of the central tools of climate economics and fulfill an important role in informing policymakers on climate mitigation, especially through the venue of the IPCC report.

CDR has become an established part of integrated modeling at least by the time of the IPCC's Fifth Assessment Report (AR5), in which negative emissions were 'a feature of most IAM scenarios' (Minx et al., 2018, p. 4). The scale of CDR in IAM scenarios can be enormous: a recent study exploring scenarios compatible with the 1.5 °C goal exhibited negative emissions of 150–1,200 $GtCO_2$ across the 21st century (Rogelj et al., 2018).[5] For comparison, annual CO_2 emissions currently stand at ∼35 $GtCO_2$/yr. The upper end of this range assumes that humanity will be able to remove the cumulative CO_2 emissions from 1980 to this day out of the atmosphere sometime later this century. Even more moderate annual rates of 5 $GtCO_2$/yr would require an industry of the size of today's oil industry, ramped up in just a few decades (Strefler et al., 2018).

The problem with such large-scale reliance on BECCS in the models is that it is highly uncertain if such a massive scale-up is actually feasible. Many authors have criticized the lack of evidence for the overly optimistic assumptions on BECCS in the models.[6] CDR is still far from delivering anywhere close to the scales assumed in the models (Minx et al., 2018). And while the speed of technical innovations has sometimes been underestimated in the past, concerns relating to the build-up of BECCS arise mainly in feasibility dimensions other than the technological. BECCS is not a single technology but a whole supply chain with different natural and technological processes interlinked across different regions and time scales (Butnar et al., 2020). The main feasibility concerns relating to BECCS, as summarized by the SR1.5, are in the ecological, social, institutional, and environmental dimensions of feasibility (IPCC, 2018, table 5.11).[7] The expert assessment in the extensive literature review of Fuss et al., for example, estimates a sustainable potential being in the range from 0.5 to 5 $GtCO_2$/yr by 2050 (Fuss et al., 2018, p. 14), much lower than the 5 to 15 $GtCO_2$/yr assumed in most scenario runs. Leading scientists have therefore dubbed relying on CDR 'the world's biggest gamble' (Rockström et al., 2016). Such a high-stake bet on unproven techniques in mitigation pathways seems epistemically problematic.

The high amounts of negative emissions in recent scenarios have established the perception that the Paris Goals all but force us to rely on large-scale CDR to limit global warming (cf. Beck & Oomen, 2021). In Rogelj et al. (2015), for example, offsetting 60–85% of fossil fuel emissions over the 21st century, CDR is described as making 1.5 °C possible. Moreover, the latest Special Report of the IPCC concluded with high certainty that keeping warming below 1.5 °C requires large amounts of CDR to be feasible at all (IPCC, 2018; Rogelj et al., 2018). BECCS in these runs was described as a 'backstop' to make 1.5 °C feasible (Beck & Oomen, 2021, p. 174). However, drawing a conclusion

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[3] In BECCS, photosynthetic processes capture atmospheric CO_2 in biomass, which is subsequently utilized in various processes and combined with carbon capture and storage to remove CO_2 from the atmosphere permanently. In the modeling environment, it performs especially well since it produces energy (or other valuable products) *and* removes CO_2 from the atmosphere at the same time. Other CDR techniques, so far generally not included in IAMs, are the energy-intense technique of Direct-Air-Capture, or means of intensifying natural sinks, such as enhancing weathering or fertilizing the oceans. The literature reviews of Fuss et al. (2018) and Minx et al. (2018) provide a good introduction to the topic of CDR.

[4] IAMs can be divided into simple cost-benefit-models that aim to compute economically 'optimal' warming levels, and complex dynamic-process models, that answer general questions of feasibility concerning fixed temperature or emission targets. Evans and Hausfather (2018) give a good low-level introduction on CarbonBrief, cf. also Weyant (2017).

[5] The most recent AR6 scenarios feature up to 1000 $GtCO_2$ as well, with the Illustrative Mitigation Pathway for the 1.5 °C scenario, which focuses on wide-spread reliance on CDR ('IMP-Neg'), including around 400–500 $GtCO_2$ (IPCC, 2022, Fig. 3.15). Following Creutzig et al. (2015), one can speak of 'large-scale' for BECCS at a bioenergy contribution above 200 EJ/yr. This corresponds well with the 1.5 °C scenarios, which in Rogelj et al. (2018) in median employ 175 EJ/yr of BECCS to remove ∼15 $GtCO_2$/yr by 2,100.

[6] For example, the expert assessment of Vaughan and Gough (2016) places seven out of ten relevant assumptions within what they call the 'danger zone' of high uncertainty *and* high influence on BECCS potential. Further concerning ecological limits cf. Creutzig et al. (2015), for social and institutional concerns, cf. Fridahl and Lehtveer (2018) and Butnar et al. (2020).

[7] The reports states that BECCS implementation depends 'on biomass availability, CO_2 storage capacity, legal framework, economic status and social acceptance' (IPCC, 2018, p. 383). Concerns relating to other CDR techniques all differ. For example, the limitations of Afforestation are mainly institutional. Direct Air Capture, not included in most scenarios at the moment, has 'moderate technological availability' and is restricted by the availability of low carbon energy and high costs (IPCC, 2022, TS5.7).

