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The (Missing) Third Pillar

Why climate policy needs to get serious about planetary waste management

Verein für Socialpolitik (VfS), Thünen Lecture
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The Social Cost of Carbon

Rising beyond already elevated levels

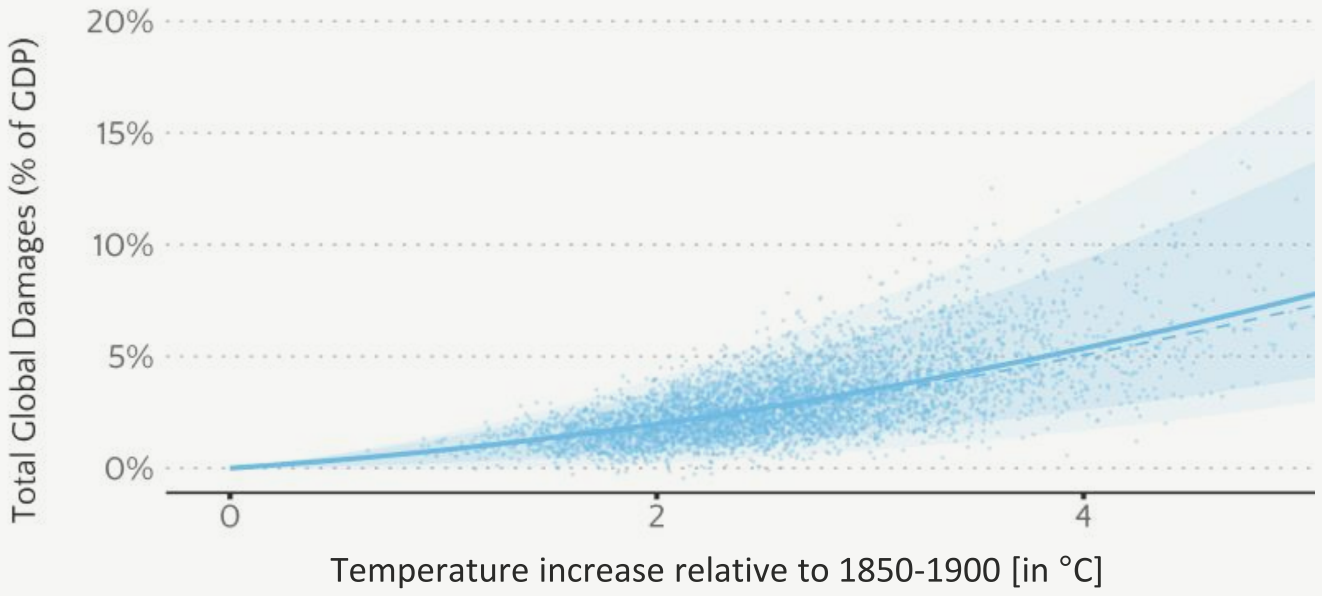
Conservative estimates of the Social Cost of Carbon (SCC)

Social Cost of Carbon (in 2020 $)

Emission Year	2.0% Near-Term Rate		
	DSCIM	GIVE	Meta-Analysis
2020	190	190	200
2030	230	220	240
2040	280	250	270
2050	330	290	310
2060	370	310	350
2070	410	340	380
2080	450	360	410

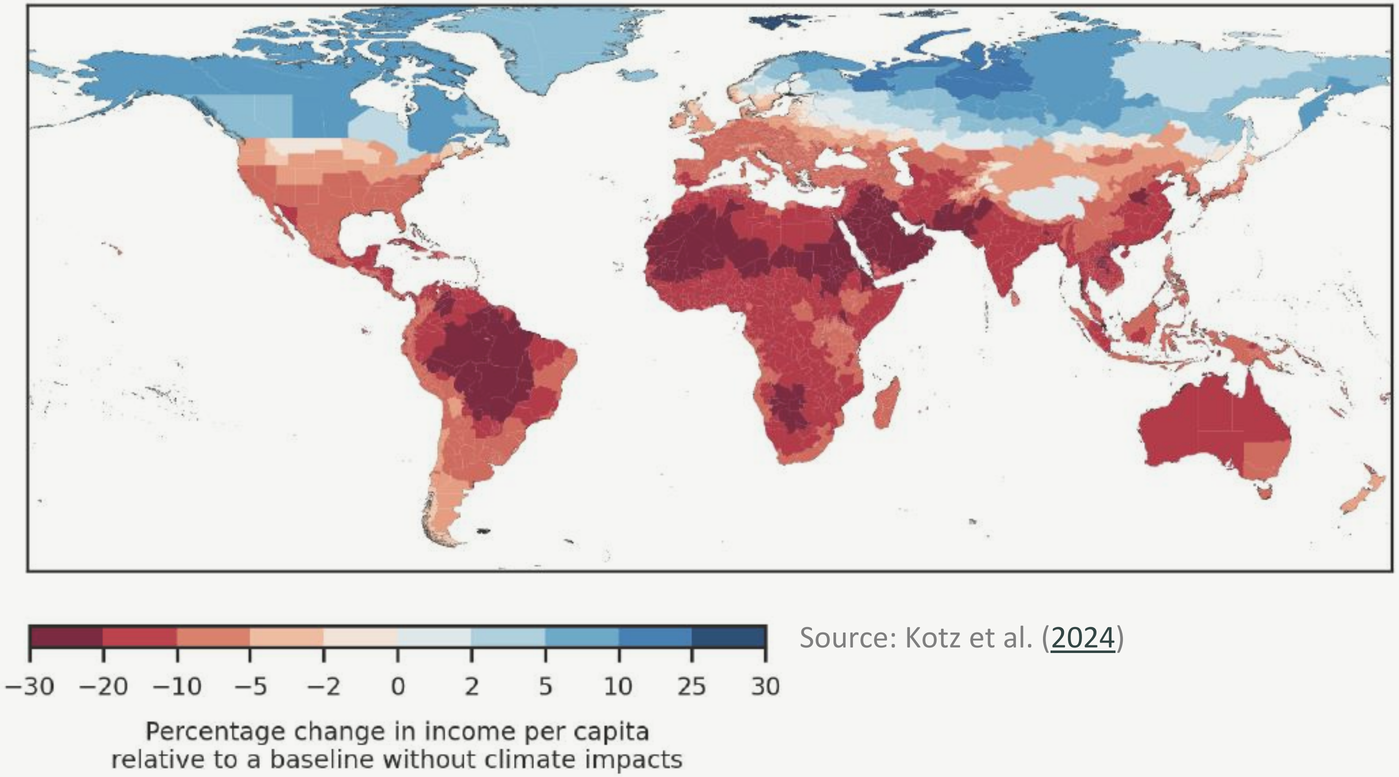
Source: EPA (2023)

Damages from meta-analysis



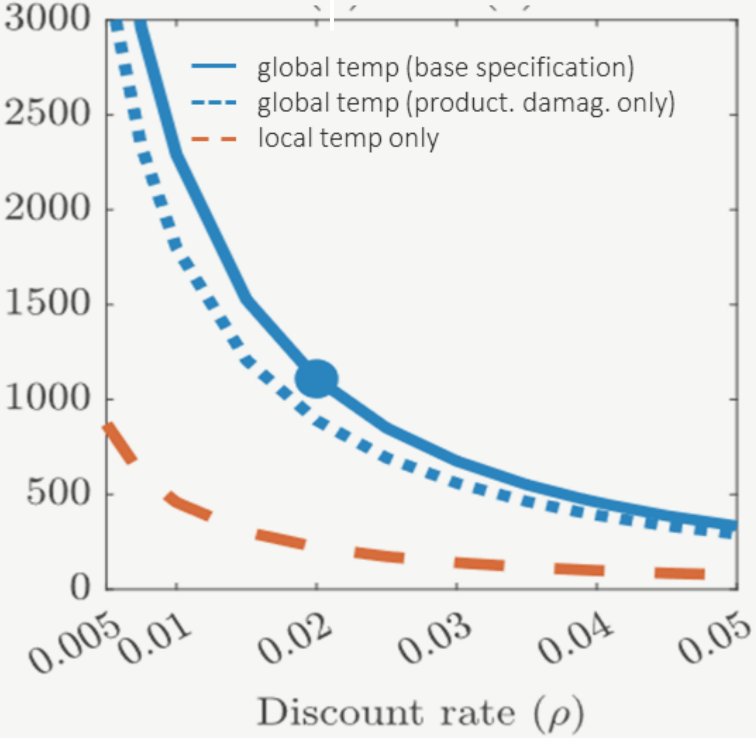
Recent estimates: Climate damages could be 20-50% of GDP in BAU until 2100, implying SCC in the range of 500-2,000 $/t$CO_2$

Still, many impacts (e.g. biodiversity, geopolitical risks) not quantified



Source: Kotz et al. (2024)

SCC [$/t$CO_2$]



Source: Bilal/Känzig (2024)

2

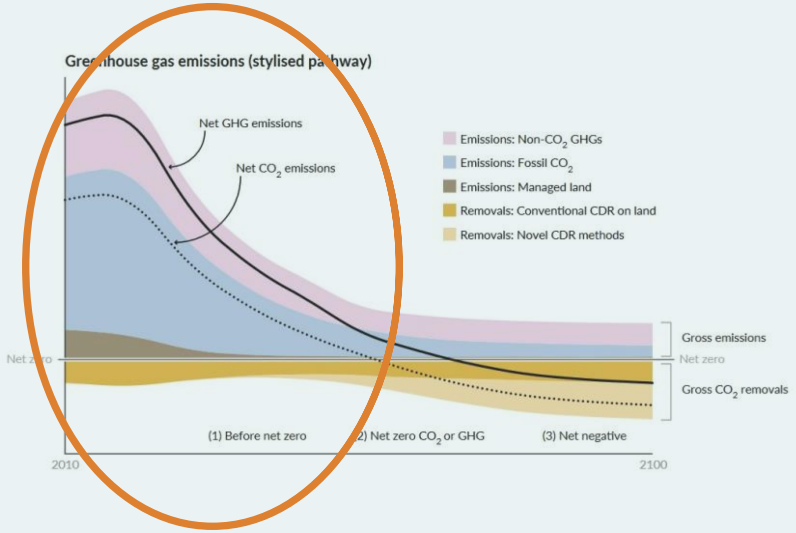
The three pillars of climate policy

Introducing carbon removals as the third pillar of climate policy

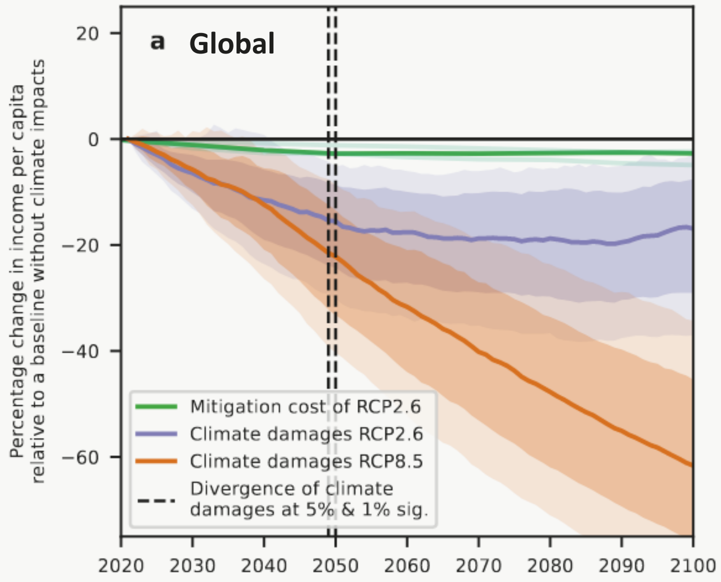
MITIGATION

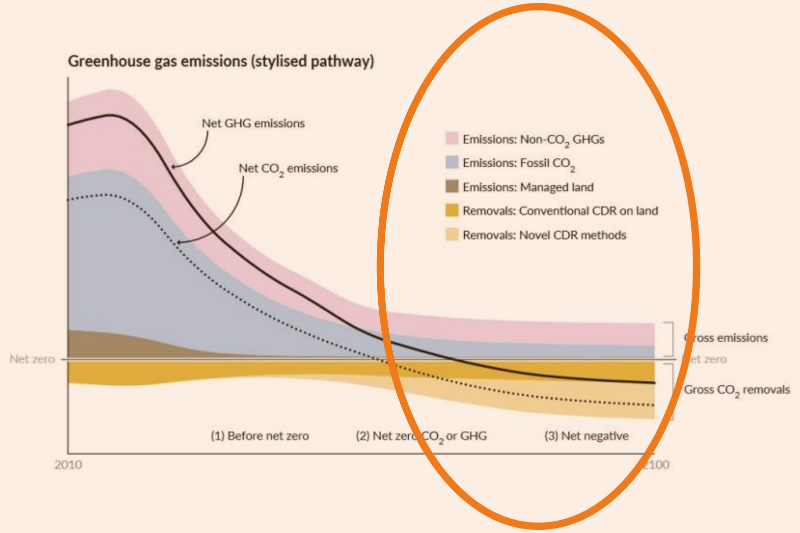
ADAPTATION

REMOVALS



+ Solar Radiation Management





Sources: Edenhofer et al (2024), Kotz et al. (2024)

