

1 How to spend a dwindling greenhouse gas budget

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6 **The Paris Agreement is based on emission scenarios that move from a sluggish phase-out of fossil fuels**
7 **to large-scale late-century negative emissions. Alternative pathways of early deployment of negative**
8 **emission technologies need to be considered to ensure that climate targets are reached safely and**
9 **sustainably.**

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11 The historic climate summit in Paris in 2015 galvanized global commitments to an ambitious yet vaguely
12 defined goal of climate stabilization. At the same time some scientists argue that the model-based
13 scenarios with 1.5- and even 2-degree temperature change targets seem unattainable and detached from
14 current political realities^{1,2}. Here we scrutinize the dominant climate mitigation scenario archetype that
15 projects low global decarbonization rates in the first half of this century followed by large negative
16 emissions in the second half, thanks to Carbon Dioxide Removal (CDR) technologies³. We call this approach
17 to mitigation timing the "Late Century CDR" scenario archetype (Figure 1a). This archetype is consistent
18 with nearly all of 2-degree scenarios covered by the Fifth Assessment Report (AR5) by the
19 Intergovernmental Panel on Climate Change (IPCC)⁴, 87% of which deploy CDR technologies in the second
20 half of the century⁵. Following this predominant archetype might not only turn out to be a risky strategy,
21 but also lead to significant environmental damages and may be economically inefficient. In "Late Century
22 CDR" scenarios, CDR mostly in the form of bioenergy with Carbon Capture and Storage (BECCS) typically
23 removes the equivalent of 20 years of current GHG emissions to reverse the temporary GHG budget
24 overshoot that is tolerated earlier on⁶. The challenges and uncertainties associated with CDR are well
25 described in the scientific literature^{5,7}, yet the scientific and political debate addressing the consequences
26 of large-scale and late deployment of CDR as a "backstop" strategy is only at an early stage. We argue that
27 a new set of scenarios needs to be generated and analyzed to inform the policy process on robust timing
28 of climate mitigation with the aim of avoiding negative side effects. Essentially, three attributes
29 characterize such budget-constrained scenarios: the timing and magnitude of global peak net emissions
30 and its speed of decline thereafter; the maximum amount of allowable deployment of biomass-based
31 CDRs; and an admissible risk threshold associated with a temperature overshoot.

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1 **Fossil decarbonization rates**

2 A recent climate mitigation assessment has suggested a roadmap for decarbonization consistent with
3 1.5°C warming to be governed by a “carbon law” requiring a 2020 emission peak, halving emissions every
4 decade thereafter and deploying BECCS to the extent of half of today’s emissions in 2100⁸. We represent
5 this approach in our “Rapid Decarbonization” archetype (Figure 1b). Our calculations confirm that such a
6 carbon law based on a 10 years half-life period could substantially reduce the amount of CDR required
7 (Figure 1b), which is also backed by more complex studies with restricted BECCS deployment and no short-
8 term mitigation delays⁹. However, although desirable, rapid emission reductions face some real world
9 challenges, including inertia in the energy system, failure to coordinate mitigation targets at global or
10 national level, or upward trends in emissions from non-point and non-CO2 GHG sources – all of which
11 underpin the rationale for CDR.

12 More sophisticated modelling approaches incorporate such challenges and yield less optimistic fossil
13 decarbonization rates. For example the scenarios combining Shared Socioeconomic Pathways (SSP) and
14 Representative Concentration Pathways (RCP)³ span a range from relatively fast mitigation (e.g. SSP1) to
15 scenarios with a delayed response. Depending on the storyline underlying their levels of mitigation
16 challenges the 2°C compatible scenarios are characterized by half-life periods of 20 years and more.
17 Higher obstacles to fossil decarbonization take place at the cost of potentially large-scale deployment of
18 BECCS in the late 21st century (see Supplementary Figures 1 and 2). More than 85% of these scenarios
19 show maximum BECCS capacity in 2100 and primary bioenergy supplying an amount equivalent to roughly
20 80% of current total primary energy demand. In currently prevailing climate mitigation scenarios from the
21 IPCC AR5 for the 1.5- and 2-degree targets BECCS is peaking at colossal rates of 8-20 Gt CO2 per year at
22 the end of the century. Another strong assumption underlying a large share of these scenarios (and more
23 than 80% of the RCP2.6 scenarios) is that net carbon emissions peak in 2020. A later peak of net emissions
24 leads to even higher BECCS deployment at the end of the century, shown in Figure 2.