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on the necessity of large-scale CDR based on the modeling results seems epistemically premature. As one indication, CDR deployment in 2 °C scenarios is 'not much lower than for 1.5 °C scenarios' (Fuss et al., 2018, p. 6). The reason for this is that CDR is not only used as a last resort in IAMs but also for purely economic reasons (Strefler et al., 2018, p. 2). The amounts arising in these scenarios are thus no direct indication on how much CDR is really 'necessary'.[8] Leading modelers recently as well stated that the 'perceived linkage between end-of-century outcomes and the amount of late-century net negative emissions is *not robust*; instead, it is to a large degree *driven by the design characteristics* that underlie the cohort of scenarios that is currently available in the literature' (Rogelj et al., 2019, p. 357, my emphasis).

As high CDR reliance in scenarios depends on contingent factors in the modeling process, analyzing the value judgments involved in modeling CDR becomes essential. CDR involves arguably greater uncertainty than other mitigation strategies. It is, therefore, necessary to consider the value position in relying on a highly uncertain technique in IAM scenarios. As the next section will show, relying on CDR in scenario modeling implies an ethically problematic value position.

3. Uncertainty in modeling assumptions and epistemic risk

As described in the last section, there is an apparent mismatch between the evidence for having large-scale CDR available and the widespread reliance on these techniques in modeling pathways. It is highly uncertain if CDR will be able to provide negative emissions in the amounts assumed. This gives rise to what Lenzi (2021) calls the 'epistemic uncertainty objection'. Lenzi states it as follows: 'it is ethically unacceptable to gamble on technologies that are currently unproven, especially when the risks associated are great' (Lenzi, 2021, p. 3).[9] Lenzi also provides a short discussion of the epistemic uncertainty objection. While CDR is 'indeed a less secure proposition than conventional mitigation' (Lenzi, 2021, p. 3), he highlights that the question concerning the status of CDR is a genuine scientific dispute with the otherwise conservative IPCC labeling BECCS as a mature technology after all.[10] The burden of proof, according to Lenzi, thus rests with the critics.

If the epistemic status of BECCS is a scientific question, how can values play a role here? The fundamental value problem concerning uncertainty in scientific studies is given by the *inductive risk argument*. This argument states that scientists need to make value judgments when confronted with whether to accept a particular proposition based on the available evidence. Since no scientific hypothesis is ever completely determined by evidence, scientists must decide when the available evidence is sufficiently strong to accept a hypothesis.[11] Value judgments arise in this question because there are often practical consequences if a hypothesis is wrongly accepted.

Scientific propositions can be wrong in two ways, so-called false positives and false negatives. *False positives* are propositions that are accepted but turn out to be wrong. *False negatives* are propositions that are not accepted but turn out to be true. These respective errors often have different practical consequences, which, according to the argument from inductive risk, need to be weighed against each other in deciding how much evidence is required to accept a hypothesis or proposition within a study. If there are more severe consequences in the false positive case than in the false negative case, then the necessary level of evidence should be high.[12] As this concerns the scientific reasoning itself, it implies that even if it is a genuine scientific question how uncertain certain assumptions are, value assumptions nevertheless need to play a role.

IAMs rely on a whole array of assumptions and theoretical propositions when modeling possible climate futures. In general, modelers answer questions concerning the feasibility of climate change in an 'if-then-fashion', projecting various climate futures for different socio-technological scenarios. An important distinction here is between projections and prediction. While predictions make claims about what will happen in the future, projections only make conditional claims about what would happen if a certain scenario realized. In projections, uncertain assumptions do not necessarily translate into uncertain results since even if the scenario does not realize, the hypothesis about what would have happened could still be valid.[13] One might call such explicit antecedents 'scenario assumptions'.

Uncertainty in modeling, however, does not stop with explicit scenario assumptions. Model runs depend on many background assumptions. These are often implicit and concern, as an example, techno-economic parameters of different mitigation means in the model.[14] The representation of CDR in the models, especially BECCS, depends on many such background assumptions, for

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[8] Since this paper investigates the value assumptions of CDR in general, one might add that further techniques such as direct air capture or enhanced weathering have so far played no role in the IPCC assessments. Individual IAM studies involving direct air capture (DAC) have recently been added (Marcucci et al., 2017; Realmonte et al., 2019; Gambhir & Tavoni, 2019). DAC captures CO_2 directly from the atmosphere and stores it underground. In contrast to BECCS, DAC consumes a lot of energy. In the few existing scenarios, DAC only phases in after 2065 but scales up rapidly to annual rates of 35–40 $GtCO_2/y$ (Fuss et al., 2018, p. 9). With DAC in the models and a single carbon budget being used over the 21st century, vast amounts of mitigation burdens are likely to be shifted into the far future.

[9] The epistemic uncertainty objection thus combines two objections: relying on CDR despite high uncertainty *and* the high risk of CDR itself. Both are entwined because some of the feasibility concerns go back to unacceptable side-effects of CDR under some circumstances (cf. Lenzi, 2021; Shue, 2017).

