Supplementary Information

Prioritizing non-carbon dioxide removal mitigation strategies could reduce the negative impacts associated with large-scale reliance on negative emissions

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1. CDR description

Table S1 provides a brief description of the various CDR approaches investigated in this study

Table S 1 Description of CDR approaches

CDR approach	Description
AR	Involves planting new forests or restoring previously forested areas to increase carbon uptake and storage in vegetation and soils through natural processes like photosynthesis and biomass accumulation
BECCS	Bioenergy with carbon capture and storage. Biomass feedstocks are grown, harvested and used for energy production in power plants or as biofuels. The CO_2 emissions from biomass combustion are captured before release and permanently stored underground
DACCS	Direct air carbon capture and storage. CO_2 is chemically extracted directly from ambient air and concentrated. The captured CO_2 gas is then transported and injected into secure geological storage sites
ERW	Enhanced rock weathering. Natural chemical weathering of silicate rocks that absorb CO_2 is enhanced by grinding and distributing minerals like basalt. This accelerates natural reactions fixing CO_2 into stable carbonates. NB: ERW is similar to Ocean Alkalinity Enhancement (OAE) but the former occurs on land while the latter occurs in oceans
Biochar	Biomass like crop residues or wood is heated without oxygen via pyrolysis to produce a stable solid carbon-rich material called biochar. When added to soils, biochar can provide long-term carbon storage and other agronomic benefits

DORCS	Direct ocean removal with capture and storage. CO_2 is chemically captured from seawater. The extracted CO_2 is transported and injected into the deep ocean at depths greater than 1000 m for secure storage

2. Supplementary Result

2.1 BECCS Vs DACCS

In our main scenario, the 1 Gt novel CDR is by DACCS only. In Tables S1-S3, we investigate the implications on our results if we had chosen BECCS instead.

Table S 2 Energy-based comparison between 1 Gt-DACCS and 1 Gt-BECCS scenarios

Indicator	1 Gt-DACCS	1 Gt-BECCS
Cumulative primary energy consumption from 2025-2050 (EJ)[a]		
Fossil fuel	1617.18	1623.12
Renewables	1609.49	1599.36
Nuclear	394.61	387.77
Cumulative final energy consumption from 2025-2050 (EJ)		
Coal and natural gas	355.48	330.13
Refined liquids	867.29	860.88
Electricity and hydrogen	1258.29	1252.28
Biomass	228.10	226.61

Marginal abatement cost of carbon by 2050 (\$/tCO_2)	2749	2856

a: Results based on GCAM's 'primary energy consumption' whiles what is reported in main paper is based on 'primary energy consumption with CCS'. Both are reported in terms of direct equivalence but both queries from GCAM produce slightly different results.

Table S 3 Emission/sequestration-based results between 1 Gt-DACCS and 1 Gt-BECCS scenarios

Indicator	1 Gt-DACCS	1 Gt-BECCS
Cumulative positive CO_2 emissions from 2050 (GtCO_2/yr)		
Building	7.98	8.00
Industry	38.22	37.96
Power	23.64	23.96
Transport	37.42	37.23
Cumulative positive non-CO_2 emissions by 2050 (GtCO_2e/yr)		
Methane	36.66	36.79
Nitrous oxides	17.88	17.85
Fluorinated gases	7.17	7.18
Cumulative net negative CO_2 emissions from 2025-2050 (GtCO_2/yr)		
LUC	17.75	17.88

Table S 4 Land/water/fertilizer results between 1 Gt-DACCS and 1 Gt-BECCS scenarios

Indicator	1 Gt-DACCS	1 Gt-BECCS
Cumulative land allocation from 2025-2050 (Mkm^2)		
Bioenergy crops	15.48	15.29
Crops	62.32	62.22
Cumulative water consumption from 2025-2050 (km^3)		
Bioelectricity CCS	0	6.90
CDR (DACCS)	13.13	0
Bioenergy crops	401.01	390.21
Electricity generation	830.84	828.89
Cumulative fertilizer demand from 2025-2050 (MtN)	107.38	105.97

2.2 Impact of subjecting land use emissions to constraint

In our main scenario, carbon emissions from land use are priced at an increasing fraction of the carbon price from fossil fuel and industry (See Method). We test this against another pathway where emissions from land use is not subjected to any form of constraint (Tables S4-6). All results are based on the 1 Gt scenario.