25

26 **Late peak BECCS**

27 For a number of reasons late century peak BECCS is problematic. The large scale deployment of BECCS
28 might turn out to be environmentally and socially damaging and thereby not be consistent with the very
29 objective of the UNFCCC and the sustainable development goals. Depending on the specific scenario
30 roughly between 200 and 1100 million ha (SSP2) and up to 1500 million ha (SSP4)¹⁰ amounting to almost
31 all of current global cropland area¹¹ are expected to be allocated to energy crop in the RCP2.6 scenarios,
32 with a largely unknown carbon debt and large-scale impacts on ecosystems functions such as biodiversity,
33 water and nutrient cycling, and regional climate attenuation. Most of the damaging conversion is planned
34 to happen in the last three decades before 2100, at a time when the pressure on land-based natural capital
35 assets is likely to be high, but still difficult to assess based on current drivers. Furthermore, land-based
36 mitigation in combination with BECCS might have a strong impact on food prices which could be
37 associated with food security even later in the century^{12,13}.

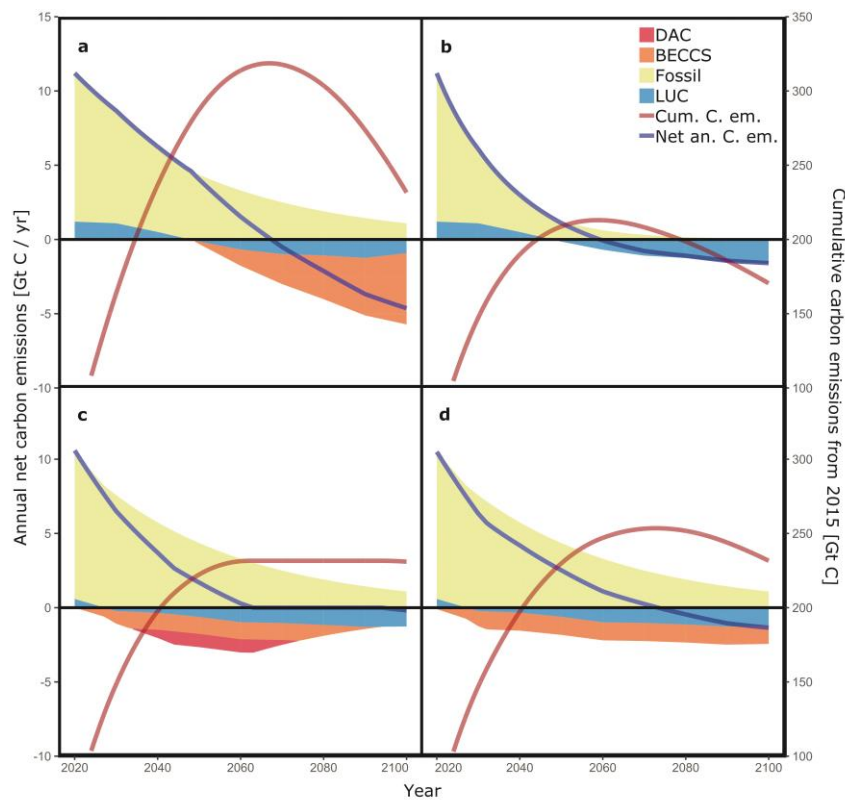
38 End of century peak BECCS would lead to large scale stranded assets. BECCS is associated with building
39 significant amounts of fixed technical capital in terms of large-scale plantations, biomass transportation
40 infrastructures, geological storages, CO2 pipelines and CCS installations. Late century peak of BECCS
41 capacity once the temperature change target is reached in 2100 lead to a situation where BECCS is no

1 longer needed in the year 2101 unless in the UNFCCC at its 100 year anniversary countries jointly decide
2 to go for an even lower temperature change target for the 22nd century.

3 Late century peak BECCS is also a consequence of an overshoot in cumulative emissions, which may be
4 associated with feedback effects from the earth system¹⁴, both with the risk of passing a dangerous
5 temperature threshold (e.g. ice sheet melting, thawing of permafrost and/or feedbacks from the carbon
6 cycle induced by other GHGs)¹⁵ and with the well-known behavior of the carbon cycle that if CO₂ decreases
7 at a steep rate, the ocean and natural ecosystems will switch from sink to sources¹⁶.

8 Finally, late-peak BECCS (or other CDRs, such as Direct Air Capture (DAC) or Enhanced Weathering) means
9 that we substantially rely on technologies that are still in their infancy^{17,5} and whose risks under large-
10 scale deployment have not been explored fully, or may prove not be scalable.