[10] Lenzi highlights that what is at stake is not the technological status of BECCS alone but the obstacles in scaling CDR up. Lenzi sees these obstacles to be 'predominantly economic', which leads to his conclusion that the dispute comes down to the larger question of 'what to make of the predictions of modeled future scenarios' (Lenzi, 2021, p. 4). However, critics also question overly optimistic assumptions concerning the ecology, governance, and technology of CDR, for example concerning yield rates, and ecological side-effects in BECCS, as well as the political feasibility of their deployment. Further critiques point out unacceptable ethical consequences, which arguably are part of feasibility considerations (cf. Räikkä, 1998).

[11] Rudner (1953); Douglas (2000, 2009); Wilholt (2009), for critique cf. Jeffrey (1956); Betz (2013). Inductive risk not only occurs in hypothesis testing but in many stages of the scientific process (Douglas, 2000). To distinguish narrow cases of hypothesis testing from other cases of value-laden inductive risks, Biddle (2016) proposed the wider label of 'epistemic risk' to these other cases.

[12] An especially illustrative example of such an asymmetry is given by Douglas (2009). In the scientific process accompanying the nuclear tests, scientist had to show that launching a nuclear bomb in the atmosphere would not start a nuclear chain reaction in the whole atmosphere. Since the consequences of this proposition, if wrongly accepted, would have been utterly catastrophic (and way worse than in the case of the false negative), the scientific reasoning needed to be bullet-proof.

[13] Much 'uncertainty' in modeled pathways stems from our future (political) decisions and thus is not epistemic. My focus is on assumptions that are largely epistemic in the sense that they can in principle be known.

[14] The distinction might be less clear than it is drawn here since what should count as explicit depends on many factors, including the communication of the results and the wider literature. If more transparent parameters such as the discount rate should be seen rather as a scenario or background assumptions is up for debate. As the SR1.5 and AR6 do not include scenarios with lower discount rate, a good case can be made to view the discount rate as a background assumption in current feasibility assessments.

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example the land available for bioenergy, the expected yield rates of crops, technological assumptions concerning CO_2 capture rates, costs, energy production rates, and implicit institutional assumption concerning the feasibility of a socially acceptable governance scheme. These assumptions are, for the most part, implicit in IAM scenarios. They are further exogenous to the models meaning that they must be made based on the wider available evidence. As BECCS is a standard feature of most IAM scenarios, at least in the AR5 and SR1.5, these background assumptions influence scenario evidence concerning all kinds of feasibility questions, for example, adequate level of carbon taxation or end dates for fossil fuels.[15]

Based on the available evidence, modelers must make assumptions about BECCS and other CDR technologies, and there is arguably considerable epistemic uncertainty related to these assumptions. If this is so, relying on large-scale CDR in the models will come with an implicit value position in weighing the respective consequences of being wrong.[16] The next section will discuss this implicit value position.

4. Value implications of relying on CDR in mitigation pathways

Scenario runs implicitly assuming large-scale CDR potential face epistemic risk. This implies that modelers are confronted with the task of weighing the consequences of being wrong in assuming large-scale CDR. Including CDR then comes with an implicit value choice. This section will analyze what this value position consists of.

Let us first look at the two idealized errors one can make in assuming CDR in order to understand the value position. Applying the inductive risk scheme to the case at hand, the *false positive error* would be the case of assuming large-scale CDR in the models, but CDR fails to deliver in the amounts assumed. In this case, pathways overestimate the potential to offset emissions and therefore include too little short-term emission reductions. Since CDR does not become available in the amounts assumed, one is left with higher emissions, exceeding the existing carbon budgets without the possibility of reversal. One therefore ends up with higher global temperatures and climate impacts.

In the inductive risk scheme, we need to weigh these consequences with the consequences of wrongly neglecting CDR in the models. This is the case of *false negatives*, where modelers drastically limit CDR or omit it altogether in mitigation pathways. However, a rapid scale-up of CDR turns out to be feasible after all. In this outcome, models ignore CDR as a means of mitigating climate change. Consequently, other mitigation means need to be relied upon more intensively. Since CDR is underestimated in this case, short-term emission reductions in the models are higher than necessary.

Inductive risk analysis suggests that scientists need to weigh the consequences of these two kinds of error in determining the level of evidence that is sufficient to accept the proposition of large-scale CDR.[17] The handling of CDR in IAMs is naturally far from this simple. Representation of CDR varies considerably between different models and studies and depends on many interconnected assumptions and mechanisms in the models.[18] Modelers, therefore, have to negotiate the web of assumptions along a continuum between the two kinds of errors introduced above. Since reliance on CDR in traditional scenarios varies considerably, individual runs will be somewhere on the continuum between the two idealized errors depending on how optimistic the CDR representation in the model is. Therefore, the two errors discussed should not be seen to necessarily apply to an individual model directly but to help illuminate the value judgments that are involved in making technological and economic assumptions on CDR.