Table S 5 Energy-based comparison between constrained and unconstrained land use emissions scenarios

Indicator	Constrained	Unconstrained
Cumulative primary energy consumption from 2025 to net zero CO_2 year (EJ)		
Fossil fuel	1555.51	1374.73
Renewables	1197.46	1243.96
Nuclear	275.51	309.21
Cumulative final energy consumption from 2025 to net zero CO_2 year (EJ)		
Coal and natural gas	221.56	278.63
Refined liquids	772.61	738.11
Electricity and hydrogen	947.27	988.43
Biomass	221.56	207.55
Marginal abatement cost of carbon by net zero CO_2 year (\$/tCO_2)	1185	1713

Table S 6 Emission/sequestration-based results between constrained and unconstrained land use emissions scenarios

Indicator	Constrained	Unconstrained
Cumulative positive CO_2 emissions from 2025 to net zero CO_2 year ($GtCO_2$/yr)		
Building	7.86	6.82
Industry	32.98	31.48
Power	22.59	19.21
Transport	34.26	32.46
Cumulative positive non-CO_2 emissions from 2025 to net zero CO_2 year ($GtCO_2e$/yr)		
Methane	31.98	31.13
Nitrous oxides	15.07	15.01
Fluorinated gases	6.21	6.15
Cumulative net negative CO_2 emissions from 2025 to net zero CO_2 year ($GtCO_2$/yr)		
LUC	14.24	-5.71[a]

a: Implies a net positive emission (higher LUC emissions than LUC sequestration)

Table S 7 Land/water/fertilizer results between constrained and unconstrained land use emissions scenarios

Indicator	Constrained	Unconstrained
Cumulative land allocation from 2025 to net zero CO_2 year (Mkm^2)		
Bioenergy crops	11.71	14.51
Crops	53.22	62.10
Cumulative water consumption from 2025 to net zero CO_2 year (km^3)		
CDR (DACCS)	9.06	12.48
Bioenergy crops	285.45	233.39
Electricity generation	654.83	673.61
Cumulative fertilizer demand from 2025 to net zero CO_2 year (MtN)	79.15	81.03

2.3 Effect of socio-economic pathway

In our main scenario, scenarios are based on SSP2. We test this against two other SSPs (1 and 5) (Tables S7-9). All results are based on the 1 Gt scenario.

Table S 8 Energy-based comparison between SSP1, 2, and 5

Indicator	SSP1	SSP2	SSP5
Cumulative primary energy consumption from 2025-2050 (EJ)			
Fossil fuel	1641.32	1617.18	1664.98
Renewables	1681.85	1609.49	1780.81
Nuclear	434.91	394.61	500.23
Cumulative final energy consumption from 2025-2050 (EJ)			
Coal and natural gas	359.22	355.48	365.54
Refined liquids	881.67	867.29	899.34
Electricity and hydrogen	1357.74	1258.29	1495.86
Biomass	214.05	228.10	203.31
Marginal abatement cost of carbon by 2050 (\$/tCO_2)	3110	2749	4075

Table S 9 Emission/sequestration-based results between SSP1, 2, and 5

Indicator	SSP1	SSP2	SSP5
Cumulative positive CO_2 emissions from 2050 ($GtCO_2$/yr)			
Building	7.89	7.98	7.74
Industry	38.08	38.22	37.80
Power	23.71	23.64	23.34
Transport	38.49	37.42	29.33
Cumulative positive non-CO_2 emissions by 2050 ($GtCO_2e$/yr)			
Methane	36.45	36.66	36.92
Nitrous oxides	17.90	17.88	18.18
Fluorinated gases	7.66	7.17	8.22
Cumulative net negative CO_2 emissions from 2025-2050 ($GtCO_2$/yr)			
LUC	17.95	17.75	17.63

Table S 10 Land/water/fertilizer results between SSP1, 2, and 5

Indicator	SSP1	SSP2	SSP5
Cumulative land allocation from 2025-2050 (Mkm^2)			
Bioenergy crops	16.12	15.48	15.92
Crops	61.37	62.32	62.05
Cumulative water consumption from 2025-2050 (km^3)			
CDR (DACCS)	13.61	13.13	16.34
Bioenergy crops	420.07	401.01	413.50
Electricity generation	863.73	830.84	911.34
Cumulative fertilizer demand from 2025-2050 (MtN)	111.67	107.38	110.08

3. Model parameterization and underlying equations for demand and supply

In this section, some underlying parameters/modelling assumptions and selected equations. Unless cited otherwise, all information are obtained from Ref. [1], and additional information not discussed or presented here can be obtained from the same source.

