Supplementary Information

Alternative carbon price trajectories can avoid excessive carbon removal

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Contents:

1. Supplementary model description

1.1. Techno-economic data of reforestation and afforestation

CO_2 emissions from deforestation and afforestation are calculated using marginal abatement cost curves. These cost curves are derived from the land-use optimization model MAgPIE (Model of Agricultural Production and its Impact on the Environment)[1,2] where land-based mitigation is incentivized by a price on GHG emissions from the land system. The objective function of MAgPIE is the fulfilment of food, livestock and material demand at minimum costs under socio-economic and biophysical constraints. While the GHG price renders deforestation and the conversion of pasture to cropland more costly, CO_2 removal through afforestation is rewarded and lowers the costs in the objective function of the MAgPIE model. Afforestation is implemented as managed regrowth of natural vegetation, thereby affecting vegetation, litter and soil carbon stocks. Carbon accumulation in living biomass follows sigmoidal tree growth curves based on a Chapman–Richards volume growth model, which is parameterized using vegetation carbon density of potential natural vegetation from the LPJmL model[3] and climate region specific mean annual increment (MAI) and MAI culmination age[4]. Soil and litter carbon densities are assumed to increase linearly over 20 years, starting from the weighted average carbon density of cropland and pasture[5,6].

1.2. Techno-economic data of BECCS technologies

Supplementary Table 1: techno-economic parameters of BECCS technologies

Technology (all with CCS)	Investment costs [US$2015/kW]	O&M costs [US$2015/GJ]	Conversion efficiency	Lifetime [years]	CO_2 Capture rate
Biomass integrated gasification combined cycle power plant	3150	5.59	0.28	40	80 %
Biomass to hydrogen	2040	6.80	0.55	35	90%
Biodiesel production with Fischer-Tropsch	3600	4.90	0.41	35	48%

1.3. Techno-economic data of DACCS

Direct air capture plants filter CO_2 directly from the ambient air. A variety of possible systems have been proposed, usually containing three main components: contactor, CO_2 absorbing material, regeneration system. The contactor must expose the CO_2 absorbing material to the ambient air and exchange saturated material for regenerated material. The CO_2 absorbing material must be able to pull large amounts of CO_2 from the atmosphere and release the CO_2 in the regenerating system. The released CO_2 is then captured and stored in geological storage formations. Depending on the absorbing material, temperatures of at least 800°C are needed for regeneration[7]. In the model, natural gas or H_2 can be used to generate the required heat. If natural gas is used, the resulting CO_2 emissions are assumed to be captured with a capture rate of 90%. Since the first demonstration plant has only started operating recently, data on costs and energy requirements is still uncertain. We rely on a literature review[7] for techno-economic parameterization, as specified in the table below.

Supplementary Table 2: techno-economic parameters of DAC

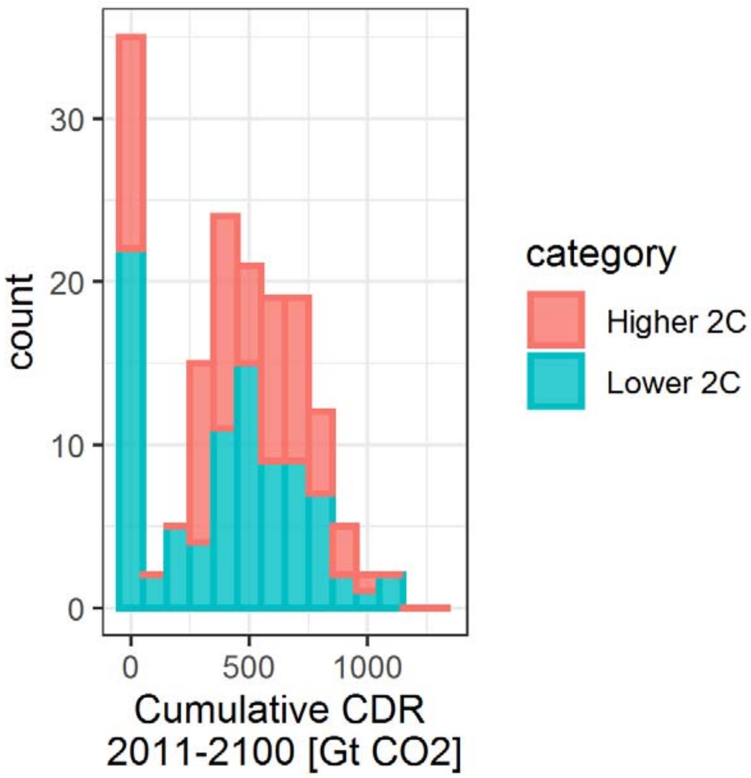
Investment costs [US$2015/(tCO2/yr)]	100
O&M costs [US$2015/(tCO2/yr)]	2.5
Lifetime [years]	20
Electricity demand [GJ/tCO2]	2
Heat demand [GJ/tCO2]	10