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The three-pillar model

$$\min_{\{A,R,M\}} SWF = D(E^n, A) + C^M(M) + C^R(R) + C^A(A) \quad (1)$$

$$s.t.\, E^n = E^{BAU} - M - R$$

FOC:

$$\frac{\partial D}{\partial E^n} * \frac{\partial E^n}{\partial M} + C_M^M(M) = 0$$

$$\frac{\partial D}{\partial E^n} * \frac{\partial E^n}{\partial R} + C_R^R(R) = 0$$

$$SCC = \frac{\partial D}{\partial E^n} = C_M^M = C_R^R \quad (2)$$

$$\frac{\partial D}{\partial A} + C_A^A(A) = 0$$

$$-\frac{\partial D}{\partial A} = C_A^A \quad (3)$$

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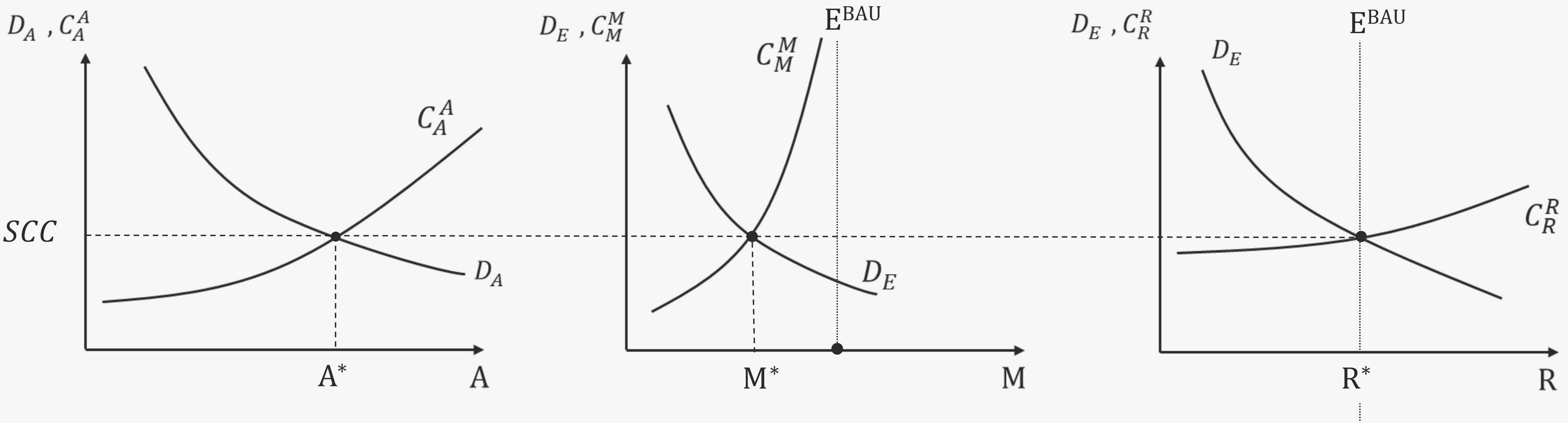
The new role of CDR in climate policy



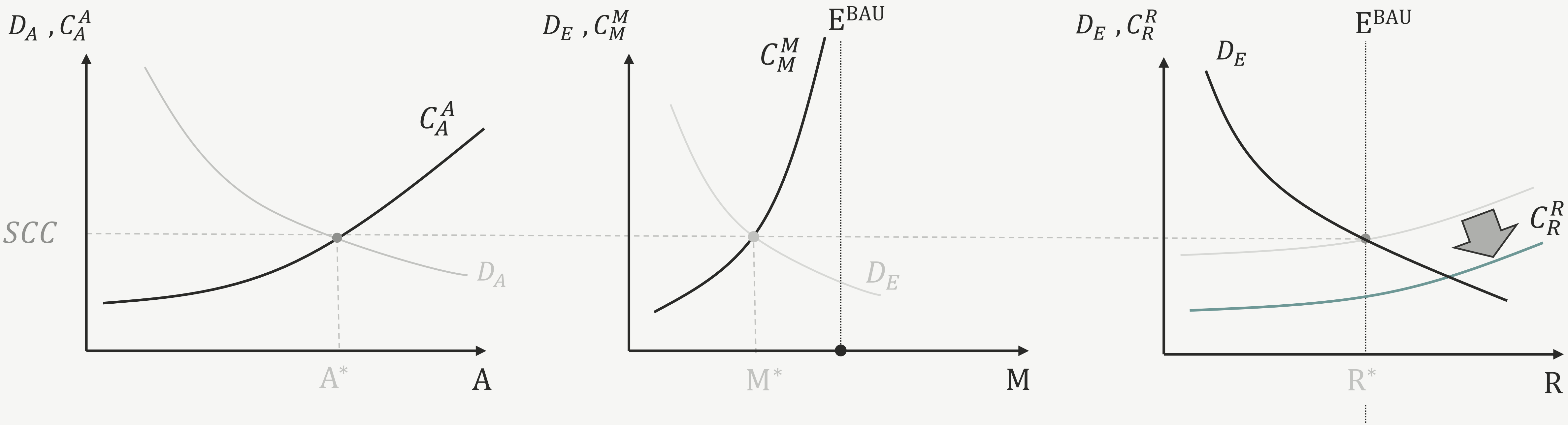
$D_{EA} < 0$ e.g. solar radiation management reduces SCC; in this example, it is a perfect substitute to mitigation and CDR

Inada condition for mitigation:

$$\lim_{M \to E^{BAU}} C_M^M = \infty$$

Fossil-free economy

The new role of CDR in climate policy



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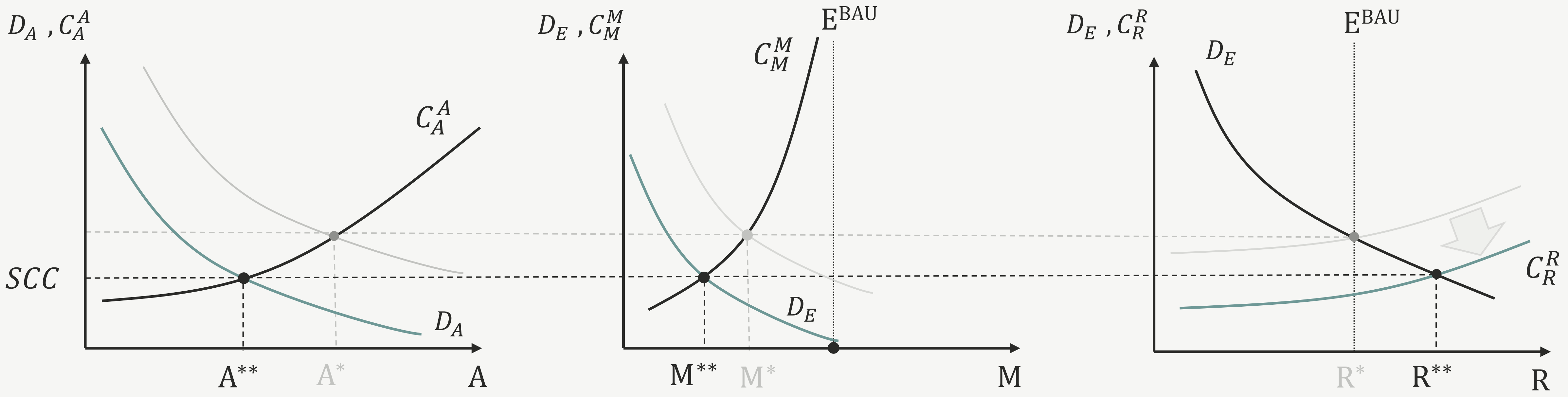
Fossil-free economy

The new role of CDR in climate policy



$D_{EA} < 0$ e.g. solar radiation management reduces SCC

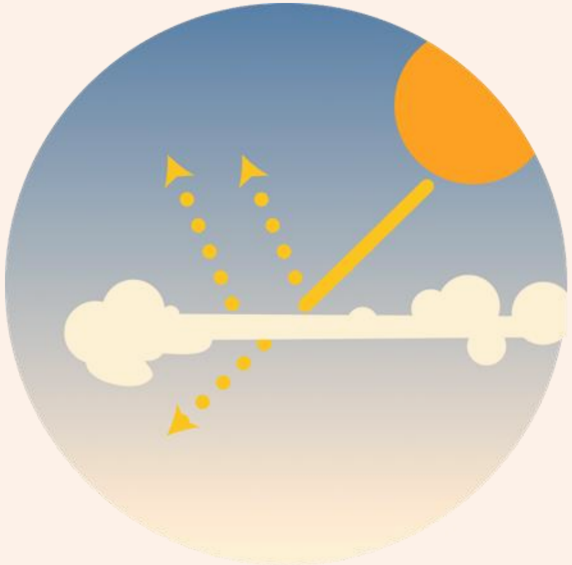
Inada condition for mitigation:

$$\lim_{M \to E^{BAU}} C_M^M = \infty$$

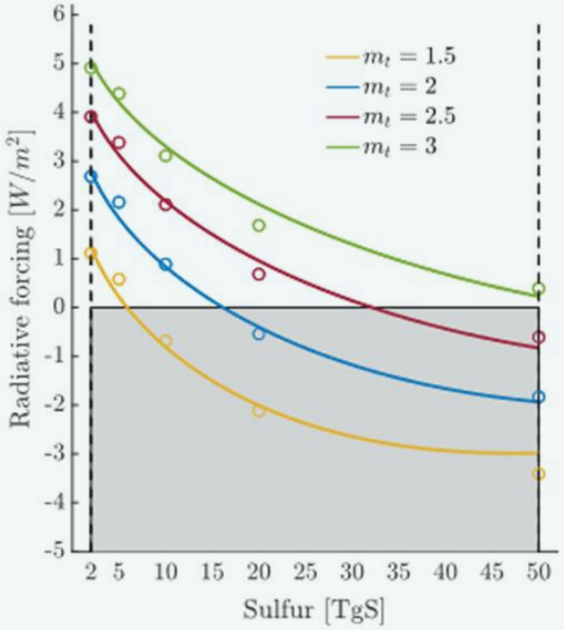
Fossil-free economy

SRM as an adaptation measure

Injection of small sulfur particles (aerosols) into the atmosphere reflects sunlight back into space



Higher concentration levels/lower radiative forcing require more sulfur → increasing marginal costs
SRM reduces the marginal SCC



Sources: MCC Berlin; Meier/Traeger (2022)

Tentative remarks on the game changer characteristics of CDR and SRM

› Could consider SRM as a way to 'undo' the temperature-related damages from net emissions. SRM can, in principle, be a perfect or an imperfect substitute to CDR and mitigation:

→ **Perfect substitute:** Temperature-induced damages are reduced without further side-effects

→ **Imperfect substitute**: SRM does not reduce damages caused by ocean acidification and induces changing precipitation patterns

› Uniform technological progress in SRM and CDR implies higher responses in removals than in adaptation if (and only if):

$$C_{AA}^{A} - \frac{D_{EE} C_{MM}^{M} (1 - \mu^2)}{C_{MM}^{M} + D_{EE}} > C_{RR}^{R}$$

› Perfect substitute μ=1, CDR is favored if $C_{AA}^{A} > C_{RR}^{R}$, cost curve seems to be steeper for SRM when C_{AA}^{A} accounts for the social cost of SRM (rel. to termination risks, env. costs, changes in regional climates, geopolitical risks), adding further convexity

› Imperfect substitute μ → 0, low level SRM deployment; additional SRM is used when SCC are high → temperature smoothing even if marginal costs of SRM are steep

Summary: CDR as a game changer for climate policy

› Carbon removal – the third pillar of climate policy – reduces the overall costs of climate policy by increasing flexibility and relaxing the Inada condition for mitigation

› CDR is likely to be preferred over SRM if:

(i) its marginal costs are flatter than of SRM. This is plausible due to the severe termination costs associated with SRM

(ii) SRM is an imperfect substitute to CDR. Then, SRM may only be deployed at low levels, primarily to smooth the temperature increase

Source: Unsplahs

3

How to manage the scarce carbon budget?