Table S 11 Fraction of CO_2 captured by transformation technologies

Supply sector	Subsector	Technology	1971	2100
Refining	Coal to liquids	Coal to liquids ccs level 1	0.818	0.818
Refining	Coal to liquids	Coal to liquids ccs level 2	0.9	0.9
Refining	Biomass liquids	Cellulosic ethanol ccs level 1	0.26	0.26
Refining	Biomass liquids	Cellulosic ethanol ccs level 2	0.9	0.9
Refining	Biomass liquids	Ft biofuels ccs level 1	0.818	0.818
Refining	Biomass liquids	Ft biofuels ccs level 2	0.9	0.9

Table S 12 Primary energy transformation technologies default cost assumptions (1975$/GJ)

Supply sector	Technology	1971	2010	2100	Improvement max	Improvement rate
Gas processing	Natural gas	0.2	0.2	0.2		
Gas processing	Biomass gasification	7.030087	7.030087		0.7	0.03
Gas processing	Coal gasification	5.285779	5.285779		0.7	0.03
Nuclear fuel gen II	Enriched uranium	0.124464	0.124464	0.124464		
Nuclear fuel gen III	Enriched uranium	0.124464	0.124464	0.124464		
Refining	Oil refining	0.84	0.84	0.84		
Refining	Coal to liquids	5.294118	5.294118		0.7	0.03
Refining	Coal to liquids ccs level 1	5.980615	5.980615		0.6	0.05
Refining	Coal to liquids ccs level 2	6.467671	6.467671		0.6	0.05
Refining	Gas to liquids	3.970588	3.970588		0.7	0.03
Refining	Cellulosic ethanol	4.74	4.74		0.7	0.03
Refining	Cellulosic ethanol ccs level 1	4.991818	4.991818		0.6	0.05
Refining	Cellulosic ethanol ccs level 2	6.850562	6.850562		0.6	0.05
Refining	Ft biofuels	7.802308	7.802308		0.7	0.03
Refining	Ft biofuels ccs level 1	8.516923	8.516923		0.6	0.05
Refining	Ft biofuels ccs level 2	8.97527	8.97527		0.6	0.05
Refining	Corn ethanol	2.38	2.38	2.38		
Refining	Sugar cane ethanol	2	2	2		
Refining	Biodiesel	1.88	1.88	1.88		

Table S 13 Electricity technology capacity factors

Supply sector	Subsector	Technology	1971	2100
Electricity	Coal	Coal (Conventional Pulverized Coal	0.85	0.85
Electricity	Coal	Coal (Conventional Pulverized Coal with CCS)	0.8	0.8
Electricity	Coal	Coal (Integrated Gasification Combined Cycle)	0.8	0.8
Electricity	Coal	Coal (Integrated Gasification Combined Cycle with CCS)	0.8	0.8
Electricity	Gas	Gas (Steam Cycle/Turbine)	0.8	0.8
Electricity	Gas	Gas (Combined Cycle)	0.85	0.85
Electricity	Gas	Gas (Combined Cycle with CCS)	0.8	0.8
Electricity	Refined liquids	Refined liquids (Steam Cycle/Turbine)	0.8	0.8
Electricity	Refined liquids	Refined liquids (Combined Cycle)	0.85	0.85
Electricity	Refined liquids	Refined liquids (Combined Cycle with CCS)	0.8	0.8
Electricity	Biomass	Biomass (conventional)	0.85	0.85
Electricity	Biomass	Biomass (conventional with CCS)	0.85	0.85
Electricity	Biomass	Biomass ((Integrated Gasification Combined Cycle)	0.8	0.8
Electricity	Biomass	Biomass ((Integrated Gasification Combined Cycle with CCS)	0.8	0.8

Electricity	Nuclear	Generation II Light Water Reactor	0.9	0.9
Electricity	Nuclear	Generation III	0.9	0.9
Electricity	Wind	Wind	0.37	0.37
Electricity	Wind	Wind with storage	0.37	0.37
Electricity	Solar	Photovoltaic (PV)	0.2	0.2
Electricity	Solar	PV with storage	0.2	0.2
Electricity	Solar	Concentrated solar power (CSP)	0.25	0.25
Electricity	Solar	CSP with storage	0.5	0.5
Electricity	Geothermal	Geothermal	0.9	0.9
Electricity	Rooftop PV	Rooftop PV	0.17	0.17

