Feasible deployment trajectories of carbon capture and storage compared to the requirements of climate targets

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1 Supplementary Figures

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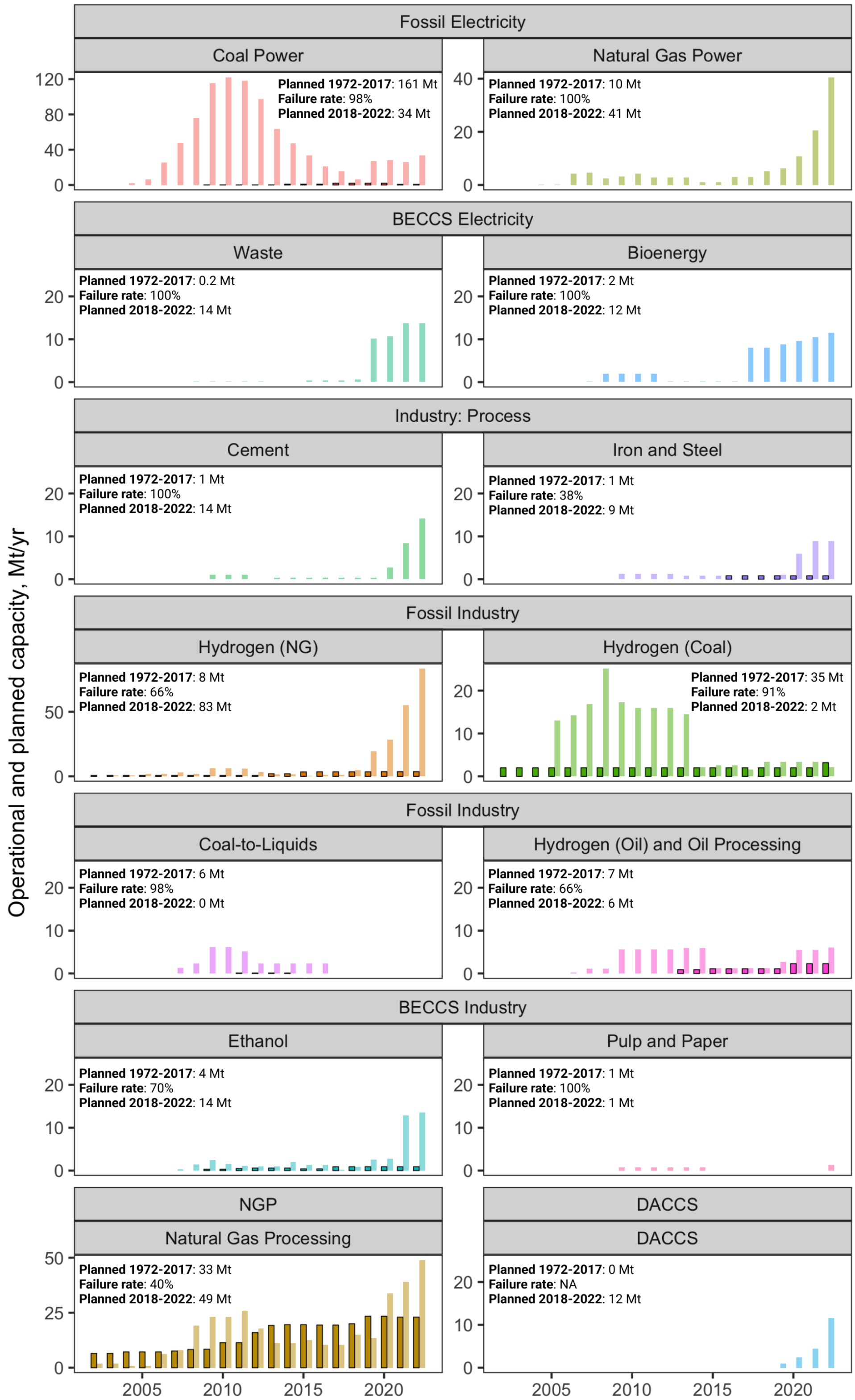


Fig. S2 | Example curve fitting of Gompertz (orange) and logistic (blue) growth models to time-series of historical (2000-2020) and future (from 2030) projections of CCS (in Gt/yr, incl. BECCS and DACCS) in the IPCC AR6 scenario ensemble [1]. The figure shows examples of logistic (blue) and Gompertz (orange) growth model fits to the combination of observed past and projected future deployment of CCS (black dots). Timeseries are truncated at the maximum annual CCS capacity to increase the goodness of fit and produce stable growth metrics in scenarios where CCS capacity starts to decrease after stable growth and saturation.