Managing the carbon budget: A simple economic rule

› **Static optimality** implies: $SCC(t) = P(t)MAC$

› Consider an aggregate net-abatement technology, including removal and mitigation

› Assuming exogenous cost change component $P(t)$

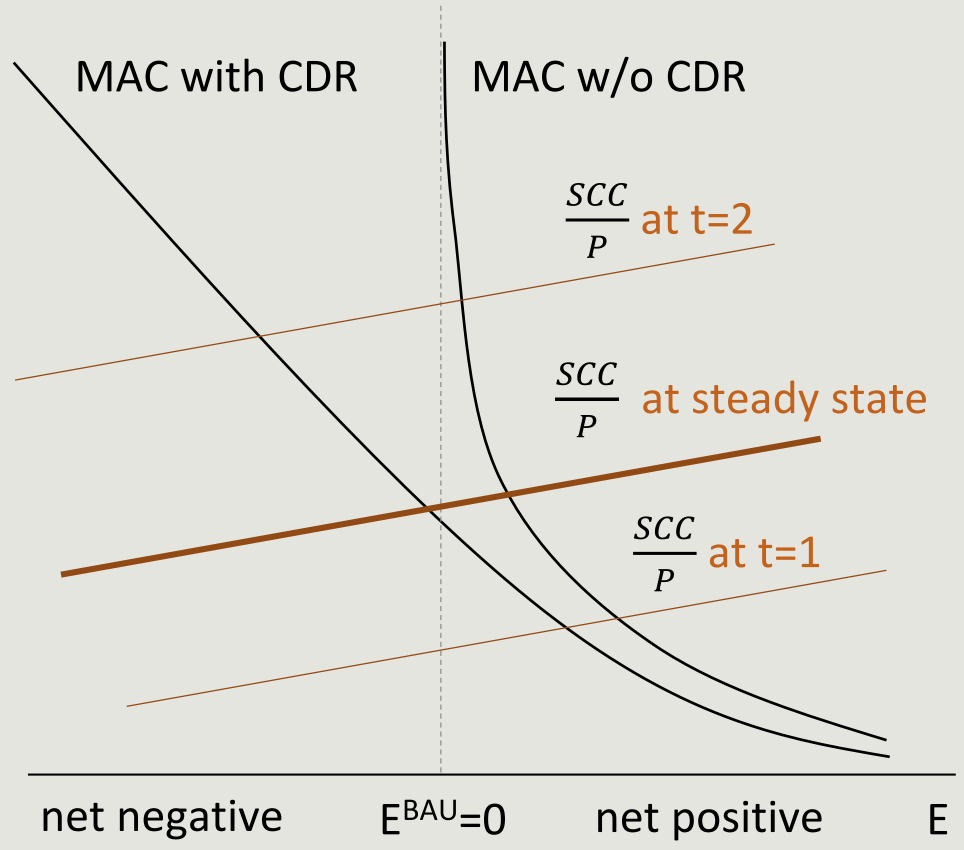
Growth rates over time: $g_{SCC} - g_P = g_{MAC}$, with $g_P < 0$ denoting cost savings in net abatement

› When $g_{SCC} - g_P > 0$, marginal abatement cost MAC grows over time ($g_{MAC} > 0$)

› As there is **no Inada condition** for the net-abatement technology, net emissions become negative when MAC sufficiently large

› **The larger the growth rate of the SCC and the faster the cost-saving technological progress, the earlier the time when the economy becomes net-negative**

Overshoot: The Inada condition over time



Initially (t=1), emissions are positive as MAC is high and SCC low

- Temperature levels increase → SCC increase as damages are convex
- Additionally, costs of net-abatement fall

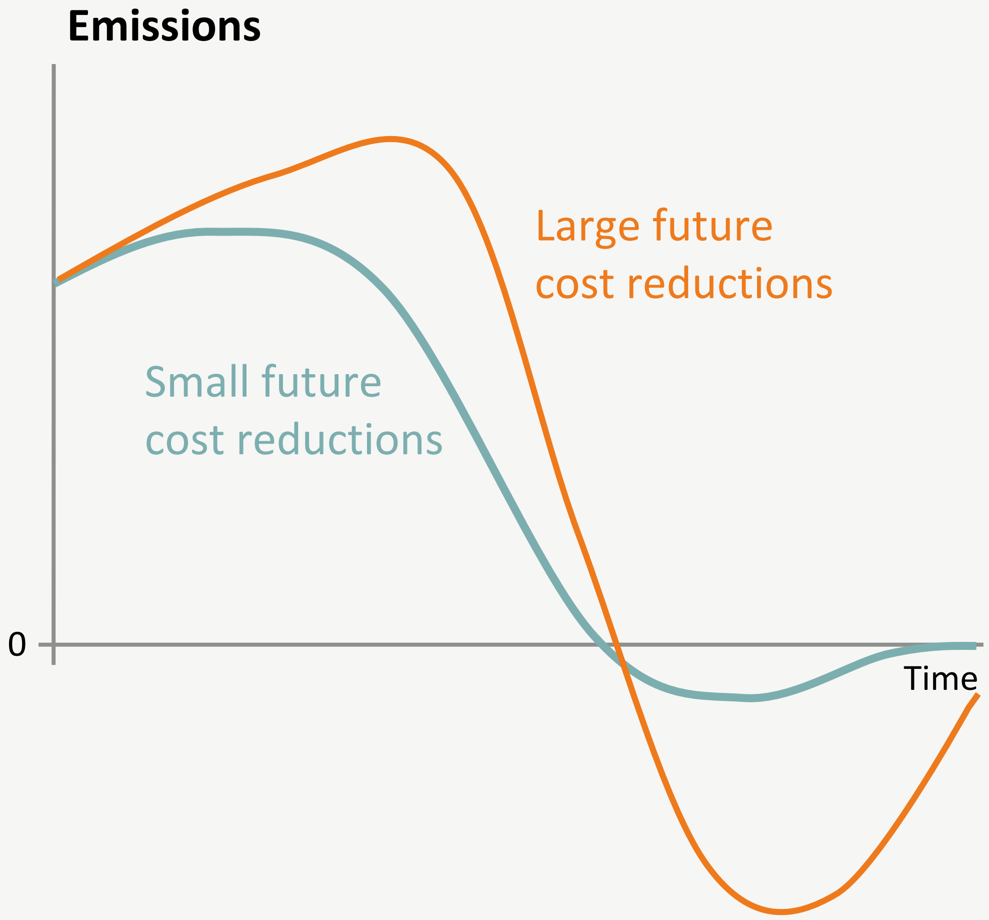
$g_{SCC} - g_P > 0$
hence, SCC/P grows

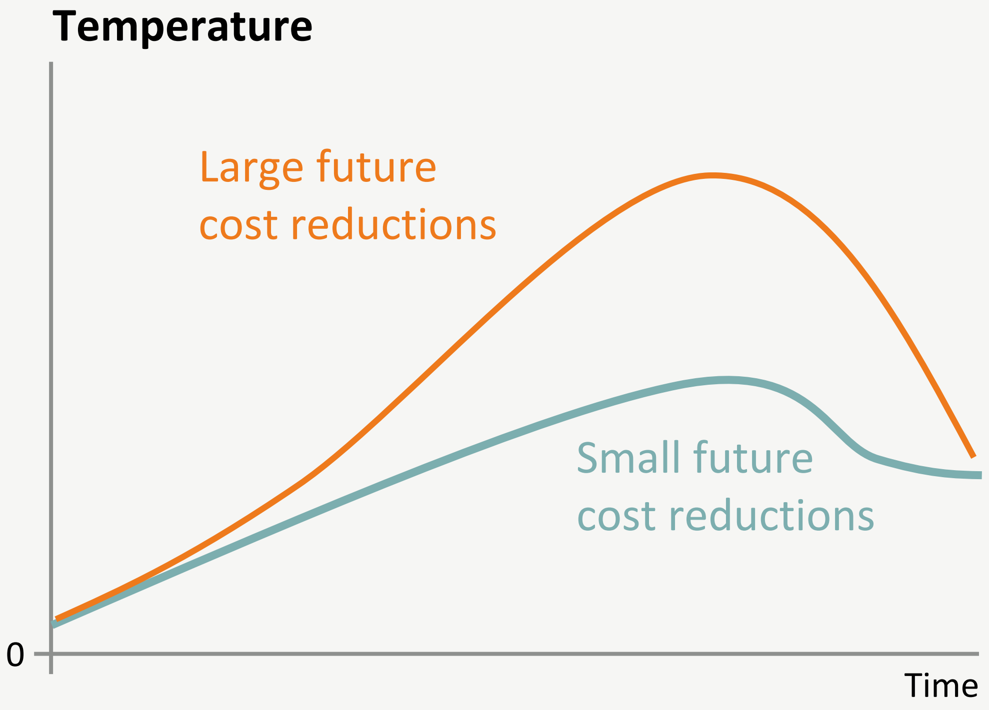
Later (t=2), emissions become negative as SCC/P has increased substantially

- Mitigation is close to 100%
- Net-abatement is largely driven by technological progress in removal technologies (not mitigation)
- With negative emissions, temperatures fall and SCC decline again

Steady state possible if technological progress ceases and SCC are constant (at net-zero emission level)

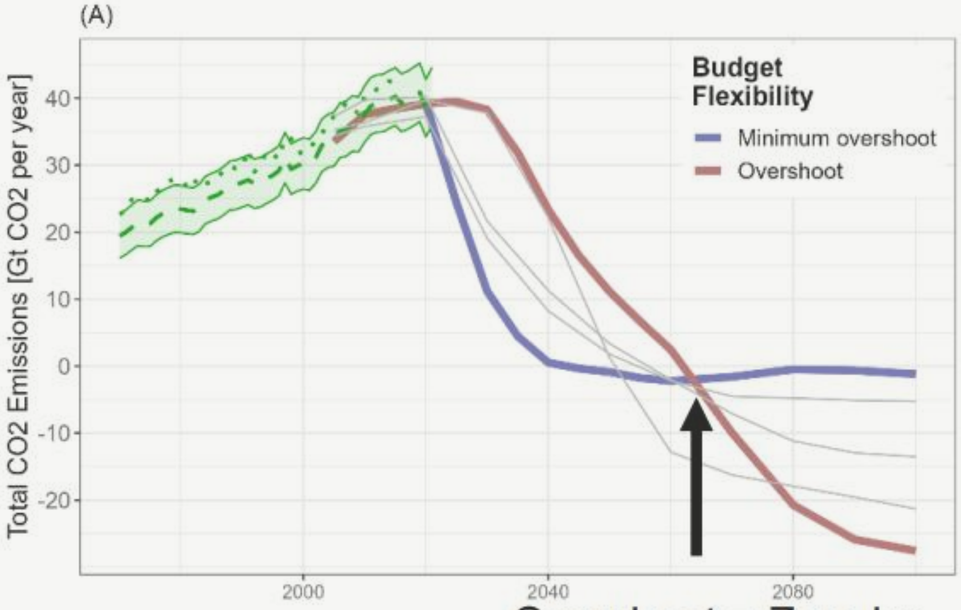
Overshooting depends on expectations about technological change





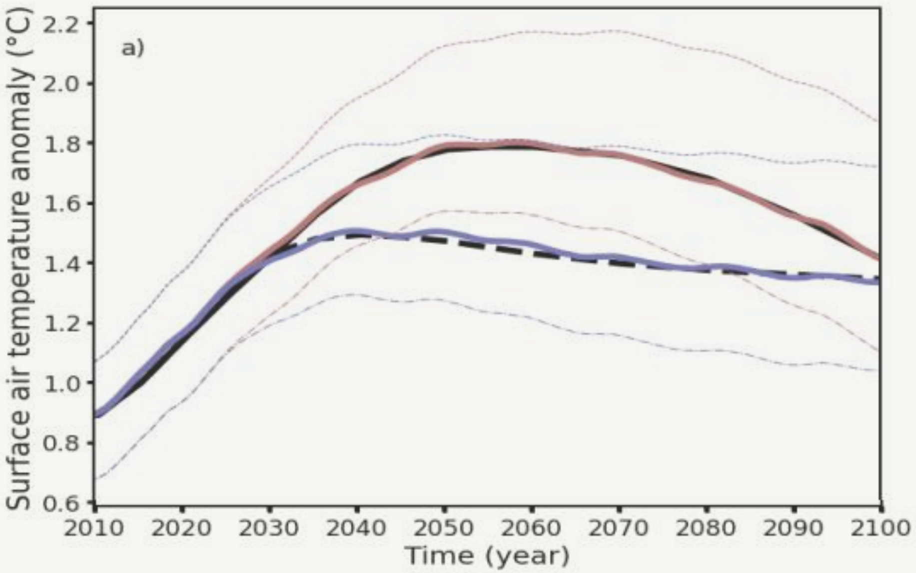
“Overshoot” allowed by more intertemporal flexibility in a cost-effective analysis