Table S 14 Electricity technology capture fractions (portion of CO_2 emissions that are captured)

Supply sector	Subsector	Technology	1971	2020	2100
Electricity	Coal	Coal (Conventional Pulverized Coal with CCS)	0.85	0.85	0.95
Electricity	Coal	Coal (Integrated Gasification Combined Cycle with CCS)	0.85	0.85	0.95
Electricity	Gas	Gas (Combined Cycle with CCS)	0.85	0.85	0.95
Electricity	Refined liquids	Refined liquids (Combined Cycle with CCS)	0.85	0.85	0.95
Electricity	Biomass	Biomass (conventional with CCS)	0.85	0.85	0.95
Electricity	Biomass	Biomass ((Integrated Gasification Combined Cycle with CCS)	0.85	0.85	0.95

Table S 15 Electricity technology retirement parameters

Subsector	Technology	Year	Lifetime	Half life	Steepness
Coal	Coal (Conventional Pulverized Coal)	Final-calibration-year	60	30	0.1
Gas	Gas (Steam Cycle/Turbine)	Final-calibration-year	45	22.5	0.1
Gas	Gas (Combined Cycle)	Final-calibration-year	45	22.5	0.1
Refined liquids	Refined liquids (Steam Cycle/Turbine)	Final-calibration-year	45	22.5	0.1
Biomass	Biomass (conventional)	Final-calibration-year	60	30	0.1
Nuclear	Generation II Light Water Reactor	Final-historical-year	60	30	0.1
Wind	Wind	Final-calibration-year	30		
Solar	PV	Final-calibration-year	30		
Solar	CSP	Final-calibration-year	30		

Geothermal	Geothermal	Final-calibration-year	30		
Coal	Coal (Conventional Pulverized Coal)	Initial-future-year	60		
Coal	Coal (Integrated Gasification Combined Cycle)	Initial-future-year	60		
Coal	Coal (Integrated Gasification Combined Cycle with Carbon Capture and Storage)	Initial-future-year	60		
Gas	Gas (Combined Cycle with Carbon Capture and Storage)	Initial-future-year	45		
Refined liquids	Refined liquids (Combined Cycle)	Initial-future-year	45		

Refined liquids	Refined liquids (Combined Cycle with Carbon Capture and Storage)	Initial-future-year	45		
Biomass	Biomass (conventional with CCS)	Initial-future-year	60		
Biomass	Biomass (Integrated Gasification Combined Cycle)	Initial-future-year	60		
Biomass	Biomass (Integrated Gasification Combined Cycle with Carbon Capture and Storage)	Initial-future-year	60		
Nuclear	Generation III	Initial-nonhistorical-year	60		
Wind	Wind with storage	Initial-future-year	30		
Solar	PV with storage	Initial-future-year	30		

Solar	CSP with storage	Initial-future-year	30		
Wind	Wind offshore	Final-calibration-year	25		
Wind	Wind offshore	Initial-future-year	25		

Note: lifetime: maximum lifetime of cohort. If no retirement function is used; the entire cohort is retired in this number of years.

half life: number of years at which 50% of the cohort is retired; using the s-curve-shutdown-decider retirement function.

steepness: shape parameter used by the s-curve-shutdown-decider retirement function.

Table S 16 Industrial energy use default efficiencies

Technology	Energy input	Secondary output	1971	2020	2050	2080	2100
Biomass	Delivered biomass		0.746423	0.797	0.81	0.823	0.828
Biomass cogeneration	Delivered biomass	Electricity	0.515677	0.56	0.577	0.595	0.604
Coal	Delivered coal		0.80808	0.891	0.909	0.926	0.936
Coal cogeneration	Delivered coal	Electricity	0.582005	0.629	0.644	0.661	0.67
District heat	District heat		1	1	1	1	1
Electricity	Electricity (industry)		0.934197	1.015	1.046	1.078	1.094
Gas	Wholesale gas		0.82583	0.898	0.926	0.955	0.969
Gas cogeneration	Wholesale gas	Electricity	0.563321	0.612	0.63	0.649	0.659
Hydrogen	Hydrogen enduse		1	1	1.03	1.062	1.078
Hydrogen cogeneration	Hydrogen enduse	Electricity	0.457	0.457	0.471	0.485	0.492
Refined liquids	Refined liquids industrial		0.917381	1.001	1.033	1.062	1.077
Refined liquids cogeneration	Refined liquids industrial	Electricity	0.565189	0.614	0.632	0.652	0.662
Coal	Delivered coal		1	1	1	1	1
Gas	Wholesale gas		1	1	1	1	1
Refined liquids	Refined liquids industrial		1	1	1	1	1