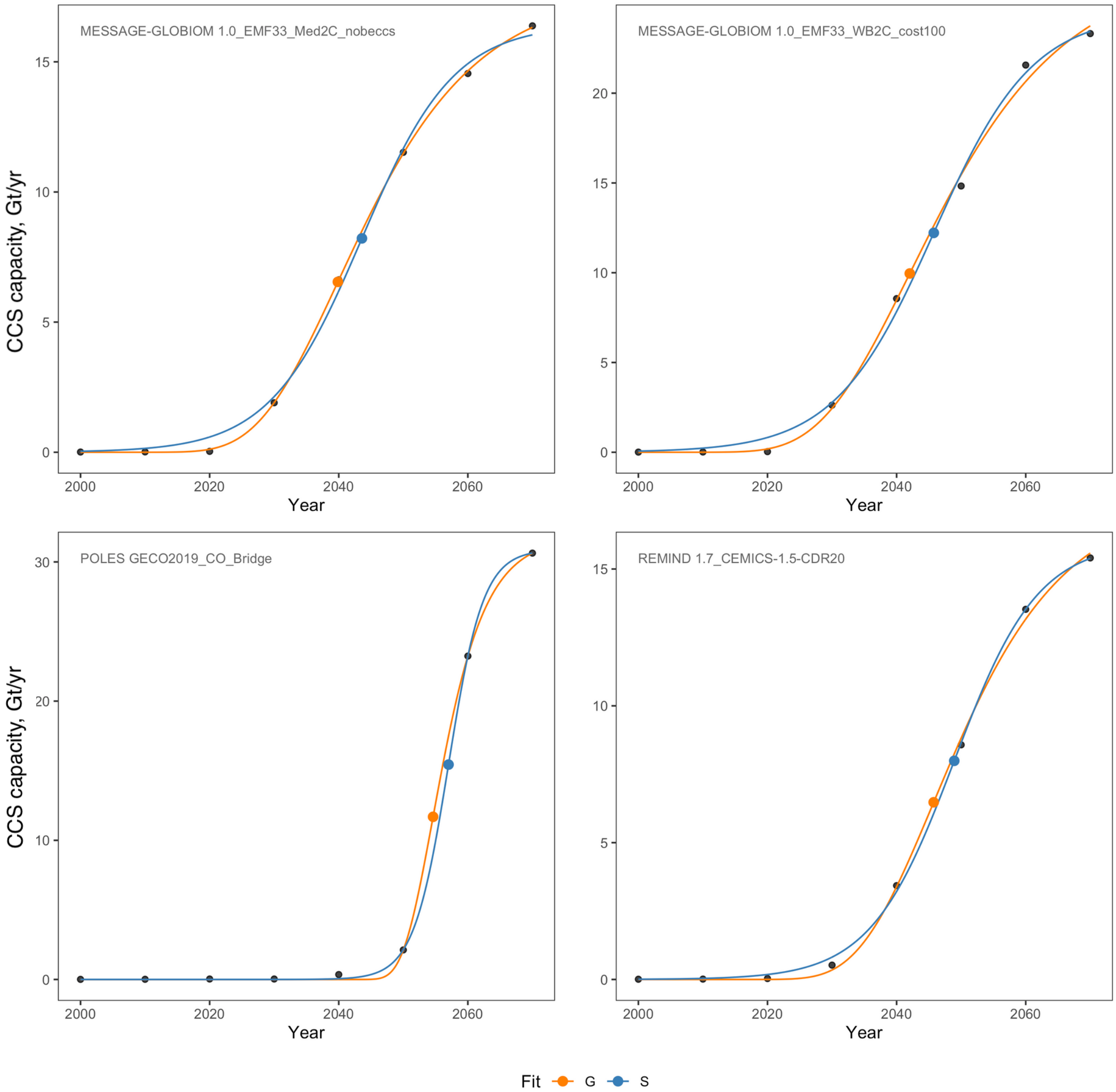


Fig. S3 | CCS capacity (incl. BECCS and DACCS) for reaching different temperature targets in the IPCC AR6 scenario ensemble [1]. This figure illustrates CCS capacity (Gt/yr) among C1-C6 IPCC scenario categories in 2030-2100. Categories vary by the global mean surface air temperature change by 2100: C1 scenarios stay below 1.5°C with no or limited overshoot with a 50% probability; C2 - below 1.5°C with high overshoot; C3 - likely below 2°C; C4 - below 2°C; C5 - below 2.5°C; C6 - below 3.0°C [2]. C1 and C2 are thus grouped as 1.5°C-compatible; C3 and C4 as 2°C-compatible; C5 as 2.5°C- and C6 as 3°C-compatible. Numbers in brackets show the number of scenarios in each category. The sample contains model families with scenarios in each temperature group (Methods). The box-plots show the interquartile range (IQR) of CCS deployment in the scenario sample: the median (second quartile) as the centre, the 25th and 75th percentiles (first and third quartiles) as the bounds of box, and the whiskers drawn within the 1.5 IQR value. Violin plots show the distribution of this values within each group.