So, what are the inductive risks of the two errors? In the case of false positives, the extreme of overestimating CDR potential, mitigation pathways rely heavily on the availability of large-scale CDR. Large CDR potential leads by design to comparably high short-term emissions.[19] If the assumption of large CDR potential turns out to be wrong and the promise of CDR does not deliver, this emission overshoot can't be sufficiently offset later on. This results in higher long-term emissions, leading to higher temperatures and more severe climate impacts. The amount of additional emissions allowed in such scenarios can be substantial. Lenzi et al. (2018) state that relying on CDR allows for temporarily exceeding the no-CDR emission pathway by up to 9 $GtCO_2$ or one-third of total emissions.[20] Basing scenarios on CDR puts us on a substantially higher emission pathway, locking in high levels of warming if CDR fails and risking creating a far more dangerous world, which tends to hurt especially vulnerable and poor communities (IPCC, 2014b, p. 40). Beyond direct impacts of higher warming levels, following such mitigation pathways also risk triggering additional climate tipping points (Lenton et al., 2019), potentially leading to cascading positive feedback and uncontrollable climate change, affecting all future generations (Steffen et al., 2018).

From an ethical point of view, this is clearly more severe than the consequences of underestimating CDR in mitigation pathways. In the false negative error, scenario modeling assumes only limited CDR availability, but CDR exceeds this expectation. Model results then have included higher short-term mitigation requirements than would have been necessary to stay within the given temperature goal. This implies comparably higher costs and greater challenges in the near future. Limited-CDR scenarios

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[15] This might have changed somewhat by the latest IPCC report AR6, which makes temperature overshoot an explicit design choice and presents scenario with high CDR as one 'Illustrative Mitigation Pathways' (IMPs) beside others, such as a low demand scenario (IPCC, 2022). In the AR5 in contrast, BECCS, was part of what the report labeled 'full technology availability' (IPCC, 2014b).

[16] In the case of IAMs, the practical consequences are foremost the result of political action guided by the knowledge produced. While no pathway will be followed directly, IAM research aims to 'map' the available policy space (Edenhofer & Kowarsch, 2015) and to give guidance on different policy options available.

[17] There would of course also be much to say on the ethical consequences of implementing CDR in practice, for example, concerning the distribution of costs or the climate risk arising from temperature overshoot. For the present purpose, however, I am interested in the value choices modelers face due to the comparatively high uncertainty of large-scale CDR deployment. Therefore, the section focuses on comparing the two kinds of errors. For some discussion of the ethics of CDR more generally, see for example Lenzi (2018, 2021).

[18] There is also considerably variation concerning different IAMs. For example, the models POLES and GCAM in some studies rely more on BECCS, with others such as REMIND or IMAGE being more conservative (cf. Butnar et al., 2020; Riahi et al., 2021). Such variations depend on differences in assumptions but are also connected with the specific methodology of the particular model. In recent updates of the representation of BECCS in GCAM, this difference became apparently smaller (Butnar et al., 2020). A full analysis of differences is beyond the scope of this paper, especially since the differences change across different studies.

[19] Scenarios with large-scale CDR often involve 'overshooting' the assigned emission budget temporarily by anticipating net-negative emissions from CDR after reaching net-zero.

[20] This figure would be even higher if other CDR technologies besides BECCS would be included in the models (Realmonte et al., 2019). Gambhir & Tavoni (2019) estimate that if we follow a 'mitigation strategy on the assumption that DAC can be scaled up […], but ultimately, we find it is not viable at scale (for example because of technical, regulatory, economic, or other limitations), we might overshoot our global temperature goal by up to 0.8 °C' (Gambhir & Tavoni, 2019, p. 408).

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in the IPCC reports consistently find large cost increases compared to 'all technologies' scenarios. Limiting Carbon Capture and Storage (CCS) for example, which is critical to most CDR, leads to the 'most significant cost increase' of all technologies (IPCC, 2014a, p. 451), with median mitigation costs being around 2.5 times higher (Kriegler et al., 2014, p. 364). According to one study, present-day carbon prices would need to double in comparison to scenarios that include CDR (Bauer et al., 2018).

The respective outcomes of the two kinds of errors thus differ in terms of what *kind* of practical implications would arise from misjudging the CDR potential. They further differ in terms of *who* would face higher burdens in case of the two kinds of errors.[21] Higher climate impacts arising from falsely relying on CDR will affect future generations, which would have to face the possibly catastrophic impacts of a world well beyond 2 °C. Many critics have highlighted the injustice of such a transfer of risk in assuming large-scale CDR (cf. Shue, 2017), which could be described as yet another instance of what Gardiner (2006) calls 'intergenerational buck-passing'. Furthermore, higher warming levels are a more existential threat to people in the Global South than to countries in the Global North.

These catastrophic consequences of overestimating CDR are in stark contrast to the other side of the inductive risk scheme. The impacts of underestimating CDR arise largely in the next few decades and fall predominantly on the present generation. These costs are therefore largely borne by the same generation running the climate scenarios and placing their policy plans on them. But not only would this avoid shifting costs to other generations, but the very rapid transformation necessary in this case in part only arises because of the political inaction within the past few decades. Even though enough knowledge was available dating back to at least 1990 (or earlier, cf. Rich, 2018), yearly global emissions since then have increased by more than 50% (Ritchie & Roser, 2017). By 2019 there have been as much global CO_2 emissions from burning fossil fuels and industrial processes after 1990 as in the 200+ years before. The consequences of underestimating CDR would thus be borne by the same generation that has used large parts of the carbon budget already. Furthermore, underestimating CDR also affects countries with high emission economies, which often have a greater historical responsibility for climate change and more resources to deal with higher burdens, more strongly than if CDR was overestimated.[22]

This distribution of risk is highly unfair. Generations and regions of the world that have no responsibility for the problem and less resources to deal with it share a greater proportion of the risk in relying on CDR in mitigation pathways.[23] Overestimating CDR not only has more severe consequences, but puts others at risk, while underestimating would mean that high emitting countries bear the inductive risk themselves. Overly optimistic assumptions on CDR imply thus a very questionable ethical position.