1.4. Trade-offs between CDR technologies

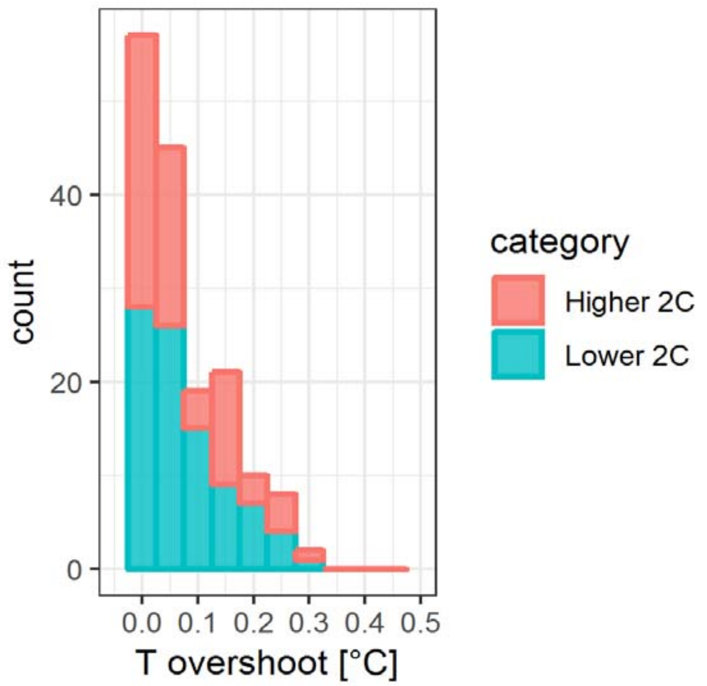
BECCS and afforestation compete for land which limits the total carbon dioxide removal potential for these two options. The marginal abatement cost curves for CO_2 emissions from deforestation and afforestation as well as the bioenergy supply curves were both derived from the MAgPIE model. The respective other technology was included in the necessary model runs, such that the land competition is taken into account.

BECCS, DACCS, and fossil CCS compete for geological storage. In REMIND, regional annual CCS is limited to 0.5% of the total available geological storage in that region. This limits total global CCS use to about 20 Gt CO_2/yr.