Table S 17 Carbon storage resource supply curve points (2005$/$tCO_2$)

Resource	Subresource	Grade	Fraction	Cost
Onshore carbon-storage	Onshore carbon-storage	Grade 1	0	0
Onshore carbon-storage	Onshore carbon-storage	Grade 2	0.005	0.1
Onshore carbon-storage	Onshore carbon-storage	Grade 3	0.1	5
Onshore carbon-storage	Onshore carbon-storage	Grade 4	0.6	10
Onshore carbon-storage	Onshore carbon-storage	Grade 5	0.295	75
Onshore carbon-storage	Onshore carbon-storage	Grade 6	0	3500

Table S 18 Calibration values for the CO_2 removal sector (MtC)

GCAM region	sector	year	value
USA	CO_2 removal	2015	2000
Africa Eastern	CO_2 removal	2015	26.58922
Africa Northern	CO_2 removal	2015	26.30296
Africa Southern	CO_2 removal	2015	25.52156
Africa Western	CO_2 removal	2015	51.65929
Australia (with New Zealand)	CO_2 removal	2015	417.4775
Brazil	CO_2 removal	2015	1012.358
Canada	CO_2 removal	2015	79.87708
Central America and Caribbean	CO_2 removal	2015	86.18576
Central Asia	CO_2 removal	2015	429.8247
China	CO_2 removal	2015	2116.542
EU-12	CO_2 removal	2015	22.06217
EU-15	CO_2 removal	2015	71.77459
Europe (Eastern)	CO_2 removal	2015	15.81593
Europe (Non EU)	CO_2 removal	2015	15.84964
European Free Trade Association	CO_2 removal	2015	6.34295
India	CO_2 removal	2015	87.41423
Indonesia	CO_2 removal	2015	16.37849
Japan	CO_2 removal	2015	66.31417
Mexico	CO_2 removal	2015	232.7633
Middle East	CO_2 removal	2015	334.5848
Pakistan	CO_2 removal	2015	7.458686
Russia	CO_2 removal	2015	313.093
South Africa	CO_2 removal	2015	5.567627
South America (Northern)	CO_2 removal	2015	161.9685
South America (Southern)	CO_2 removal	2015	470.9671
South Asia	CO_2 removal	2015	8.830837
South Korea	CO_2 removal	2015	0
Southeast Asia	CO_2 removal	2015	165.692

Taiwan	CO_2 removal	2015	0.307808
Argentina	CO_2 removal	2015	331.3725
Colombia	CO_2 removal	2015	136.5132

Table S 19 CO_2 capture rates for DAC and process heat DAC technology

Supply sector	Subsector	Technology	1971	2100
Process heat DAC	Gas ccs	Gas ccs	0.95	0.95
CO_2 removal	DAC	High temperature DAC (natural gas)	1	1
CO_2 removal	DAC	High temperature DAC (electricity)	1	1
CO_2 removal	DAC	Low temperature DAC (heat pump)	1	1

Table S 20 Parametrizations for DACCS Technologies.

Technology	Scenario	Natural gas ($GtCO_2$)		Electricity ($GtCO_2$)		Non-energy cost (2015 $\$tCO_2$)		Water (m^3/tCO_2)	
		2020	2030	2020	2030	2020	2030	2020	2030
High temperature DACCS (natural gas)	SSP1-sustainable development	8.1	5.3	1.8	1.3	296	185	4.7	
	SSP2-middle of the road		5.3		1.3		185		
	SSP5-fossil fueled development		5.3		1.3		78		
High temperature DACCS (fully electric)	SSP1-sustainable development	_		6	5	384	186	4.7	
	SSP2-middle of the road				5		186		
	SSP5-fossil fueled development				5		101		
Low temperature DACCS (electric heat pump)	SSP1-sustainable development	_		5.5	2.5	402	235	_	
	SSP2-middle of the road				2.5		235		
	SSP5-fossil fueled development				2.5		137		

Values are assumed to remain constant after 2030 (Adapted from Ref. [2])

Fig. S1 and S2 represent enhanced weathering supply curves for GCAM regions included and not included in Beerling et al. [3], respectively. Both figures are adapted from Ref. [4].