At this point, one could object that the pattern of inductive risk is not particular to mitigation pathways relying on CDR but generalizes to all highly stringent mitigation pathways. Could not the same be said about the LED scenario, which 'bets' on very low energy demand being realized? This alternative scenario, which is included in the IPCC SR1.5, is a low energy demand scenario that manages to stay below 1.5 °C without CDR (Grubler et al., 2018). This scenario relies on an energy demand far below today and below all current other IAM scenarios. It is hard to judge how the uncertainty of such a massive demand-side reduction compares to CDR. It might be equally high. I think there are two important differences though: *First*, scenarios such as the LED have only played the role of alternative scenarios and thus should be seen as explicit scenario assumptions rather than background assumptions. Similar value questions might arise if LED would have been the standard approach. However, *second*, the pattern of inductive risk is somewhat different in that the feasibility risk of LED depends less on environmental constraints but more on (malleable) social constraints. Further, the feasibility risk of LED seems to be occurring much closer to the present than in the CDR scenario, making LED less of a bet on the future (Brutschin et al., 2021).

As explained in section 2, IAMs deploy CDR not only as a last resort but CDR is an economically driven feature of mitigation scenarios. Though few, there are some alternative scenarios in IAMs explicitly limiting CDR and reaching stringent targets by higher investments in low-carbon technologies. 1.5 °C scenarios thus can be based to a lesser degree on CDR, and at least '2 °C scenarios do not yet fundamentally depend on negative emissions at large scale', Minx et al. (2018, p. 13). Moreover, alternative strategies for stringent climate mitigation, such as post-growth narratives (Hickel et al., 2021; Keyßer & Lenzen, 2021) or interaction with other sustainability policies (Bertram et al., 2018), have been largely neglected in IAMs. Of course, such stringent scenario must also be analyzed in terms of implicit value implications.

In relation to CDR, this analysis suggests that underestimating CDR would likely be way less severe than overestimating CDR potential in assessments with IAMs. The inductive risk scheme then suggests a comparably cautious approach in assuming CDR and would demand a high level of evidence in the feasibility of large-scale CDR. The favorable assumptions on BECCS in much of the IAM literature thus implies a questionable value position.

5. A bias in IAMs

The preceding sections have argued that assumptions on CDR face comparably high uncertainty but feature as a central

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[21] IAMs typically present outcomes only in aggregated costs defined as global cumulative discounted consumption losses but issues of distribution are very important to questions of global and intergenerational equity (cf. IPCC, 2014b, p. 458). For a discussion on the importance of including distributive aspects and how distributive weights could be included, cf. Adler (2016); Adler et al. (2017); Budolfson et al. (2017).

[22] Such differences in responsibility are drastic. Countries such as Germany or Russia, for example, alone have more than twice the historic emissions than all of the African countries combined, and historical emissions of states like Niger or Congo are less than 0.1 percent of the historical emissions of the Top 5 countries (Ritchie & Roser, 2017).

[23] This makes two common principles of fairness in burden-sharing applicable (cf. Caney, 2010). The *Polluter-Pays-Principle (PPP)* states that the agents (typically nation-states) responsible for a problem should bear more of the burden (Caney, 2005). States who have gained in the past by imposing costs on others (without their consent) should shoulder additional burdens to restore equality (Shue, 1999, p. 534). The PPP is widely recognized, including as a guiding principle of environmental policy of both the OECD and the EU (Munir, 2013). While the exact interpretation is of course disputed, arguably the unaccounted historic emissions of the Global North pose such a case of costs inflicted on others, for which a duty to contribute more to mitigating climate change arises. A second widely discussed principle is the *Ability-to-Pay-Principle (APP)*. It states that those who have a greater ability to pay should bear a greater burden in mitigating climate change. In contrast to the PPP, the APP is not based on causal contribution, but forward-looking ability. Its basic rationale is that since *someone* must bear the costs of combating climate change, it is only fair to distribute these costs according to each nation's ability (Caney, 2010, p. 214). Shue (1999) notes that these principles generally converge on the same practical conclusion, namely that the wealthy industrialized nations should foremost bear the costs of climate change.

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mitigation strategy for most results of scenario modeling. Further, the distribution of risk between the two errors – overestimating CDR or underestimating it – would imply a relatively cautious approach to assuming large-scale availability of CDR. However, IAM scenarios include a great amount of CDR and thereby implicitly represent a questionable and one-sided answer to questions of distributive and intergenerational justice. Results from IAMs unduly imply such a normative position when answering general questions concerning the feasibility of climate mitigation pathways.