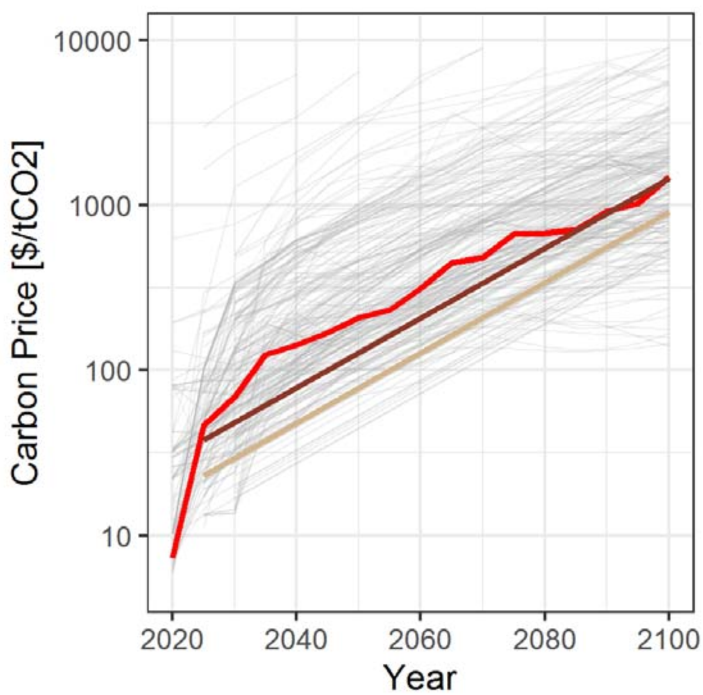
2. Supplementary figures



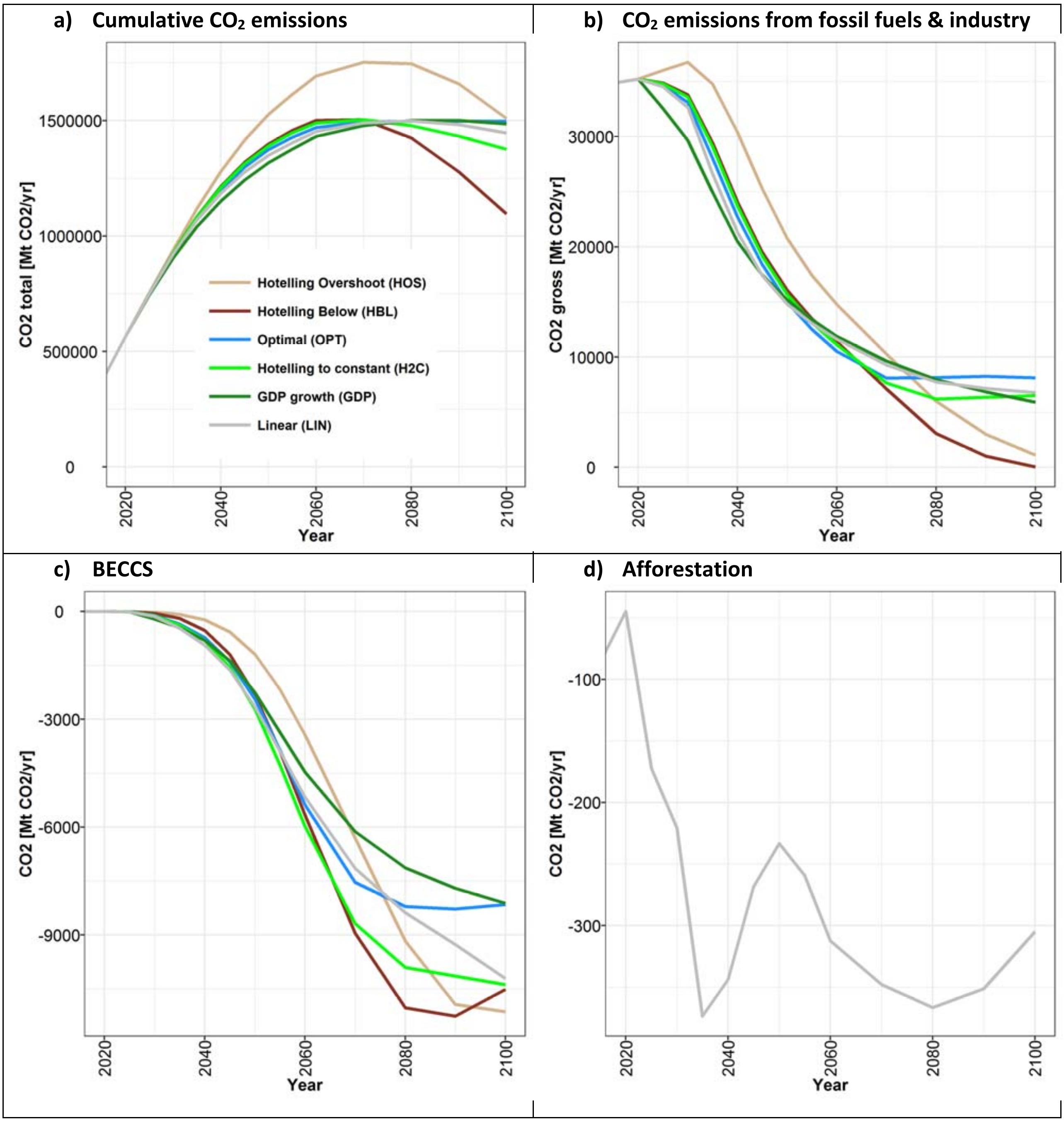
Supplementary Figure 1: Histogram of cumulative CDR use from 2011-2100 in 2°C scenarios in the IPCC Special Report on Global Warming of 1.5°C (SR1.5). We distinguish two different categories of 2°C scenarios: higher 2°C (probability between 50% and 66% of staying below 2°C, red) and lower 2°C (probability of at least 66% of staying below 2°C, blue), as defined in the database of the SR1.5 (https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/login).