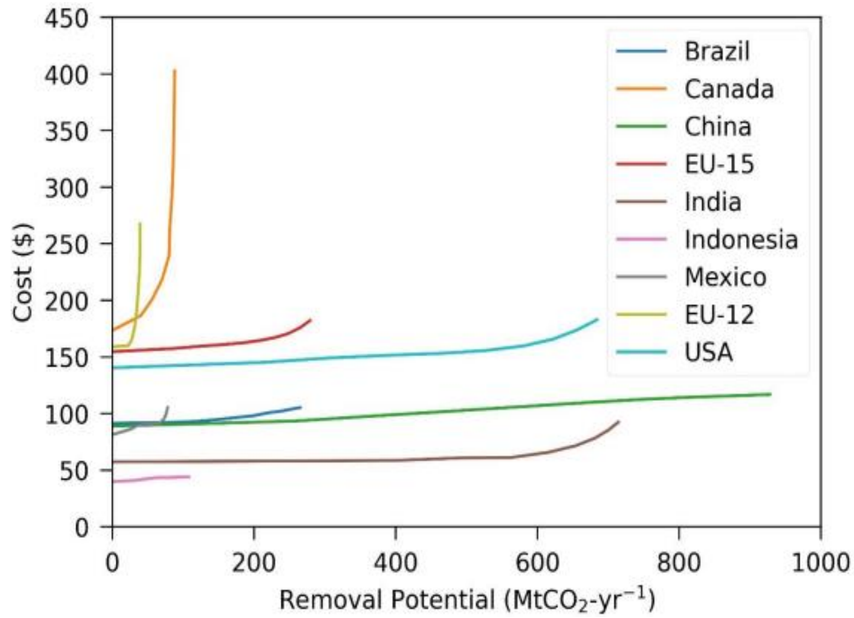

Fig. S 1 Enhanced weathering supply curves for GCAM regions(a)

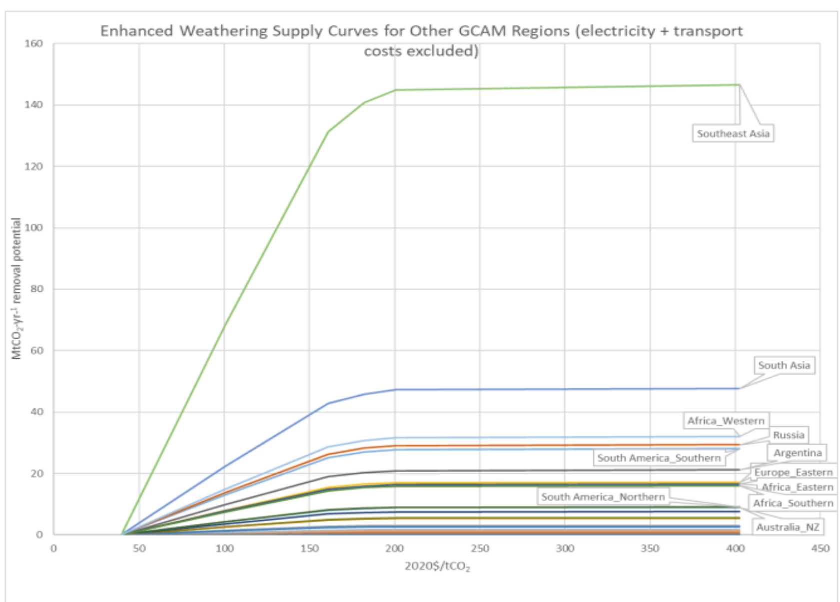

Fig. S 2 Enhanced weathering supply curves for GCAM regions (b)

Table S 20 and S21 represents enhanced weathering cost adder and electrical energy inputs (Assumes rock comminution to 20 um) for enhanced weathering, respectively from Streffler et al. [5] and Adapted from Ref. [4].