If this analysis is adequate, this can be described as a *normative bias* implicit in integrated modeling of CDR. A bias is a systematic error that favors particular results over others.[24] In this case, IAMs systematically favor a particular policy option in CDR over competing strategies. I argued that this implicitly advances a certain value position in modeling results, which favors present over future generations and shifts risk away from high-emitting countries. The implicit appeal to such a position makes this bias normative. Since there are good epistemic reason to think that CDR is a less secure proposition than other mitigation options, this indicates that there are methodological reasons for the over-reliance on CDR.

The previous sections mentioned that IAMs include overly favorable assumptions relating to BECCS. This section will make this assessment more systematic. Generally, IAMs have been criticized for being based on a large optimism toward market-based and technological solutions, favoring carbon taxes and innovations as a means of tackling climate change rather than more socially based interventions (cf. Anderson, 2019). In relation to the bias in favor of over-relying on CDR, three aspects of modeling CDR are especially influential: (1) idealized implementation, (2) perfect foresight, and (3) discounting.

The first factor that I alluded to a couple of times in the paper is an *idealized implementation*. CDR partly thrives in the model world due to its idealized and overly optimistic representation. BECCS, for example, is especially valuable in the models since it simultaneously produces energy or energy products and negative emissions. Such a double benefit depends on several assumptions, for example increasing yield rates despite climate impacts, which in sum ‘display only a small sample of the overall assumption space, focusing on the corner of technological and political optimism’, as Creutzig et al. (2015, p. 8) write.[25] Idealization and abstraction in general are of course necessary aspects of modeling. Models need to leave certain aspects out. In this case, however, idealization risks favoring speculative technologies, of which side-effects and downstream costs are not well understood. Some authors, for example, question how efficient of a sink BECCS in practice it will be, if one considers wider impacts, such as emissions in the transportation of CO_2 or the effect of soil degradation (which releases carbon from the ground) (Brack & King, 2020; Fajardy & Mac Dowell, 2017; Fajardy et al., 2019; Harper et al., 2018). Köberle (2019) points out that costs of BECCS might well be underestimated due to the ‘[l]ack of representation of governance and sustainability concerns — such as monitoring and verifying the carbon balance of the BECCS chain or managing impacts on food prices’ (Köberle, 2019, p. 112). While idealization could also affect other comparatively speculative scenarios (e. g. concerning behavioral change), at least until recently, BECCS was the go-to solution for making ambitious climate targets feasible.

The second factor favoring CDR is *perfect foresight*. Most IAMs employ perfect foresight and thus are based on the framework of a central planner who knows future technological development perfectly well. Such a policy planer will defer mitigation burdens into the future if it is cost-efficient in the long term. With CDR, this becomes especially beneficial since the model ‘knows’ perfectly well that CDR can provide large amounts of negative emissions in the latter half of the century. Such a planer will wait for this development, which can cheaply ‘undo’ emissions later. This is not a good proxy for the real world but tends to mask the uncertainty of CDR within the model. Perfect foresight benefits speculative technologies like CDR, which thrives in the model world but pose great feasibility risks in reality.

The third large driving factor for CDR deployment is *high discount rates* (Emmerling et al., 2019; Köberle, 2019).[26] Discount rates in dynamic process IAMs are typically around 5–6%, for example, in the REMIND models (Luderer et al., 2015). Evidence on scenario results with discount rates lower than 5% is, for example, completely absent from the modeling results of the AR5 (IPCC, 2014a).[27] While the status of discount rates in Cost-Benefit-optimizing IAMs has been widely discussed by ethicists (cf. Broome, 2008; Caney, 2009), the effects on the new generations of IAMs studying feasibility are far less well explored. High discount rates make future efforts comparably cheap. Since CDR is assumed to build up over decades and become available in large amounts only in the latter half of the century, the competition between mitigation now and removal later is given a significant cost advantage by high discount rates. At a discount rate of 5%, mitigation costs of $1b in 50 years (when much of CDR is happening in the scenarios) are factored in at only $90 m, or

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[24] The status of certain biases is a frequent topic of discussion in the philosophy of science, for example, in industry-sponsored research or on questions of feminist philosophy. It is typically seen as an epistemic failure that arises from the influence of interests or ideology on scientific results. In the case at hand, the bias arises as a result of methodological choices. I will not investigate the deeper background of this bias here. Gardiner (2011, part E) gives an excellent analysis on moral corruption, which could be one avenue of further inquiry. On the politician of IAMs, cf. for example the discussion in Haikola et al. (2019). The bias should *not* be understood as the result of individual malpractice. Also, the analysis here is not suggesting that individual researchers or studies are biased in comparison to some community standards, a way biases could be understood as well (cf. Wilholt, 2009), but that the IAM literature as a whole exhibits a normative bias.

[25] Interestingly, PV, for example, seems to be systematically underestimated in the IPCC scenarios (Creutzig et al., 2015; Jaxa-Rozen & Trutnevyte, 2021).