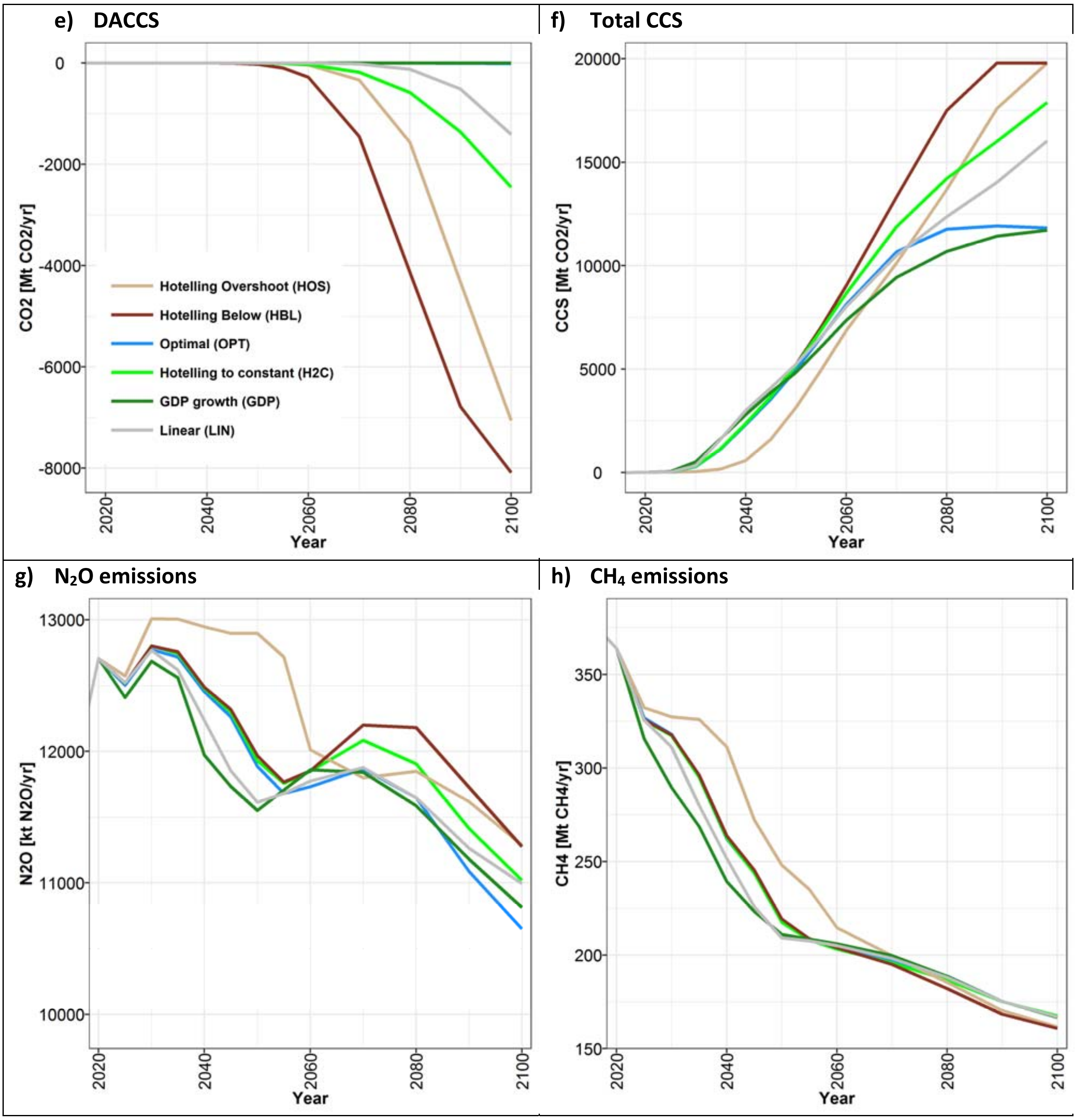
Supplementary Figure 2: Histogram of difference between peak temperature and end-of-century temperature in 2°C scenarios in the SR1.5. We distinguish two different categories of 2°C scenarios: higher 2°C (probability between 50% and 66% of staying below 2°C, red) and lower 2°C (probability of at least 66% of staying below 2°C, blue), as defined in the database of the SR1.5 (https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/login).



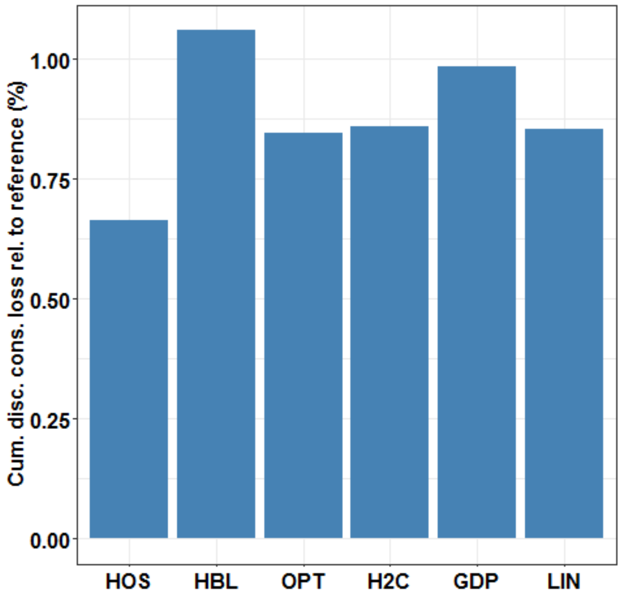
Supplementary Figure 3: Carbon price pathways in all scenarios in the SR1.5. The thick red line shows the median value of all SR1.5 scenarios (https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/login). The dark and light brown lines show the Hotelling Below and Hotelling Overshoot scenarios, respectively, for comparison.