Table S 21 Enhanced Weathering Cost Adder

	Upper bound	Best estimate	Units
Investment	$14	$6	$/t rock
O&M	$59	$26	$/t rock
Total non-cost fuel	$73	$31	$/t rock
	$242	$104	$/t CO_2
Difference between upper bound + best estimate (2020 cost adder for GCAM assumption; declines to zero by 2050)	$138		$/t CO_2

Table S 22 Electrical energy inputs for enhanced weathering

Best estimate	0.66	GJ/tCO_2
Lower bound	0.23	GJ/tCO_2
Upper bound	2.03	GJ/tCO_2

Table S22 represents electrical energy input derivation for DORCS paired with reverse osmosis desalination. Non-fuel cost (based on Ref [6]) and non-energy cost assumptions for DORCS are shown in Tables S23 and S24, respectively and they are adapted from Ref. [4]. Similarly, GCAM's assumption for DORCS (Adapted from Ref. [4]) is shown in Table S25.

Table S 23 Electrical Energy Input Derivation for DORCS paired with reverse osmosis desalination.

Row	Value	Units	Source
1	0.075	kWh kg^{-1} CO_2 captured (capture energy only; standalone capture energy equal to this value)	Ref. [6]
2	277.77	kWh/GJ	Unit conversion
3	3.666667	$kgCO_2/kgC$	Unit conversion
4	9.89E-04	GJ electricity / kgC captured	Calculation [1]/[2]*[3]
5	13.1	m^3 ocean water / kg captured CO_2	ref
6	48.03	m^3 ocean water / kg captured C	Calculation [5]*[1]
7	2.5	m^3 seawater processed / m^3 desalinated water produced	GCAM assumption
8	5.15E-05	GJ elec / m^3 desalinated water (CO_2 capture only)	Calculation [4]/[6]*[7]
9	2.20E-02 - 6.30E-03	GJ elec / m^3 desalinated water (desalination)	GCAM assumption

Table S 24 Non-fuel costs of DORCS

Ocean capture scenario	CapEx ($ $kg^{-1}CO_2$)	Non-fuel opex ($ kg^{-1} CO_2)			Total ($ kg^{-1} CO_2)	GDP deflator from 2020 to 1975	1975 ($$kg^{-1}$ C)
		O&M	Labor, tax, insurance	Replacements			
Co-located	0.18	0.05	0.06	0.18	0.47	3.79	0.45
Stand-alone	1.07	0.18	0.27	0.18	1.7		1.64

Table S 25 Non-energy cost assumptions for DORCS paired with reverse osmosis desalination.

Row	Description	Value	Units	Source
1	non-fuel costs of CO_2 capture for co-located DORCS	0.45	1975$/kgC	*
2	m^3 ocean water / kg captured C	48.03	m^3/kgC	[6]
3	m^3 seawater processed / m^3 desalinated water produced	2.5	unitless	GCAM assumption
4	Non-energy cost adder for CO_2 capture	0.023	$1975/$m^3$ desalinated water	Calculation [1]/[2]*[3]
5	Non-fuel cost of desalinated water (reverse osmosis technology)	0.38	$1975/$m^3$ desalinated water	GCAM assumption
6	Total non-fuel cost of DORCS + reverse osmosis	0.40	$1975/$m^3$ desalinated water	Calculation [4]+[5]

*Based on Supplementary Table 2 from Ref. 4

Table S 26 GCAM Assumptions for Direct Ocean Capture.

	Electricity input (GJ/tCO2)	Non-fuel cost (2020$/tCO2)
Stand-alone	16.5	1700
Co-located with desalination (carbon capture only)	0.26	470

Table S26 represents biochar demand and supply assumptions (based on Ref. [7]). Table is adapted from Ref. [4] .

Table S 27 *Biochar supply and demand assumptions*

Metric	Value	Unit	Source
Non-energy cost	45.93	2007 USD per ton of feedstock	[8]
Biomass input	3.65	Tons of switchgrass per ton of biochar	
Natural gas input	211.19	MJ per dry ton of biochar	
Syngas co-product	20095	MJ per dry ton of biochar	
Net syngas co-product	19884	MJ per dry ton of biochar	
Application rate	10 - 20	Tons of biochar per hectare	[9,10]
Yield improvements	12 (tropical irrigated) 19 (tropical rainfed) 10 (temperate irrigated) 15 (temperate rainfed)	Percentage	
Carbon sequestered	70	Percentage	[11]

Selected equations are presented below, additional model underlying equations can be obtained directly from Ref. [1]

Technology or subsector share

GCAM uses one of two different logit formulations to calculate the shares for each technology or subsector.