Markedly different emission pathways fulfill same carbon budget



Overshoot = Zero by 2050 and Negative emissions thereafter

Peak difference in global warming 0.35°C



Source: Bauer et al. (2023)

Summary: Overshoot

› Even when positive, net emissions are initially optimal, increasing climate damages and technological progress lead to net-negative emissions → optimal overshooting

› Overshooting will be large when significant cost-reduction or increasing SCC are expected

› CDR is a hedging strategy against bad climate news (increasing SCC) and bad news about technological change in mitigation

› For a given carbon budget, additional intertemporal flexibility like borrowing can lead to overshoot

› Steady state with net-zero emissions can be reached when technological progress in CDR has ceased

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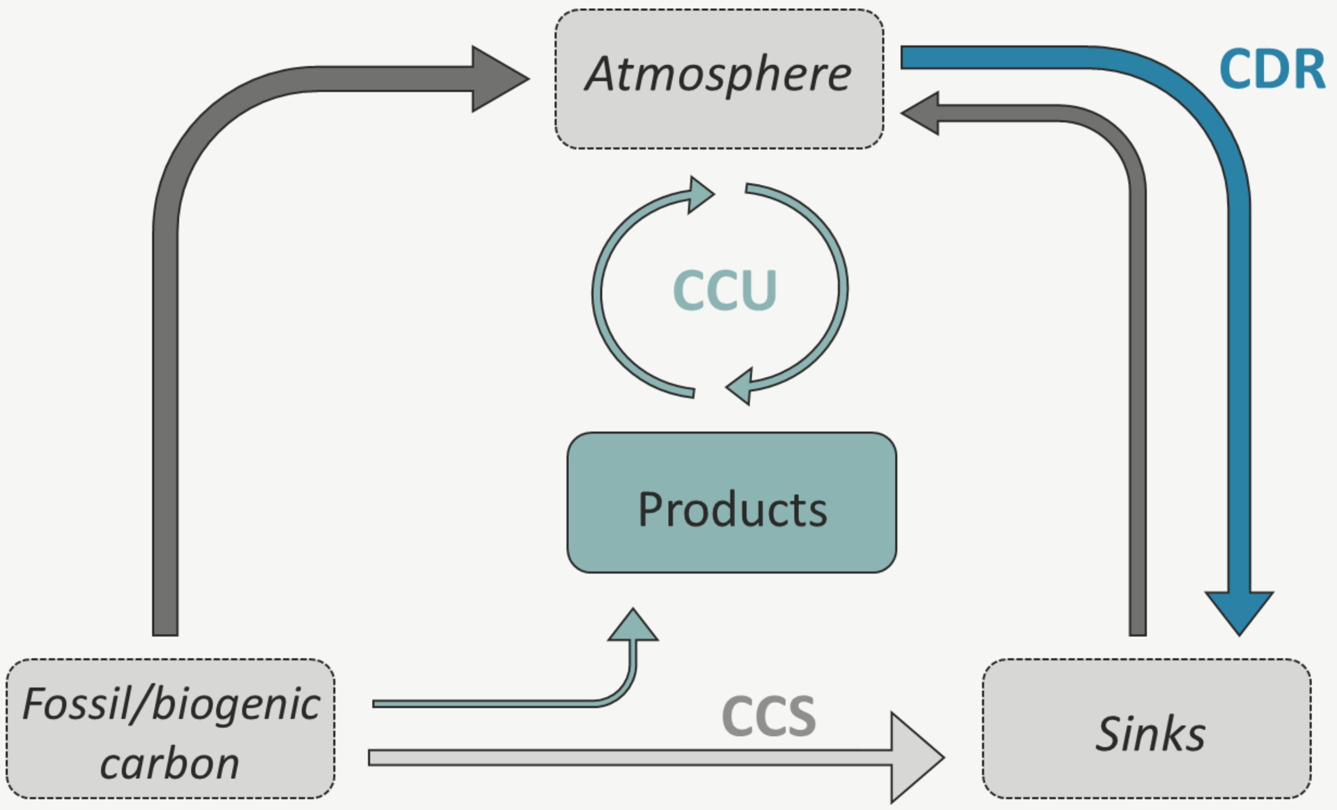
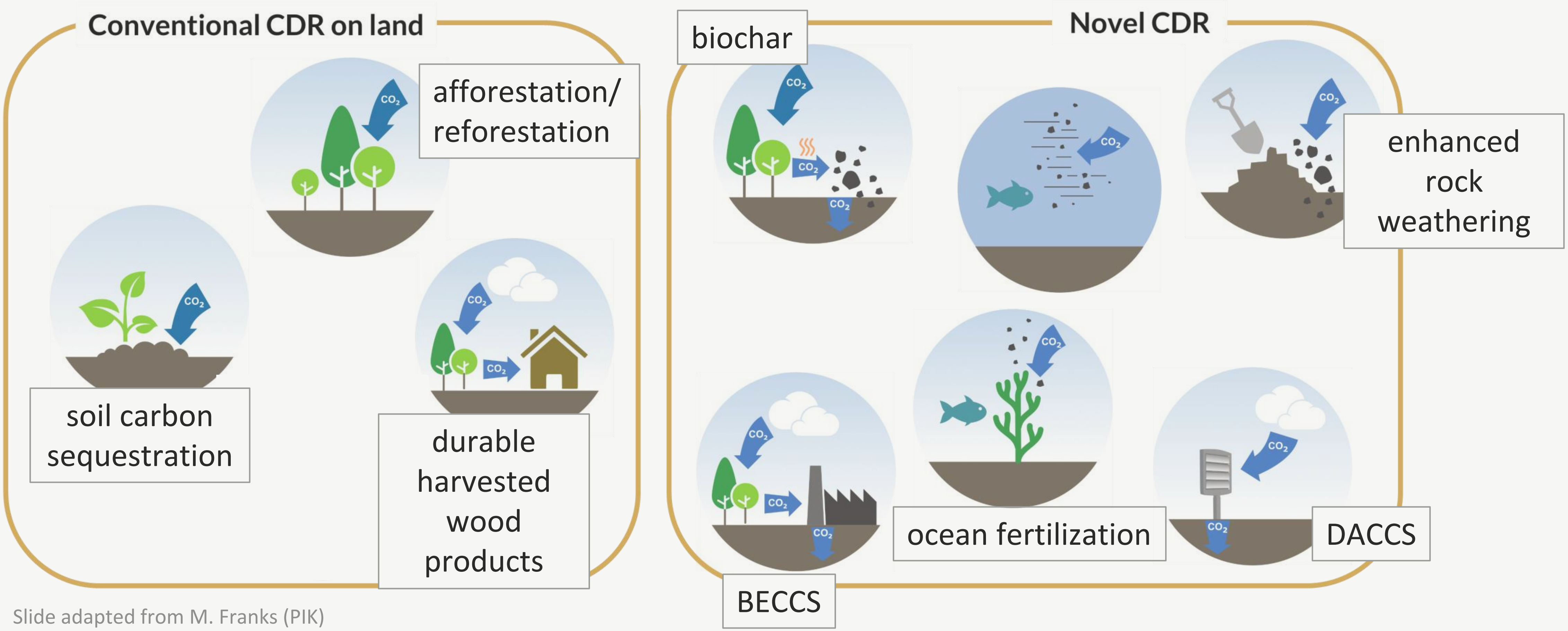
The choice of CDR technologies

Managing the carbon cycle



Source: own representation based on Carbon Gap (2022);
Smith, Geden, Nemet et al. (2024)

Novel CDR methods need to be developed and deployed

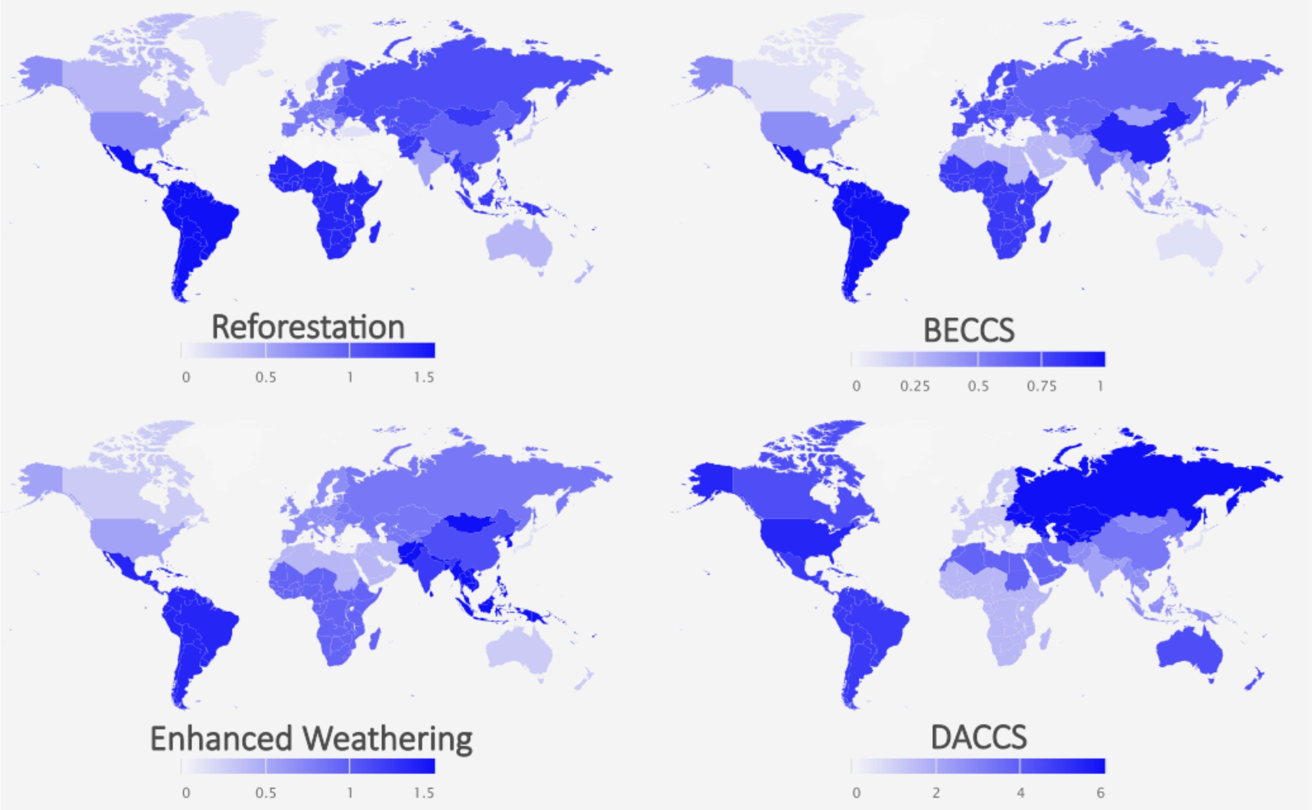


Slide adapted from M. Franks (PIK)

A CDR portfolio approach relies on varying regional contributions

- Carbon removal potential and relative competitiveness of CDR options vary by region
- Developing a diverse portfolio of CDR options enables all countries to deploy significant quantities
- A diverse portfolio increases CDR availability while reducing reliance on individual options (like BECCS)

Regional CDR deployment in 2100 [$GtCO_2$/yr]



Source: J. Strefler (PIK)

The economic value of non-permanent carbon removals

- Many removals do not store carbon for infinite time
- Extreme case: CCU (where carbon is stored for months in products like synfuels)
- Conceptually, we can differentiate permanent removal P and non-permanent removal R in a simple dynamic model

$$\min NPV\ (Damages + Cost)$$

Subject to:

Atmospheric carbon stock

$$\frac{dX}{dt} = E - P - R + \delta Z$$

removal ↓ ↑ reversal

Non-atmospheric carbon storage

$$\frac{dZ}{dt} = R - \delta Z$$

E = Emissions

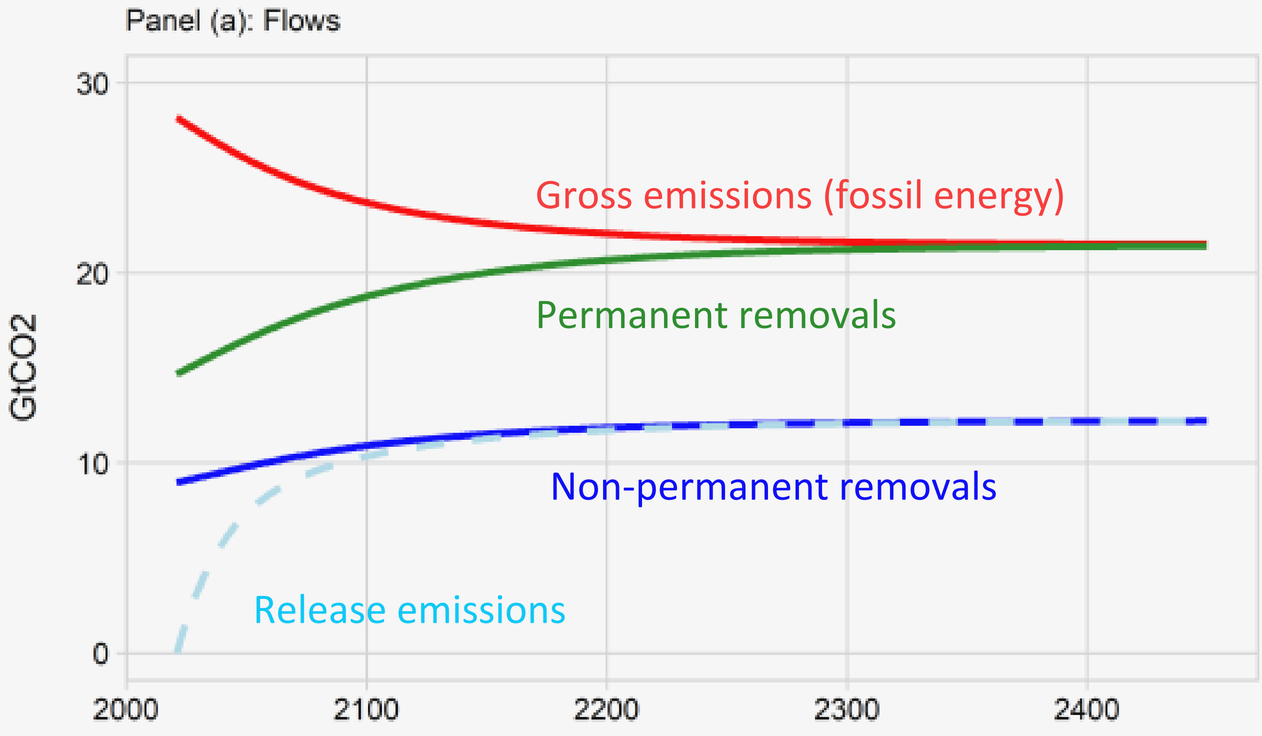
P = Permanent removal

R = Non-permanent removal

δZ = Release from removal at rate δ

Non-permanent removals do not change the climate target but allow for intertemporal cost smoothing

- Use of non-permanent removals for cost-smoothing
- Sisyphean task of managing the carbon cycle



Source: Franks et al. (2024)

Summary: Choice of technology

- CDR is an important set of technologies which enables the industrial management of the carbon cycle when combined with CCU and CCS
- Developing a diverse portfolio of CDR options enables all countries to deploy significant quantities
- The value of non-permanent carbon removals is reflected in the social cost of removals, which differs from the social cost of carbon emissions
- The regulator has to fulfill a "Sisyphus-like" task to replace non-permanent removals continuously
- Therefore, the subsidies of non-permanent removals are lower than the price of permanent CDR, depending on the storage time
- Non-permanent removals allow for intertemporal cost-smoothing

Sisyphus, by Titian, 1548–49 (adapted for CO_2)

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CDR and international cooperation

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A simple cooperation game

- Extend cooperation model (Barret) by mitigation M and removal R
- N symmetric countries maximize individual pay-offs

$$\pi_i = b\bar{M} - \frac{c}{2}M_i^2 - \frac{r}{2}R_i^2$$

- Key extension: mitigation causes supply-side leakage LR
- Aggregate net emissions:

$$\bar{M} = N\big((1 - LR)M_i + R_i\big)$$

Strategic aspects of mitigation and CDR for an individual country

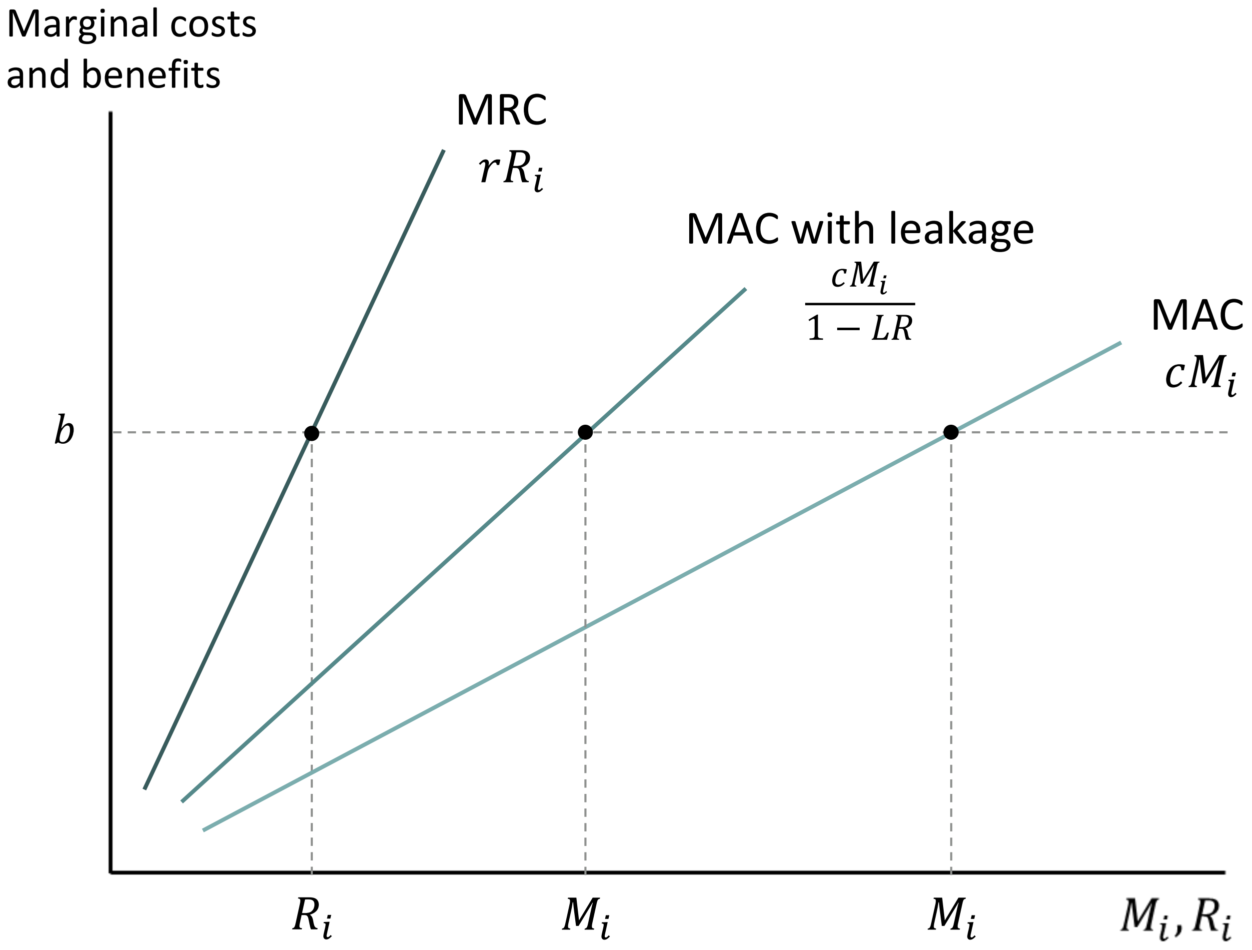
- Mitigation may cause carbon leakage (LR) on fossil fuel markets

- I.e., LR% of domestic mitigation is offset by emission increases abroad

$$b = \frac{cM_i}{1 - LR}$$

- Removal does not create leakage on fossil fuel markets

$$b = rR_i$$



Nash equilibrium of climate policy

- Socially optimal net mitigation $\bar{M}^* = N^2\left(\frac{b}{c}+\frac{b}{r}\right)$
- Mitigation in Nash equilibrium $\bar{M}^N = N\left(\frac{b}{c}(1-LR)^2+\frac{b}{r}\right)$
- Relative short-fall in abatement $\frac{\bar{M}^N}{\bar{M}^*} = \frac{1}{N}\frac{(1-LR)^2+\frac{c}{r}}{1+\frac{c}{r}}$

Illustration for N=5, LR=30%:

Technological progress in CDR can increase international ambition level considerably (here by 60%) →

Leakage LR	Relative slope marginal removal over marginal mitigation cost curve, r/c				
	0,1	0,5	1	2	4
0%	0,20	0,20	0,20	0,20	0,20
30%	0,19	0,17	0,15	0,13	0,12

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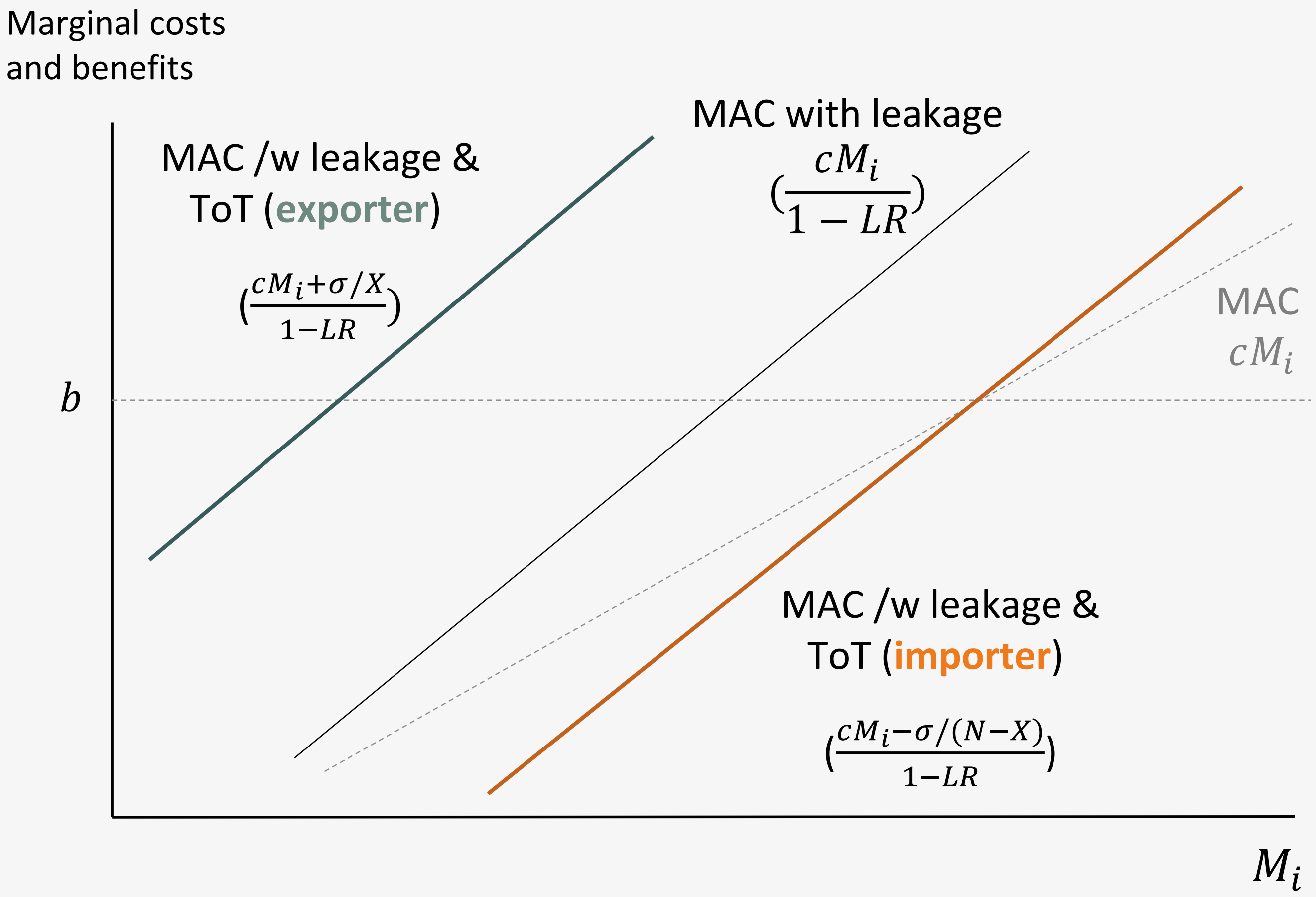
Including terms-of-trade effects: Mitigation