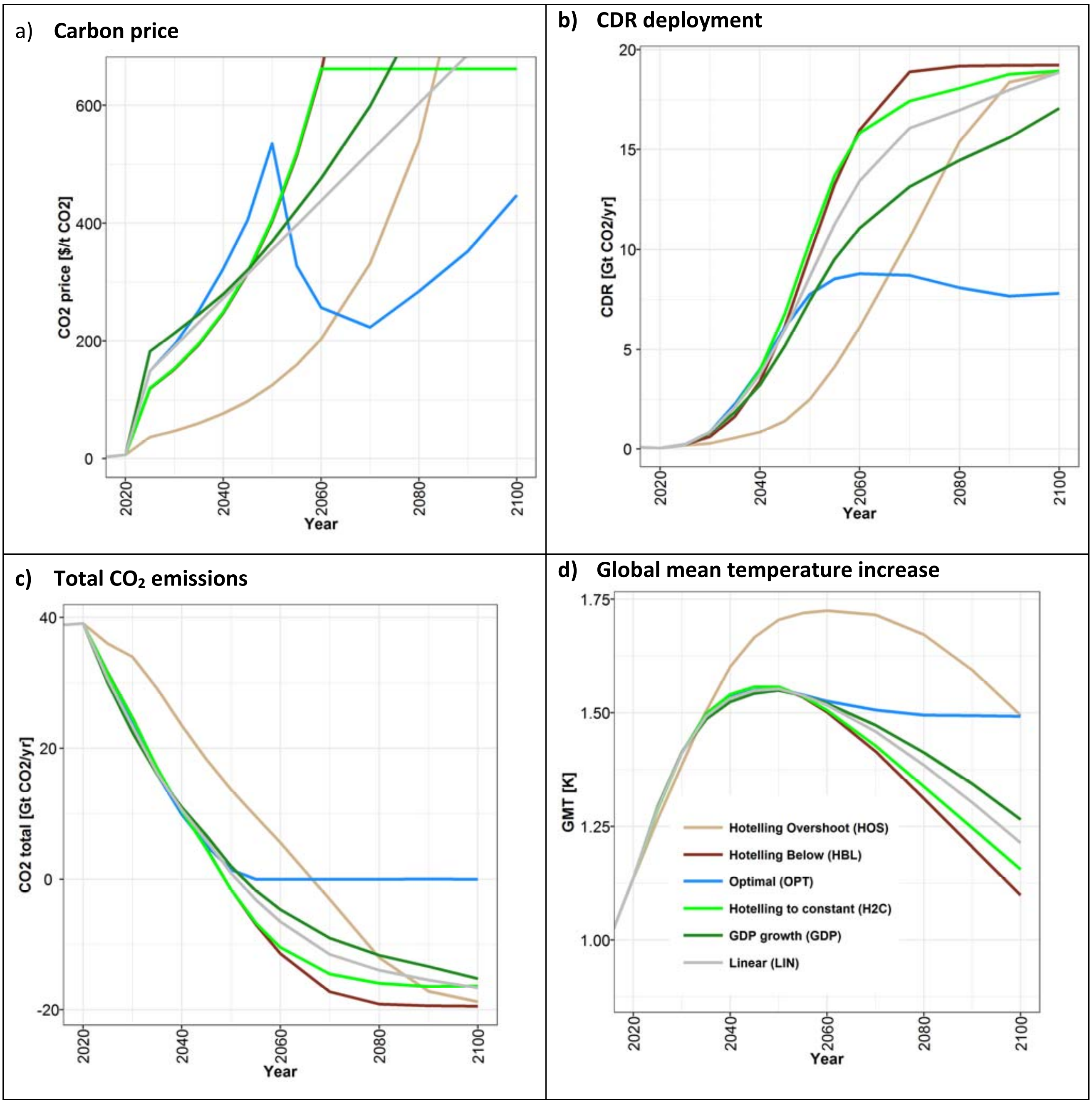
a) Cumulative CO₂ emissions
b) CO₂ emissions from fossil fuels & industry
c) BECCS
d) Afforestation
CO2 total [Mt CO2/yr]
CO2 gross [Mt CO2/yr]
CO2 [Mt CO2/yr]
Year
Hotelling Overshoot (HOS)
Hotelling Below (HBL)
Optimal (OPT)
Hotelling to constant (H2C)
GDP growth (GDP)
Linear (LIN)