[26] Discounting is one of the most discussed topics concerning IAMs. For our purpose, I will only give a brief overview. Modeling climate mitigation efforts demands aggregating welfare over many generations. This is typically done by deploying a ‘social rate of discount,’ which discounts future welfare to a net present value. The social rate of discount combines two components: discounting due to pure time preference on the one hand and discounting due to an assumed increase in wealth on the other. Pure time preference is the general preference of people not to defer consumption, impatience so to say, but in intergenerational settings, it effectively also gives lower weight to the well-being of future generations. A positive pure time preference thus can be said to implement the current generation’s selfishness into the models – or, as a recent blog article stated, the ‘discount rate is the degree to which we don’t care about the future’ (Smith, 2021). The second component of the social discount rate emerges from the marginal utility of wealth. The same good in a richer society is worth less than in poorer societies, and since the models assume economic growth to continue, this gives rise to so-called ‘growth discounting’ (Nordhaus, 1997, p. 317). Especially high values on pure time preference seem hard to justify from an ethical point of view. In contrast, some economists even have proposed that negative discount rates are more appropriate in the context of climate policy (Fleurbaey & Zuber, 2012).

[27] This is also far higher than in a recent survey among economists, in which three-quarters find a median discount rate of 2% acceptable, and 92% place the SDR somewhere in the interval of 1–3% (Drupp et al., 2018, p. 111). In this light, it is somewhat surprising, that most climate mitigation modeling is done at such rates and often does not even include lower values in sensitivity runs.

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9%, in terms of present value – thus, even very costly CDR becomes highly competitive in relation to short term mitigation.

Discounting consequently has an enormous impact on CDR deployment in the models. Recent modeling exercises confirm this. Reducing the discount rate from 5% to 2% would halve CDR deployment in the models (Gambhir & Tavoni, 2019, p. 407), and more than double carbon prices today (Emmerling et al., 2019). This would result in a reduction of a budget overshoot by 300 $GtCO_2$ in 2 °C scenarios – that is the equivalent of 9 years of current emissions put less on the promise of large-scale CDR becoming available. In sum, with the current framework, high discount rates take much of the responsibility for large-scale CDR deployment in the models. As Köberle (2019) writes, CDR 'may be entering the solution space of IAMs for the 'wrong' reasons (discounting) rather than the role they were originally included for (hedging uncertainties)' (Köberle, 2019, p. 109).

This third factor is arguably normative in a further sense. Many commentators agree that the discount rate is a proper moral parameter in IAMs, which should be determined by ethical considerations.[28] The other two factors are in themselves epistemic and go back to methodological and empirical decisions. As argued above, such epistemic questions, however, sometimes involve value judgments. In the context of feasibility assessments, the two factors implicitly contribute to the overreliance on CDR, which, as argued, involves a problematic value position that favors the present generation over the future and favors high emission countries over more vulnerable regions. This makes this bias in favor of CDR an ethical issue.

I argued that IAM results exhibit a normative bias in favor of postponing mitigation burdens into the far future. CDR is given an undue advantage by three systematic assumptions: idealized implementation, perfect foresight, and high discount rates.

6. Norms for good policy-advising modeling

The previous section has argued that three main factors explain the bias in favor of CDR deployment in IAM scenarios. Taken together, they contribute to the large-scale reliance on CDR despite doubts about its feasibility and the divergence from what would be a reasonable default position according to the inductive risk analysis. The important question then becomes how policy-advising climate modeling could be convened in a better way.

Douglas' discussion of the argument from inductive risk concludes that scientists have to take the responsibility of making value judgments themselves in conducting scientific studies. Since value judgment due to inductive risk reoccurs many times in the 'internal' stages of the scientific process, scientists need to make these decisions, and since they have the necessary knowledge, they are in a good position to do so (Douglas, 2009, pp. 81–82). While this line of reasoning seems appropriate for many of the value choices occurring in integrated modeling due to inductive risk, it is inadequate for the larger case at hand. This is due to the salience and large influence of the value choice involved. Modeling CDR is a good case in which value choices can be made explicit and thus deferred back to the policymakers and the public, if assumptions on CDR can be linked to a more general value position.[29]

Substantial efforts are becoming visible in this direction. Not only have there been more studies with limited CDR potential lately, but also an increasing awareness of the bias involved in IAM studies exists. A group of leading modelers, for example, analyzed the implicit tendency of overshooting the carbon budget and thus proposed a new scenario-logic, which aims to transform 'questions of intergenerational equity into explicit design choices' (Rogelj et al., 2019, p. 357). A consequent model intercomparison study based on this framework for the first time systematically explored how to meet stringent targets with limited overshoot. Utilizing a discount rate of 2%[30], it finds, in contrast to the reported costs in earlier studies, the long-term overall costs to actually be *lower* with less CDR reliance (Riahi et al., 2021, p. 1,065). Riahi et al., acknowledges that the standard IAM framework 'by design, favours postponement of mitigation action until later in the century' (Riahi et al., 2021, p. 1,065). The new logic, if adopted, would tackle one critical aspect of the discussed bias by transforming the amount of *net* negative emission into explicit scenario parameters.[31]

Without having the space to give a specific discussion of this scenario framework, I will instead outline two general norms of good policy-advising science that support these developments and give good guidance for the future. Carrier (2021) proposes two general strategies for dealing with values in policy-advising science, which are helpful to the case at hand. In his paper, Carrier elaborates on the general question of what norms should guide science-based policy advice in light of a value-entrenched science, which must keep its independence while at the same time providing policy-relevant knowledge. The first norm is to make value choices transparent and 'subject to explicit judgment' (Carrier, 2021, p. 9). As Carrier highlights, this general strategy finds wide support in the philosophy of science but is not as straightforward as one might assume. Values choices occur at all stages of scientific practice and often go unnoticed. Interestingly, Carrier illustrates the complexity of making value choices explicit by the famous disagreement between Stern and Nordhaus on the discount rate in cost-benefit IAMs.