- X fossil fuel exporters, N-X fossil fuel importers
- Mitigation reduces (global) fuel demand, reducing fuel prices
- **Importers** gain from a terms-of-trade effect σ that scales with M_i, implying higher mitigation

$$b = \frac{cM_i - \sigma/(N-X)}{1 - LR}$$

- **Exporters** lose accordingly, implying lower mitigation

$$b = \frac{cM_i + \sigma/X}{1 - LR}$$



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Including terms-of-trade effects: Removal

- X fossil fuel exporters, N-X fossil fuel exporters

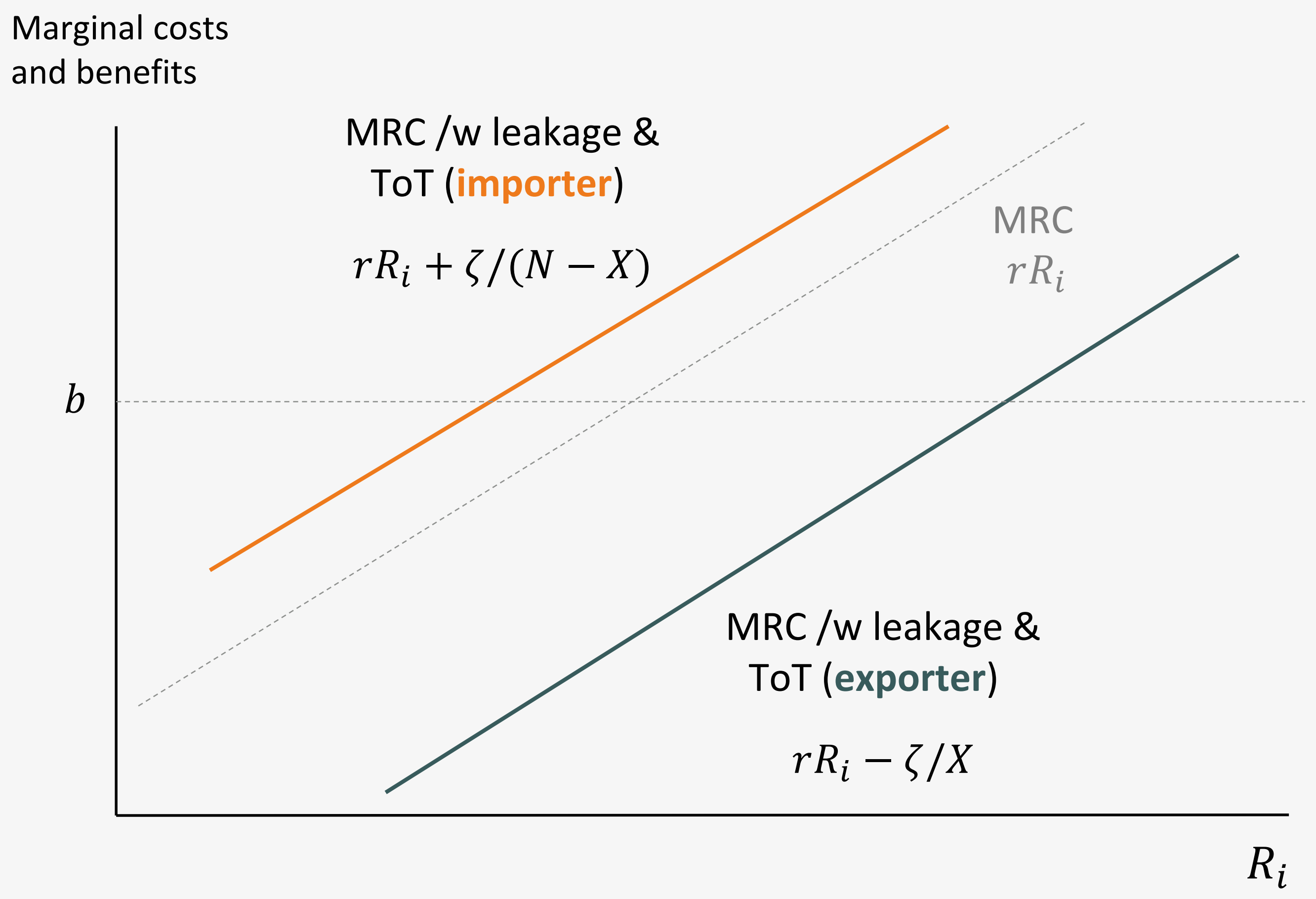
- Removal increases (global) fuel demand, increasing fuel prices

- **Importers** lose from a terms-of-trade effect ζ that scales with M_i, implying lower removal

$$b = rR_i + \zeta/(N - X)$$

- **Exporters** gain accordingly, implying higher removal

$$b = rR_i - \zeta/X$$



Implications for climate policy design in a Nash equilibrium

- Leakage: Carbon price on mitigation is lower than on removals
- Terms-of-trade effects:
  - Importers increase carbon price on mitigation (relative to CDR)
  - Exporters increase carbon price on removals (relative to mitigation)
- We should expect oil exporters to strongly subsidize CDR
- EU should impose a tax on oil and gas of 60 $/tCO_2$ in order to capture resource rents

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… further cooperation incentives are needed for the social optimum

Climate clubs, tariffs, technology protocols

› Nordhaus (2015); Lessmann et. al. (2009)

International Transfer schemes

› Kornek/Edenhofer (2020)
› Finus et al. (2024)

The potential of SRM to enhance cooperation in mitigation seems to be limited

› Finus/Furini (2024)
› McEvoy (2024)
› Meier/Traeger (2022)

Source: Unsplahs

6

The case for a European Carbon Central Bank

Prices versus quantities meets European reality

CDR expenditures likely amount to billions and trillions by 2050

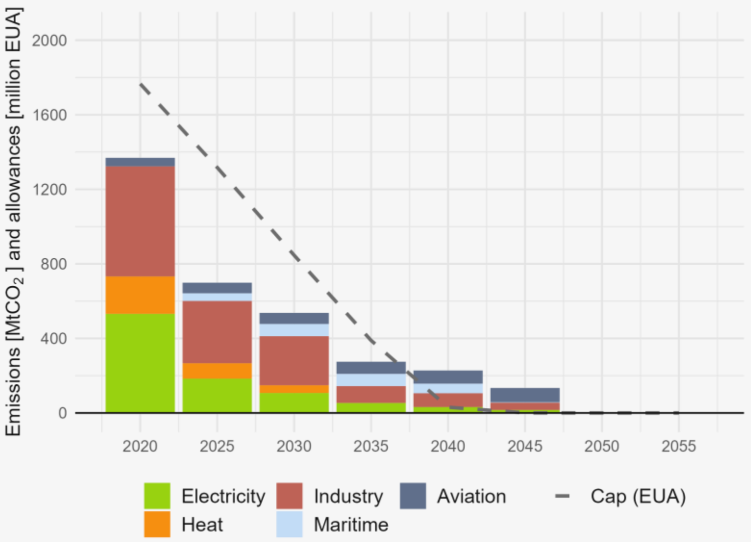
	Global	EU	
Needs	5-15 $GtCO_2$	0.3-0.6 $GtCO_2$	Smith et al. (2024); EU Commission (2024) EU Commission (2018)
Costs	100-300 $/$tCO_2$		
Expenditures	€450-4,000 billion	€30-160 billion	Exchange rate $/€: 0,90 (⌀ 2019-23)
GDP in 2023 in 2050	€83 trillion €142 trillion	€11 trillion €19 trillion	World Bank (2024); EUROSTAT (2024); Assumed growth rate/yr: 2%
Expenditures [in % of GDP]	**0.3-3%**	**0.1-1%**	

Note: Back-of-the-envelope calculation; based on Edenhofer et al. (2024) for global and Edenhofer/Leisinger (2024) for EU-wide expenditures

“First-best” CDR integration can halve long-run ETS allowance prices

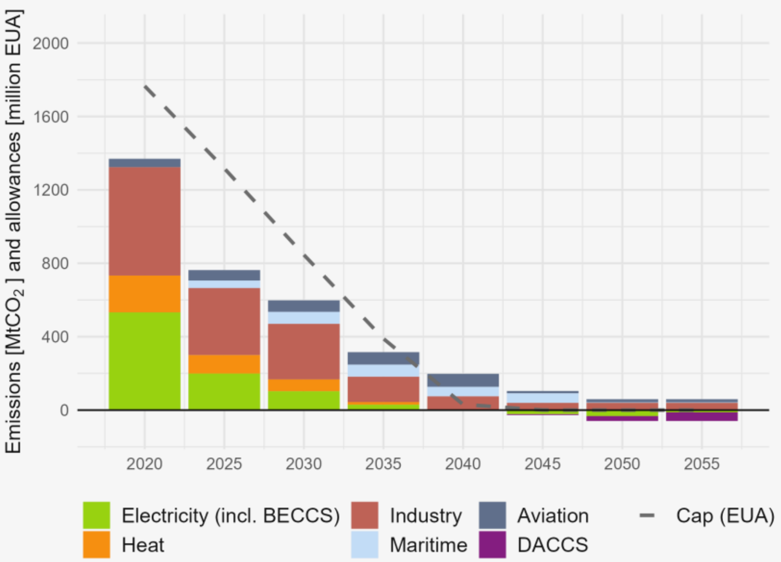
Sector emissions under status quo

BECCS and DACCS excluded from EU ETS



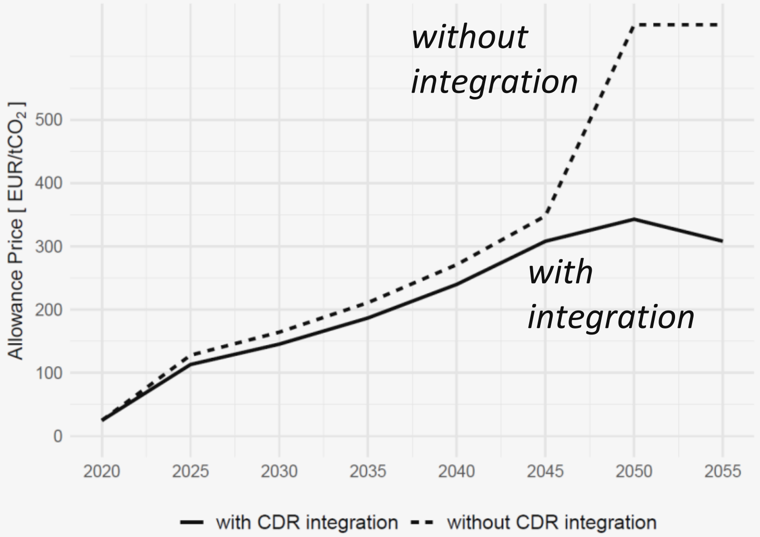
Sector emissions under CDR integration

BECCS and DACCS integrated into EU ETS



Allowance prices

Without/with BECCS and DACCS integration



Source: Sultani et al. (2024)

Assumption: Banking constrained from 2045 onwards

How to make emissions trading fit for net-negative?