e) DACCS
CO2 [Mt CO2/yr]
0
-2000
-4000
-6000
-8000
Hotelling Overshoot (HOS)
Hotelling Below (HBL)
Optimal (OPT)
Hotelling to constant (H2C)
GDP growth (GDP)
Linear (LIN)
2020
2040
2060
2080
2100
Year
f) Total CCS
CCS [Mt CO2/yr]
20000
15000
10000
5000
0
2020
2040
2060
2080
2100
Year
g) N₂O emissions
N2O [kt N2O/yr]
13000
12000
11000
10000
2020
2040
2060
2080
2100
Year
h) CH₄ emissions
CH4 [Mt CH4/yr]
350
300
250
200
150
2020
2040
2060
2080
2100
Year

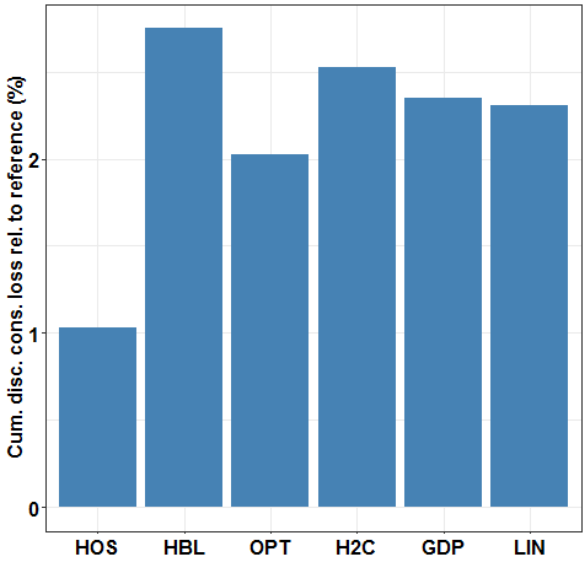
i) Cumulative discounted consumption loss until 2100 with respect to current policies



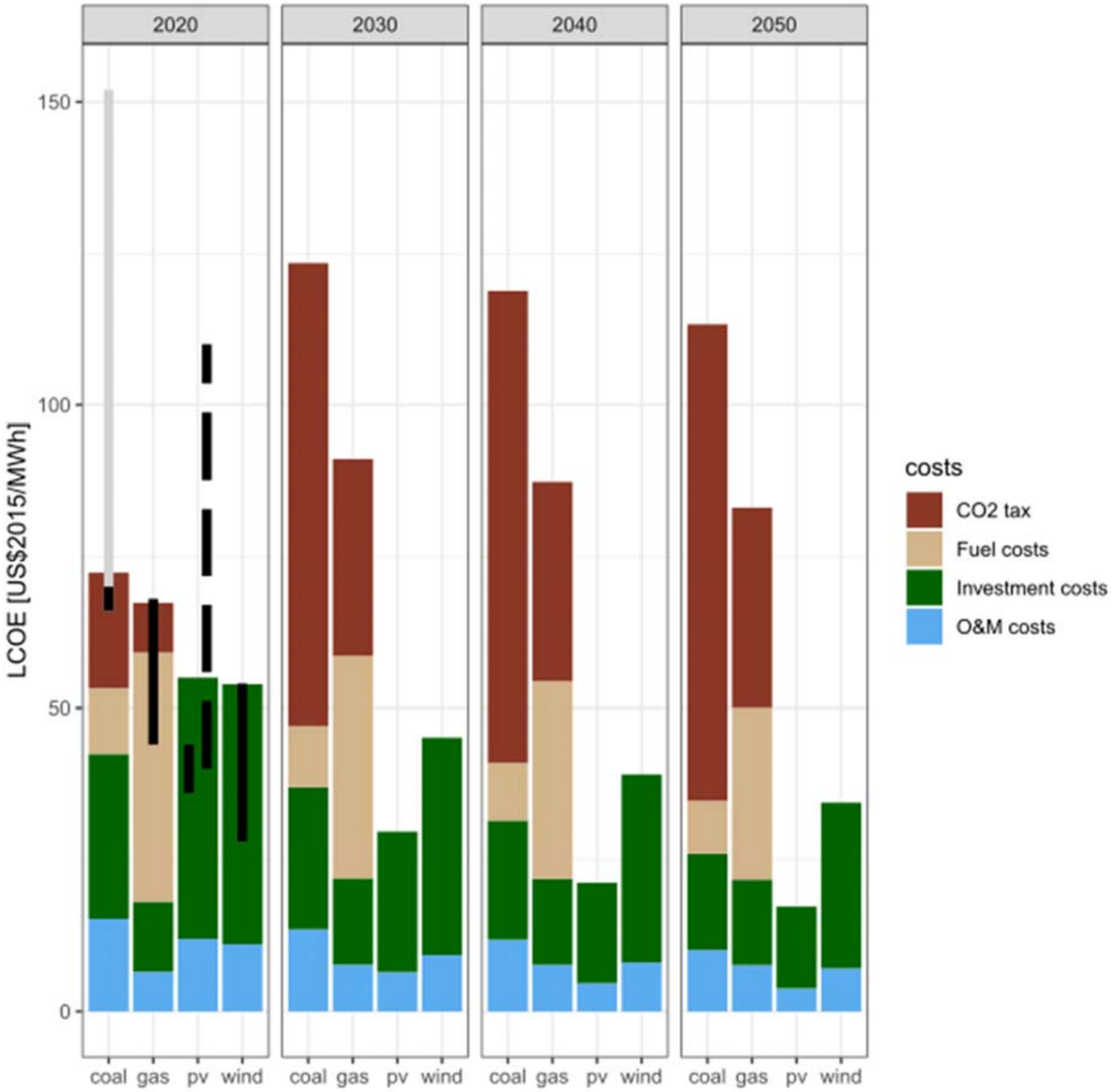
Supplementary Figure 4: Additional emission and CDR pathways and consumption losses for all six scenarios. a) cumulative CO_2 emissions, b) CO_2 emissions from fossil fuels and industry, carbon removed due to c) afforestation, d) BECCS, e) DACCS, f) total amount of CCS, g) global N_2O emissions, h) global CH_4 emissions, i) cumulative discounted (discount rate 5%, base year 2020) consumption loss as compared to a scenario with continued current policies until 2100 for the Hotelling Overshoot (light brown), Hotelling Below (dark brown), Optimal (blue), Hotelling to Constant (light green), GDP Growth (dark green), and Linear (gray) scenarios.