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13 **Figure 1: Four archetypes of emission pathways leading to a 2°C warming target with peak emissions in 2020.** Projections are
14 based on a “threshold exceedance budget” of 232 Gt C for 2015–2100 including an RCP8.5 non-CO₂ forcing²³. Blue lines depict
15 annual net C emissions, red lines are cumulative C emissions. a) “Late Century CDR”: Late century BECCS deployment results in a
16 substantial overshoot of cumulative emissions (half-life of fossil phase-out = 25 years); b) “Rapid Decarbonization”: A “carbon
17 law” with 10 years half-life makes CDR obsolete since cumulative emissions stay well below the budget; c) “No Overshoot”: CDRs
18 ramp up early and phase out towards the end of the century to avoid an overshoot in cumulative emissions, BECCS is limited to
19 1.2 Gt C/yr (equaling the BECCS-capacity of the “Minimize CDR” archetype), the remainder is captured by DAC (half-life of fossil
20 phase-out = 25 years); d) “Minimize CDR”: BECCS is spread evenly over the century thereby minimizing its capacity. No other
21 CDRs are deployed (half-life of fossil phase-out = 25 years). AFOLU-sector C-price for a) and b) increases exponentially from 0 (in
22 2020) to 200 (in 2100), for c) and d) it is constant at 40 USD₂₀₀₀ per t CO₂.

23

1 **Why early CDR?**

2 The arguments above point to the undesirability of the currently dominant “Late Century CDR” climate
3 mitigation archetype. However, early deployment of BECCS in deterministic and perfect foresight
4 scenarios does not occur due to discounting over a 100 year time horizon. Discounting in conjunction with
5 a limited carbon budget induces an exponentially increasing carbon price¹⁸, reflecting a time preference
6 for deferring investments at typically 5% per annum.

7 There are a number of compelling reasons for early deployment, and thus substantially reduced peak
8 deployment, of CDR. In fact, the original concept of CDR deployment was framed in a climate risk
9 management framework with anticipative implementation of recarbonization measures of landscapes,
10 optionally to be augmented by BECCS and other forms of long-term carbon storage later, if climate change
11 risk signals become eminent¹⁹. Also in cases where an overshoot is found to be too risky from a climate
12 science perspective, deployment of early CDR becomes more valuable²⁰. Finally there is the argument of
13 intergenerational equity to carry the burden of mitigation efforts. Early decarbonization (Figure 1b) of
14 the fossil sector will minimize or avoid altogether the need to deploy engineered CDR technologies of
15 potentially high economic and environmental costs to be incurred by a generation which is just being
16 born. For mitigation pathways where engineered CDR is unavoidable (e.g. Paris agreement) the
17 application of an intergenerational equity principle would suggest to spread the deployment of
18 engineered CDR more evenly, but at much smaller deployment rates, within the 21st century.

19

20 **Alternative archetypes**

21 In addition to the existing “Late Century CDR” archetype and the recently introduced “Rapid
22 Decarbonization” approach, we suggest the production of new scenarios along alternative archetypes.
23 These archetypes are characterized by early deployment of mostly biological and terrestrial CDR, which
24 might deliver important ecosystem services by recarbonizing landscapes. We illustrate all archetypes of
25 climate mitigation pathways in Figure 1 and benchmark these in Figure 2. Moreover, we quantify the value
26 of early action with respect to mitigation by comparing “peak 2020” archetypes to the same scenarios
27 where only the peak of net emissions is delayed from 2020 to 2025 followed by a “carbon law” for fossil
28 emission phase-out effective from 2030 (see Supplementary Figure 3). For a detailed discussion on the
29 construction of these scenarios see Supplementary Information.

30 The “No Overshoot” archetype (Figure 1c) avoids exceedance of the cumulative emissions budget by early
31 introduction of CDR. This archetype is most conservative with respect to the need to resort to a CDR
32 backstop later in the century. The “Minimize CDR” archetype is about early deployment and ramping-up
33 BECCS to an allowable maximum to be maintained throughout the century (Figure 1d). This strategy
34 minimizes the peak CDR capacity, but still has an overshoot in cumulative emissions. These two new
35 archetypes show similar early BECCS deployment, resulting in an option to choose between two
36 alternative pathways between 2030 and 2040. At that point in time new findings from climate science and
37 technological innovation could be incorporated to refine the negative emission strategy (e.g. deployment
38 of DAC instead of BECCS). Like the majority of RCP2.6 scenarios (Supplementary Figure 1), the “Late
39 Century CDR” archetype as well as the two new archetypes are based on half-life periods of 25 years,
40 while the “Rapid Decarbonization” type is characterized by a 10 year “carbon law”.