First step: Integrating removals in the EU ETS

- If a firm removes and permanently stores a ton of CO_2, it can generate a removal credit and sell it in the ETS
- Cost-efficient abatement and removal

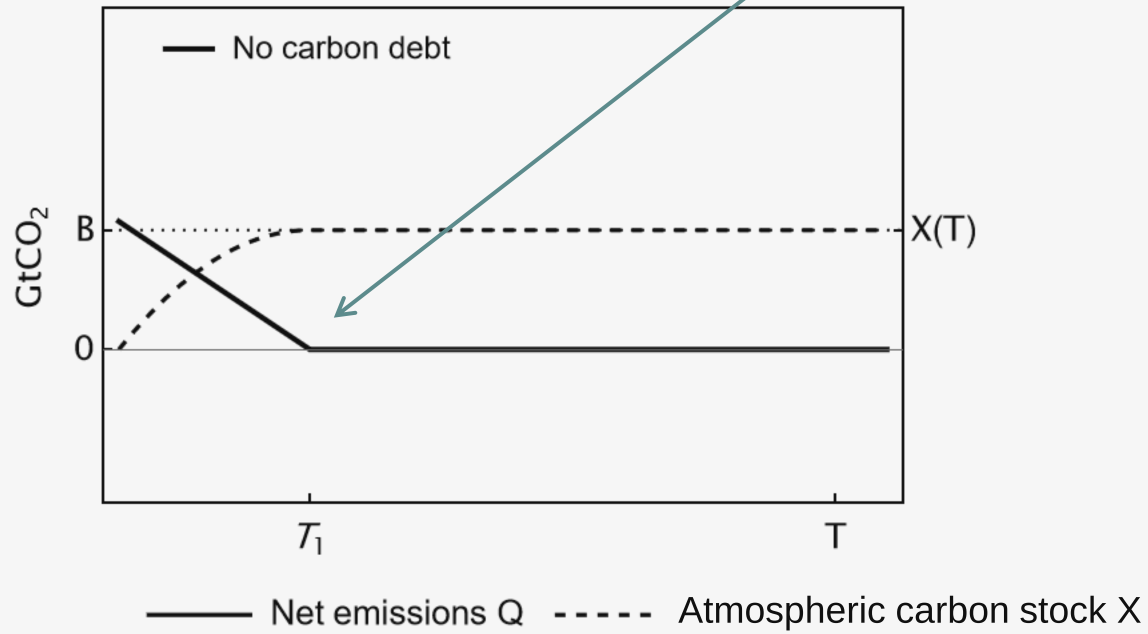
Problem: Integration can ensure net-zero emissions (where all residual emissions are offset) but not net-negative emissions

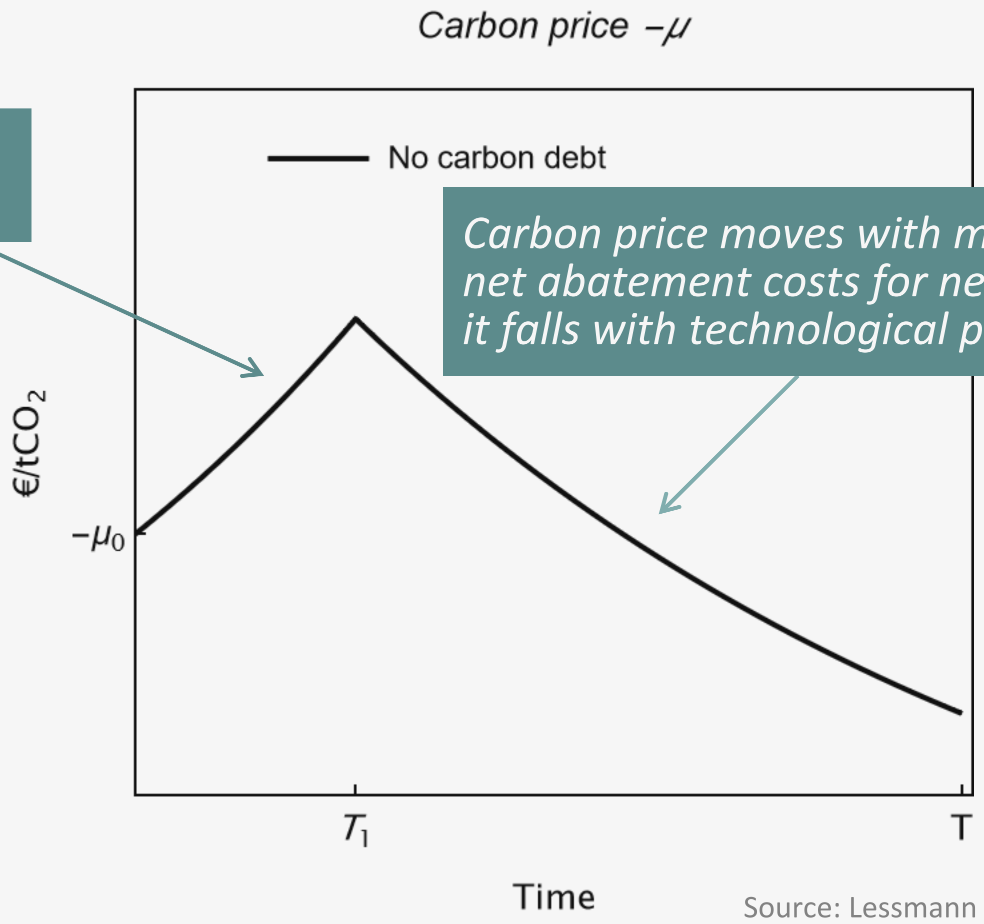
- Either, government would need to buy additional removal credits and bank/delete them (at high fiscal costs & uncertainty about the optimal time path)
- Or, creation of clean-up certificates to increase intertemporal flexibility of the ETS

The augmented ETS with integrated carbon removals

1. Integrating CDR in conventional EU ETS

Carbon price = marginal net abatement cost for net-zero emissions





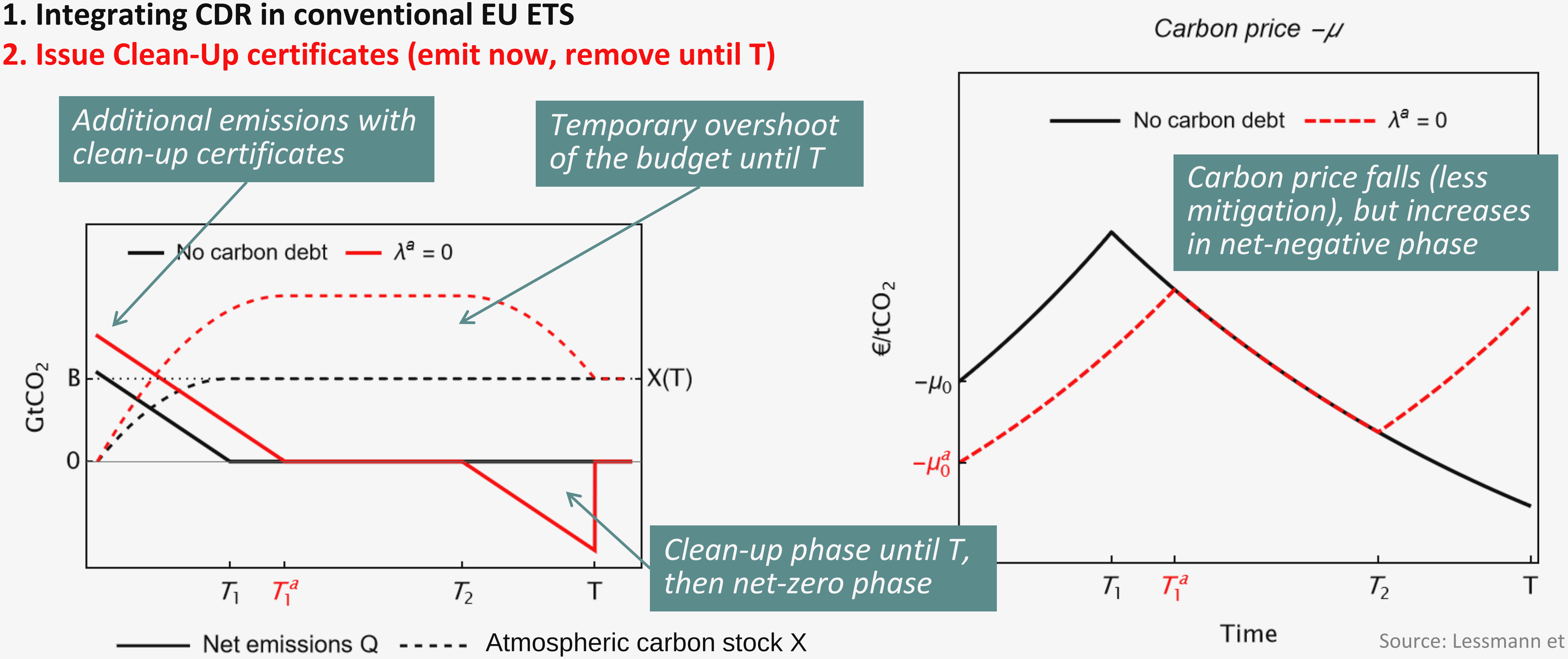
Carbon price moves with marginal net abatement costs for net-zero; it falls with technological progress

Source: Lessmann et al. (2024)

Emission trading with clean-up certificates

1. Integrating CDR in conventional EU ETS

2. Issue Clean-Up certificates (emit now, remove until T)



Source: Lessmann et al. (2024)

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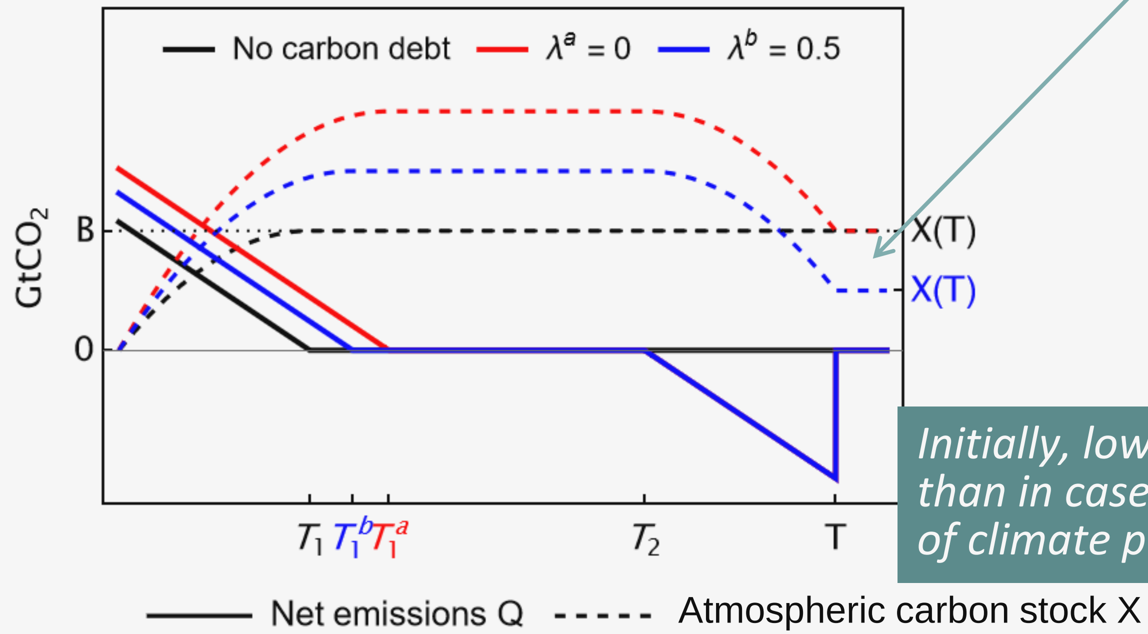
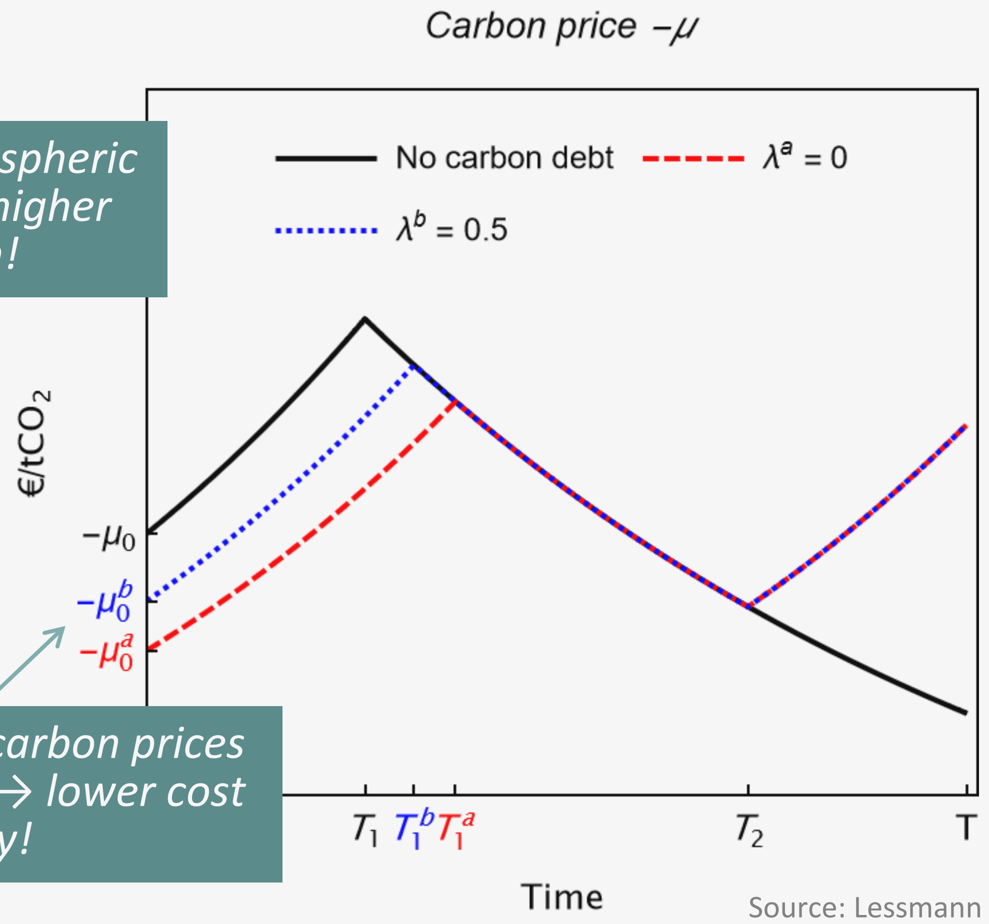
Exploiting intertemporal efficiency gains:
Lower carbon prices with higher ambition levels are possible

1. Integrating CDR in conventional EU ETS
2. Issue Clean-Up certificates (emit now, remove until T)
3. Reduce the conventional cap → Win-Win

At T, lower atmospheric carbon stock → higher climate ambition!