a) Carbon price
CO2 price [$/t CO2]
0
200
400
600
2020
2040
2060
2080
2100
Year
b) CDR deployment
CDR [Gt CO2/yr]
0
5
10
15
20
2020
2040
2060
2080
2100
Year
c) Total CO₂ emissions
CO2 total [Gt CO2/yr]
-20
0
20
40
2020
2040
2060
2080
2100
Year
d) Global mean temperature increase
GMT [K]
1.00
1.25
1.50
1.75
2020
2040
2060
2080
2100
Year
Hotelling Overshoot (HOS)
Hotelling Below (HBL)
Optimal (OPT)
Hotelling to constant (H2C)
GDP growth (GDP)
Linear (LIN)

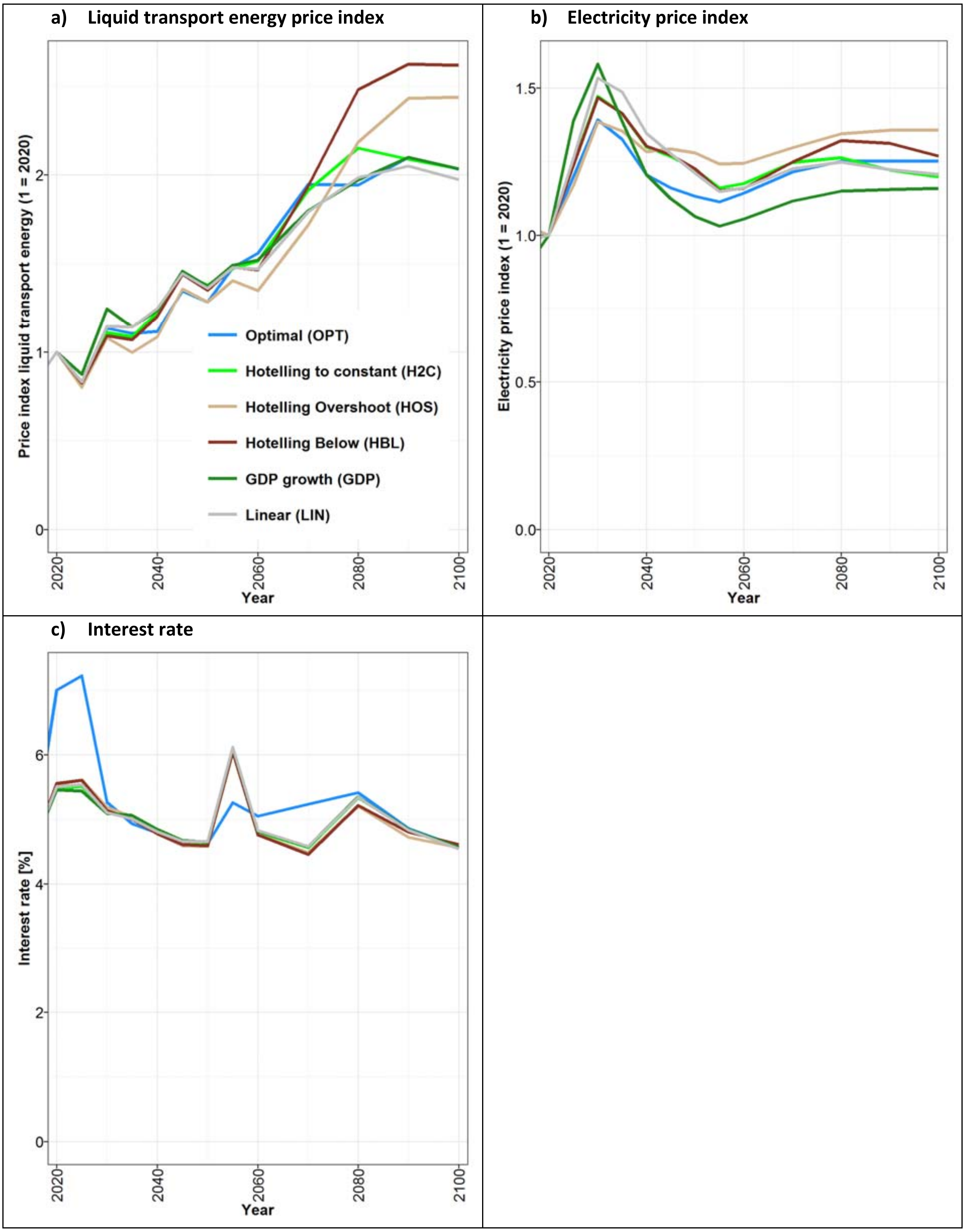
e) Cumulative discounted consumption loss



Supplementary Figure 5: Scenario characteristics as shown in Figure 1 for 1.5°C scenarios. Similar to Figure 1 we show a) Carbon price, b) CDR deployment, c) total CO_2 emissions, d) global mean temperature increase, and in addition e) cumulative discounted (discount rate 5%, base year 2020) consumption loss with respect to a scenario with continued current policies until 2100 for the scenarios Hotelling Overshoot (light brown), Hotelling Below (dark brown), Optimal (blue), Hotelling to Constant (light green), GDP Growth (dark green), and Linear (gray), but with a carbon budget of 670 Gt CO_2 from 2018 onwards, i.e. compatible with a 1.5°C target.



Supplementary Figure 6: Levelized costs of electricity production in the US from coal, natural gas, solar PV, and wind onshore in a REMIND scenario with continued current policies for 2020-2050. For comparison, the black lines gives the range of current prices based on Lazard[8] (solid) and Bolinger et al.