1 In Figure 2, the level of performance of all archetypes in each benchmark category is visually supported
 2 by a color gradient from green (good performance) to red (bad performance). The discounted cost
 3 minimizing “Late Century CDR” archetype is outperformed in each of the selected benchmark categories.
 4 “No overshoot” minimizes stranded assets and the risk associated with temperature overshoots at
 5 potentially large near-term costs for early and large scale CDR (including DAC). “Minimize CDR” represents
 6 a trade-off between benchmark performance and necessary investments to achieve moderate levels of
 7 CDR. “Rapid decarbonization”, if applied early, could essentially make CDR obsolete. However, if delayed,
 8 its environmental and socio-economic impact depends on the CDR strategy at hand. Combined with end
 9 of century BECCS, as proposed by Rockström et al.⁸ it would lead to an essential increase in the overshoot
 10 level and potential stranded assets. The effect of delaying peak annual net emissions for only 5 years is
 11 striking for all of the archetypes leading to extreme figures especially for the “Late Century CDR”
 12 archetype, such as an alarming overshoot level of 116 Gt C and a potential natural land loss of 33%
 13 compared to year 2000 levels.

		Archetypes					
		“Late Century CDR” ^f	“Rapid Decarbonization” ^e	“No Overshoot” ^f	“Minimize CDR” ^f		
Characteristics	PEAK	2020	BECCS from 2050	Early and fast decarbonization	Early BECCS and other CDRs	Early BECCS	
		2025	BECCS from 2030 and other end of century CDRs required	Fast decarbonization and late century BECCS	Early BECCS and large scale other CDRs	Early BECCS	
Benchmarks	Natural land lost ^a	PEAK	2020	26%	6%	8%	8%
			2025	33%	10% ^g	20%	19%
	Potential stranded assets ^b	PEAK	2020	53%	0%	0%	13%
			2025	71%	31% ^g	2%	32%
	Overshoot level ^c	PEAK	2020	87 Gt C	0 Gt C	0 Gt C	22 Gt C
			2025	116 Gt C	77 Gt C ^g	0 Gt C	56 Gt C
	Backstop reliance ^d	PEAK	2020	8-9 yrs	0 yrs	1 yr	2-3 yrs
			2025	11-12 yrs	3-5 yrs ^g	1-2 yrs	6-7 yrs

(a) Compared to year 2000 levels; (b) Percentage of today’s primary energy consumption; (c) Gt C budget overshoot; (d) Amount of carbon emissions to be captured in the late 21st century (from 2080 onwards) expressed in years of current emissions; (e) Half-life period of fossil emission phase out = 10 years; (f) Half-life period of fossil emission phase out = 25 years; (g) Includes late century BECCS.

14 **Figure 2: The new archetypes “Minimize CDR” and “No Overshoot” are benchmarked against prevailing archetypes “Rapid**
 15 **Decarbonization” and “Late Century CDR” based on results from our own model calculations presented in the supplementary**
 16 **material.** The level of performance is visually supported by a color gradient from green (good performance) to red (bad
 17 performance). Different time horizons for the peak of net carbon emissions illustrate the value of early action. Peak 2020 is
 18 illustrated in Figure 1, peak 2025 in Supplementary Figure 3. The prevalent “Late Century CDR” archetype, if delayed, would
 19 require BECCS to be initiated not long after 2030, culminating in a 116 Gt C cumulative emission overshoot, thereby potentially
 20 creating stranded assets to the extent of roughly 2/3 of our present primary energy consumption and requiring CDR technologies
 21 to recapture the equivalent of more than 10 years of present emissions between 2080 and 2100. Only the undelayed “Rapid
 22 Decarbonization” scenario as well as the “No Overshoot” scenario are characterized by lower BECCS capacities in the second half
 23 of the century, the latter relying on heavy deployment of other negative emissions technologies, if mitigation is delayed.
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1 **Conclusion**

2 We conclude that the timing of mitigation actions, in particular of negative emission technologies, needs
3 to be urgently revisited in the analyses of ambitious climate targets. We argue that considerations of both
4 intergenerational equity and climate/environment safety motivate early and moderate -- rather than
5 extreme -- deployment of negative emission technologies as well as a timely peak in net carbon emissions
6 as early as 2020. As a consequence all of the near-term and mid-century net emission reduction targets
7 should be reformulated including targets of early action on CDR technology portfolios. Furthermore, our
8 calculations point to significant indirect land use effects and other cascading impacts of delayed actions
9 in phasing out fossil fuel emissions. There is an inter-temporal substitution between sluggish fossil fuel
10 emissions today and undesirable land use and food system impacts later. Policy assessments informing
11 near-term technology preferences should therefore account for such lagged environmental and social
12 external costs.

13 Yet, early development of CDRs will be associated with significant policy challenges as witnessed by the
14 debates around biofuels²¹, avoided deforestation and forest carbon sequestration²². Transforming the 570
15 million farms to be climate smart and incentivizing 1.6 billion people who economically depend on forests
16 to become early movers in “No overshoot” and “Minimize CDR” scenarios is a formidable global policy
17 challenge. We call for a discourse on effective strategies, starting with more detailed global gap
18 assessments of the archetypes, and then mainstreaming the gained insights into Nationally Determined
19 Contributions (NDCs) and implementation plans.

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