This interdisciplinary debate that emerged from this disagreement led to discounting being now described as 'a success story' of reaching deeper value transparency in climate economics (Bistline et al., 2021, p. 4). While this is most certainly true for Cost-Benefit-Analysis, it has unfortunately not carried on into the assessment of mitigation strategies with DP-IAMs. In DP-IAMs the discount rate is rarely varied and should therefore be described as a background assumption. This should be corrected. Further, the discussion above shows how questions of intergenerational and global justice also appear in technological assumptions, which might be thought of as even harder to explicate. While some assumptions, such as the discount rate, are typically reported, many other assumptions can be hard to find or interpret. Importantly, from a value perspective, what must be made transparent is the underlying value position and

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[28] This might in fact be a little more complicated, with some aspects of discounting also involving epistemic questions (Mintz-Woo, 2021b). Nevertheless, a wide agreement exists that ethical judgments play a direct and important role in determining the discount rate.

[29] I am not proposing that all value judgments in IAMs can be handled this way. For classical cases of inductive risks, see also Havstad and Brown (2017), who discuss the limits of deferring value choices in the case of inductive risk.

[30] However, variation of the discount rate is only done ex-post (except for one model in the additional material), thus only affecting the cost estimates without showing the implications of different discount rates on CDR deployment.

[31] A good sign is that the new AR6 also distinguishes overshoot scenarios and limited-overshoot scenarios (IPCC, 2022).

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the influence these value choices have on the results (Bistline et al., 2021). The first step in countering the normative bias in integrated modeling is thus to be explicit about the value assumption involved in mitigation pathways.

The second strategy is to increase the plurality of research and thus elaborate the complete room left for social choice. 'The expert ambition should […] be to enable politicians to make good fact- and value-based choices' (Carrier, 2021, p. 13). Central to this ambition, in light of the deep entrenchment of values in science, is to provide an 'array' of '*alternative value-laden policy packages*' (Carrier, 2021, p. 12). This task would involve increasing scenario plurality, modeling equally speculative technologies, institutional changes, or behavioral changes. More diverse scenarios could helpfully inform and broaden the public deliberation (Lenzi, 2019) and reduce the one-dimensional reliance on CDR (Köberle, 2019, p. 112). Since there is no way to keep value choices out of scenario design, modelers should embrace plurality concerning important value dimensions.

Plurality could be better realized if different *normative* positions concerning intergenerational and international justice would be more directly incorporated into a scenario framework. As one salient ethical dimension ingrained in mitigation pathways, this could include scenarios with high, low, and no privilege for current generations, but also modeling pathways with a privilege for future generations. Such scenarios could be represented by different discount rates (including negative ones). However, as the discussion above showed, one must also more broadly implement such normative commitments within the models, for example, by limiting CDR to limit the ability to defer burdens onto future generations. Modeling such a value-explicit set of scenarios would help inform about the consequences of different value positions and help reduce the bias of integrated modeling in the current literature. Further value dimensions concern issues of global distributive justice or different welfare concepts.

More plural and transparent scenario evidence would enable policymakers and the public to make better value-based decisions on climate policy. Achieving transparency, however, is a difficult task given the enormous complexity of IAMs. Providing extensive model documentation and parameter transparency can be overwhelming for both modelers and users (Butnar et al., 2020, p. 12). It, moreover, would not be sufficient for being transparent concerning implicit value assumptions. Further, given the entangled nature of many value assumptions in IAMs, different value positions might not be simply plugged into existing model scenarios. To generate a more transparent and plural set of value-laden mitigation pathways, climate ethicists will need to engage more fully with existing IAM pathways and modelers need to become more aware of implicit value judgments. This arguably requires extensive interdisciplinary dialog and modelers, social scientist, and ethicists need to start collaborating in the creation of value-explicit scenarios (Lenzi & Kowarsch, 2021).

A more comprehensive and normatively explicit set of scenarios would provide more useful and adequate scientific knowledge and would help inform the public deliberation on climate mitigation. Ethically informed scenario frameworks could shed light on the different commitments involved in taking certain value positions, which are present in parts of the public and the political discourse, but so far stay uninformed by integrated modeling. This could further safeguard against the risk of one-sided value commitments in modeling results being lost in the discussion and communication of the results.

Conclusions

I have argued that the 'technical' assumption on large-scale CDR availability involves considerable value choices concerning intergenerational and global justice questions. The current practice of large-scale reliance on CDR involves a commitment to a particular normative position in integrated modeling, which I argued is in tension with intergenerational and global justice. I outlined systematic assumptions in IAMs that lead to this bias by unduly favoring CDR and thus partly causing the reliance on CDR in pathways of economic modeling. IAM research faces the challenge of how to improve policy-advising modeling. The two main principles following Carrier (2021) are being explicit about the value choices and aiming for a plurality of value-laden policy studies. IAM research would need to appreciate the dimensions of intergenerational and global justice more explicitly in scenarios and aim to provide scenario evidence on the whole array of plausible value-laden mitigation pathways.

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