The first option, also known as the relative-cost-logit, is:

$$s_i = \frac{\alpha_i c_i^{\gamma}}{\sum_{j=1}^{N} \alpha_j c_j^{\gamma}} \tag{1}$$

where s_i is the share of technology or subsector i, α_i is the share weight, c_i is the cost of technology or subsector i, and γ is the logit exponent.

The second option, also known as the absolute-cost-logit, is:

$$s_i = \frac{\alpha_i \exp(\beta c_i)}{\sum_{j=1}^{N} \alpha_j \exp(\beta c_j)} \tag{2}$$

where s_i is the share of technology or subsector i, α_i is the share weight, c_i is the cost of technology or subsector i, and β is the logit exponent.

Transportation service demand

The demand (D) for transportation services (e.g., passenger-km, tonne-km) in region r and time period t is given by the following equation:

$$D_{r,t} = D_{r,t-1} \left(\frac{Y_{r,t}}{Y_{r,t-1}}\right)^{\alpha} \left(\frac{P_{r,t}}{P_{r,t-1}}\right)^{\beta} \left(\frac{N_{r,t}}{N_{r,t-1}}\right) \tag{3}$$

Where Y is the per-capita GDP, P is the total service price aggregated across all modes, N is the population, and α and β are income and price elasticities, respectively.

Transportation subsector competition

At the subsector level, the subsector competition may add the time value of transportation, as shown in the equation for the price (P) of mode i, in region r and time period t:

$$P_{i,r,t} = \sum_{j=1}^{N} \left(\alpha_{j,i,r,t} * P_{j,i,r,t}\right) + \frac{W_{r,t} * V_{i,r,t}}{S_{i,r,t}} \tag{4}$$

In the equation above, j refers to any of N technologies within subsector i, and α is the share of technology j in subsector i. Where this equation differs from the subsectors elsewhere in GCAM is the final term, the wage rate (W) multiplied by the "time value multiplier" (V), divided by the average speed of the mode (S).

Transportation technology cost

The costs of transportation technologies are computed as follows, for technology j in subsector i, region r, and time period t:

$$P_{j,i,r,t} = \frac{P_{f,r,t} * I_{j,i,r,t} + N_{j,i,r,t}}{L_{j,i,r,t}} \tag{5}$$

In this equation, P_f stands for the fuel price, I is the vehicle fuel intensity, N is the levelized non-fuel cost (expressed per vehicle-km), and L is the load factor (persons or tonnes per vehicle).

Direct Air Capture for Carbon Dioxide Removal

We use GCAM's (unmodified) logit choice model for economic choice between DACCS technologies. This includes the "choice" to not deploy DACCS and instead use other mitigation or negative emissions technologies (i.e., the "no-DAC" technology). The share s_i of any DACCS technology with price pi is computed as follows:

$$s_i = \frac{\alpha_i * \exp{(\beta * p_i)}}{\sum_{j=1}^{N} \alpha_j * \exp{(\beta * p_j)}} \tag{6}$$

Where:

α_i = the shareweight of the technology.

β = the logit coefficient, which determines how large a cost difference is required to produce a given difference in market share.

Total technology cost

The total cost for a technology is the sum of the cost of the technology, the cost of its inputs, and any GHG value:

$$C = t + \sum_{j=1}^{n} i_j + \sum_{k=1}^{m} g_k - \sum_{l=1}^{o} v_l \tag{7}$$

Where C is the total cost, t \$ is the exogenously specified technology cost (capturing capital cost and operating & maintenance costs), i_j is the cost of input j (e.g., a fuel), g_k is the GHG value of gas k, and v_l is the value of secondary output l. Costs vary by region, technology, and year.

Renewable resource supply

The specific supply curve in each region for wind and solar is assigned three parameters, detailed in the following equation:

$$Q = maxSubResource * \frac{P^{CurveExponent}}{(MidPrice^{CurveExponent} + P^{CurveExponent})} \tag{8}$$

Where Q refers to the quantity of electricity produced, P the price, and the remaining parameters are exogenous, with the names in the XML input files corresponding to the names in the equation above. $maxSubResource$ indicates the maximum quantity of renewable energy that could be produced at any price, $CurveExponent$ is a shape parameter, and $MidPrice$ indicates the price at which 50% of the maximum available resource is produced.

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