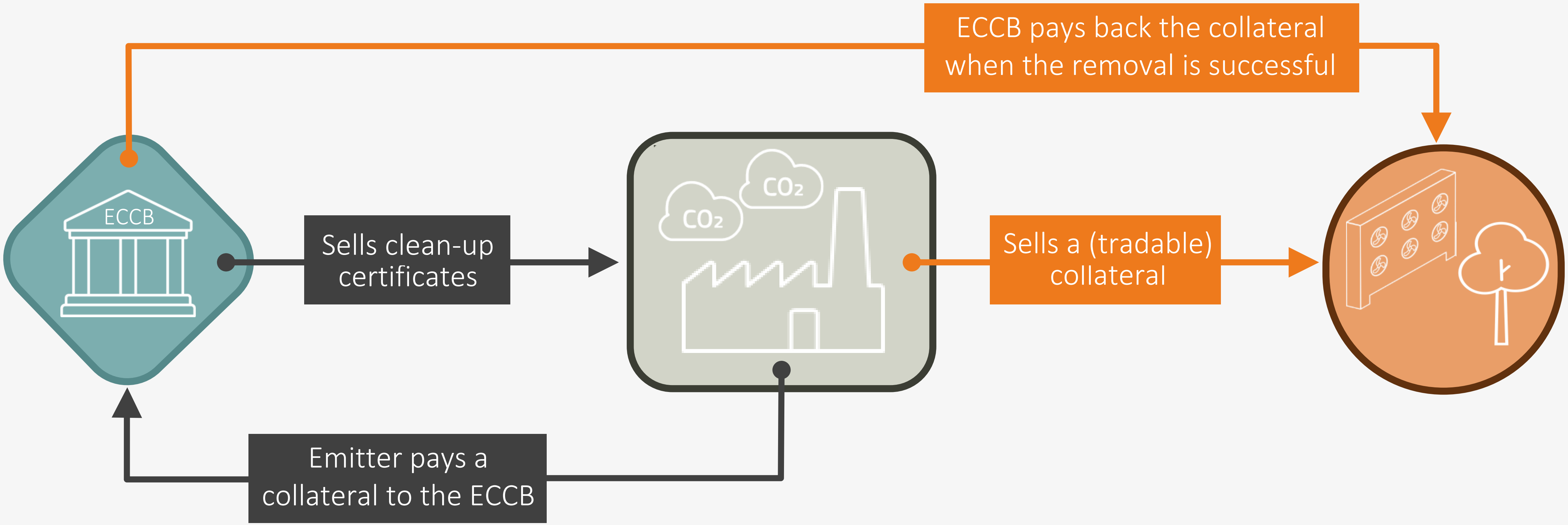




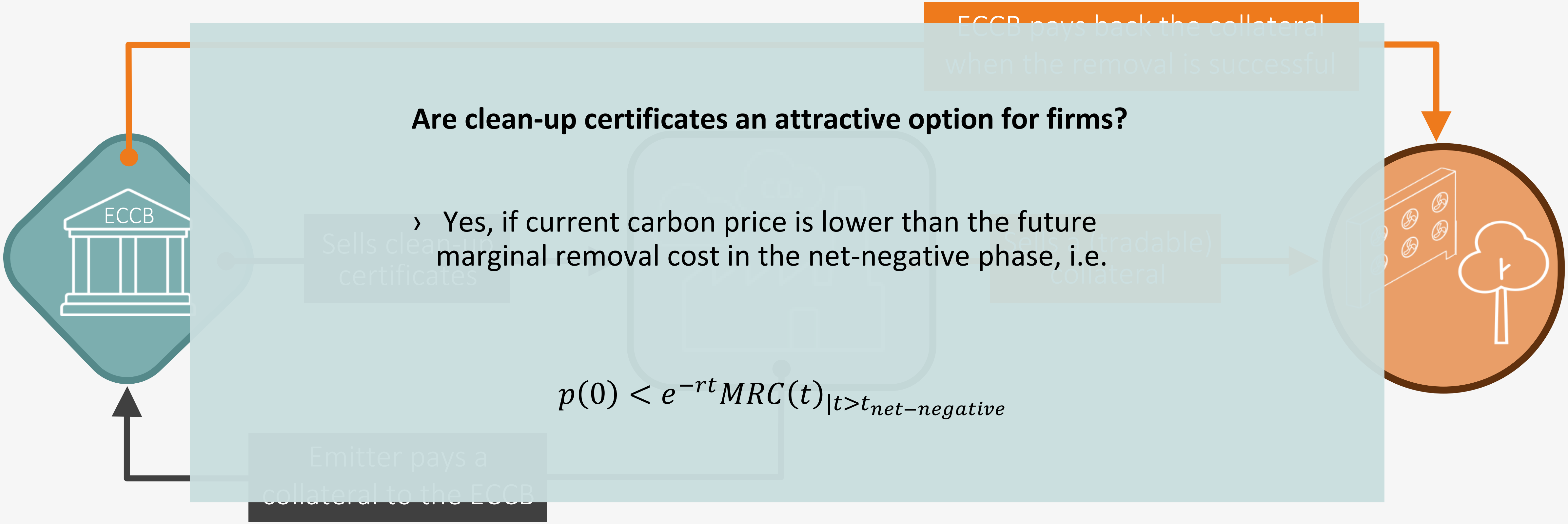
Initially, lower carbon prices than in case 1. → lower cost of climate policy!

Source: Lessmann et al. (2024)

The case for a European Carbon Central Bank



The case for a European Carbon Central Bank



Are clean-up certificates an attractive option for firms?

› Yes, if current carbon price is lower than the future marginal removal cost in the net-negative phase, i.e.

$$p(0) < e^{-rt} MRC(t)_{|t>t_{net-negative}}$$

Functions and challenges related to a European Carbon Central Bank

Functions

- Overshoot can be controlled directly
- Addresses the commitment problem of the regulator
- Creates a CDR market with strong enforcement capacity (“lender of last resort”)
- Creates a market for scaling up CDR

Challenges

- Unintended distributional consequences
- Weak mandate might lead to soft intertemporal budget constraint
- Unpriced land-use emissions might induce adverse effects on biodiversity
- Lack of democratic legitimacy

7

Taking stock

Why is CDR a gamer changer in climate policy?

Conclusion

- Carbon removals enable management of overshoot and smooth the costs of transition: CDR creates large sectoral and intertemporal flexibility
- Seemingly, adaptation is the game changer for climate policy. However, SRM becomes increasingly constrained because of steeper marginal costs compared to CDR. Additionally, the social costs of carbon become steeper over time
- Instead, CDR is the game changer for climate policy. Technological progress in the CDR sector lowers the amount of mitigation and adaptation, and reduces the costs of climate policy significantly
- CDR can help enhance international cooperation. Carbon removals unravel the geopolitics of residual emissions and can contribute to enhancing international cooperation
- A European Carbon Central Bank could manage the overshoot, address the liability problem of the regulator and act as lender of last resort in case of (strategic) bankruptcy of firms

Thank you!

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References

References

Bauer, N., Keller, D. P., Garbe, J., Karstens, K., Piontek, F., Bloh, W. von, Thiery, W., Zeitz, M., Mengel, M., Strefler, J., Thonicke, K., & Winkelmann, R. (2023). Exploring Risks and Benefits of Overshooting a 1.5 °C Carbon Budget over Space and Time. Environmental Research Letters, 18(5), 054015. https://doi.org/10.1088/1748-9326/accd83

Bilal, A., & Känzig, D. R. (2024). The Macroeconomic Impact of Climate Change: Global vs. Local Temperature. NBER Working Paper No. W32450. https://ssrn.com/abstract=4826056

Carbon Gap. (2022). A Guide to Certifying Carbon Removal. https://carbongap.org/wp-content/uploads/2022/11/Carbon_Gap_White_Pater_Oct22_updateCRCF.pdf

Edenhofer, O., Franks, M., Kalkuhl, M., & Runge-Metzger, A. (2024). On the Governance of Carbon Dioxide Removal – A Public Economics Perspective. FinanzArchiv/European Journal of Public Finance, 80(1), 70–110. https://doi.org/10.1628/fa-2023-0012

Edenhofer, O., & Leisinger, C. (2024). Das Klimaschutzprogramm der EU und Bundesregierung. In J. L. Lozán, H. Graßl, D. Kasang, M. Quante, & J. Sillmann (Eds.), Warnsignal Klima: Herausforderung Wetterextreme—Ursachen, Auswirkungen & Handlungsoptionen (pp. 345–350). Wissenschaftliche Auswertungen. https://www.klima-warnsignale.uni-hamburg.de/buchreihe/herausforderung-wetterextreme/

EPA. (2023). Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances. https://www.epa.gov/environmental-economics/scghg

Finus, M., & Furini, F. (2024). On the Credibility of Threats to Avoid the Deployment of Solar Geoengineering. Environmental Economics and Policy Studies. https://doi.org/10.1007/s10018-024-00407-2

References

Finus, M., Furini, F., & Rohrer, A. V. (2024). The Stackelberg vs. Nash-Cournot Folk-Theorem in International Environmental Agreements. Economics Letters, 234, 111481. https://doi.org/10.1016/j.econlet.2023.111481

Franks, M., Gruner, F., Kalkuhl, M., Lessmann, K., & Edenhofer, O. (2024). Pigou’s Advice and Sisyphus’ Warning: Carbon Pricing with Non-Permanent Carbon Dioxide Removal. https://doi.org/10.2139/ssrn.4828800

Kornek, U., & Edenhofer, O. (2020). The Strategic Dimension of Financing Global Public Goods. European Economic Review, 127(103423). https://doi.org/10.1016/j.euroecorev.2020.103423

Kotz, M., Levermann, A., & Wenz, L. (2024). The Economic Commitment of Climate Change. Nature, 628(8008), 551–557. https://doi.org/10.1038/s41586-024-07219-0

Lessmann, K., Kalkuhl, M., Gruner, F., & Edenhofer, O. (2024). Pay Back Your Carbon Debt. Emissions Trading with Clean-Up Certificates. CESifo Working Paper No. 11167. http://dx.doi.org/10.2139/ssrn.4875544

Lessmann, K., Marschinski, R., & Edenhofer, O. (2009). The Effects of Tariffs on Coalition Formation in a Dynamic Global Warming Game. Economic Modelling, 26(3), 641–649. https://doi.org/10.1016/j.econmod.2009.01.005

McEvoy, D. M., McGinty, M., Cherry, T. L., & Kroll, S. (2024). International Climate Agreements under the Threat of Solar Geoengineering. Journal of the Association of Environmental and Resource Economists, 11(4), 853–886. https://doi.org/10.1086/728140

Meier, F., & Traeger, C. P. (2022). SolACE - Solar Geoengineering in an Analytic Climate Economy. Available at SSRN: https://ssrn.Com/Abstract=3958821 or https://doi.org/10.2139/ssrn.3958821

References – ctd.

Nellinger, L., (2014), An Unexpected Discovery: Johann Heinrich von Thuenen and the Tragedy of the Commons. Thünen-Series of Applied Economic Theory - Working Paper No. 135. https://www.econstor.eu/handle/10419/93143

Nordhaus, W. (2015). Climate Clubs: Overcoming Free-Riding in International Climate Policy. American Economic Review, 105(4), 1339–1370. https://doi.org/10.1257/aer.15000001

Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., & Vaughan, N. E. (2024). The State of Carbon Dioxide Removal Report 2024. https://www.stateofcdr.org/resources

Sultani, D., Osorio, S., Günther, C., Pahle, M., Sievert, K., Schmidt, T. S., Steffen, B., & Edenhofer, O. (2024). Sequencing CDR into the EU ETS. CESifo Working Paper No. 11173. https://www.cesifo.org/en/publications/2024/working-paper/sequencing-carbon-dioxide-removal-eu-ets