[9] (dashed). The range of current prices from Lazard for coal includes plants with CCS; we would therefore concentrate on values on the lower end and marked the higher values in grey. LCOEs here consist of investment costs, operation and maintenance costs, fuel costs, and the costs for CO_2 emissions.



Supplementary Figure 7: Additional economic indicators. a) Liquid transport energy price index, b) electricity price index, c) interest rate for the scenarios Hotelling Overshoot (light brown), Hotelling Below (dark brown), Optimal (blue), Hotelling to Constant (light green), GDP Growth (dark green), and Linear (gray).

3. Supplementary Tables

Supplementary Table 3: Carbon price development for the three main scenarios.

Carbon price [$/tCO_2$]	**2025**	**2030**	**2040**	**2050**	**2100**
Hotelling Overshoot	23	30	49	79	907
Hotelling Below	38	48	78	127	1460
Optimal	36	48	79	128	384

Supplementary Table 4: CDR deployment for the three main scenarios.

CDR deployment [Gt CO_2/yr]	**2025**	**2030**	**2040**	**2050**	**2100**
Hotelling Overshoot	0.18	0.24	0.58	1.4	18.5
Hotelling Below	0.18	0.28	0.87	2.6	18.9
Optimal	0.18	0.33	1.1	2.7	8.5

Supplementary Table 5: Total CO_2 emissions for the three main scenarios.

Total CO_2 Emissions [Gt CO_2/yr]	**2025**	**2030**	**2040**	**2050**	**2100**
Hotelling Overshoot	37.1	36.9	30.0	19.5	-17.4
Hotelling Below	35.9	33.9	23.4	13.7	-18.8
Optimal	35.7	33.2	22.1	12.8	0

4. Supplementary references

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