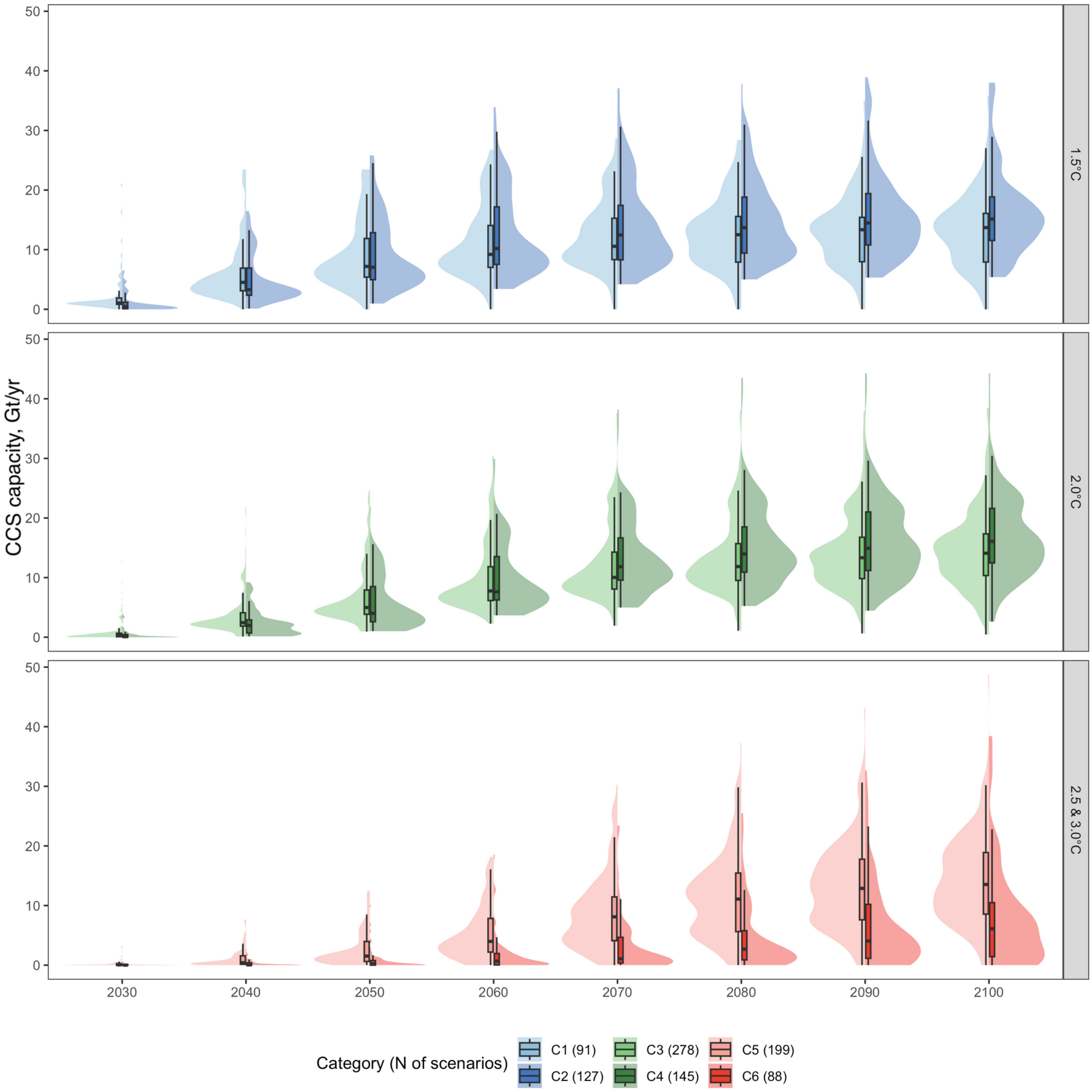


Fig. S4 | Average growth model parameters of CCS deployment in the IPCC AR6 scenario ensemble, grouped by temperature outcome. **a**, maximum annual growth rates (G_{2020}, Gt/yr), the year of maximum growth ($TMax$), and maximum capacity (saturation level, in Gt/yr) in every 1.5°C-2.5°C-compatible scenario. **b**, interquartile ranges (IQR) of G_{2020} by temperature group. **c**, IQR of the year of maximum growth ($TMax$) by temperature group. The box-plots show the interquartile range (IQR) of growth parameters in the scenario sample: the median (second quartile) as the centre, the 25th and 75th percentiles (first and third quartiles) as the bounds of box, and the whiskers drawn within the 1.5 IQR value. Each parameter is calculated from fitting Gompertz and logistic growth function (Methods). Average values of the two models are used.

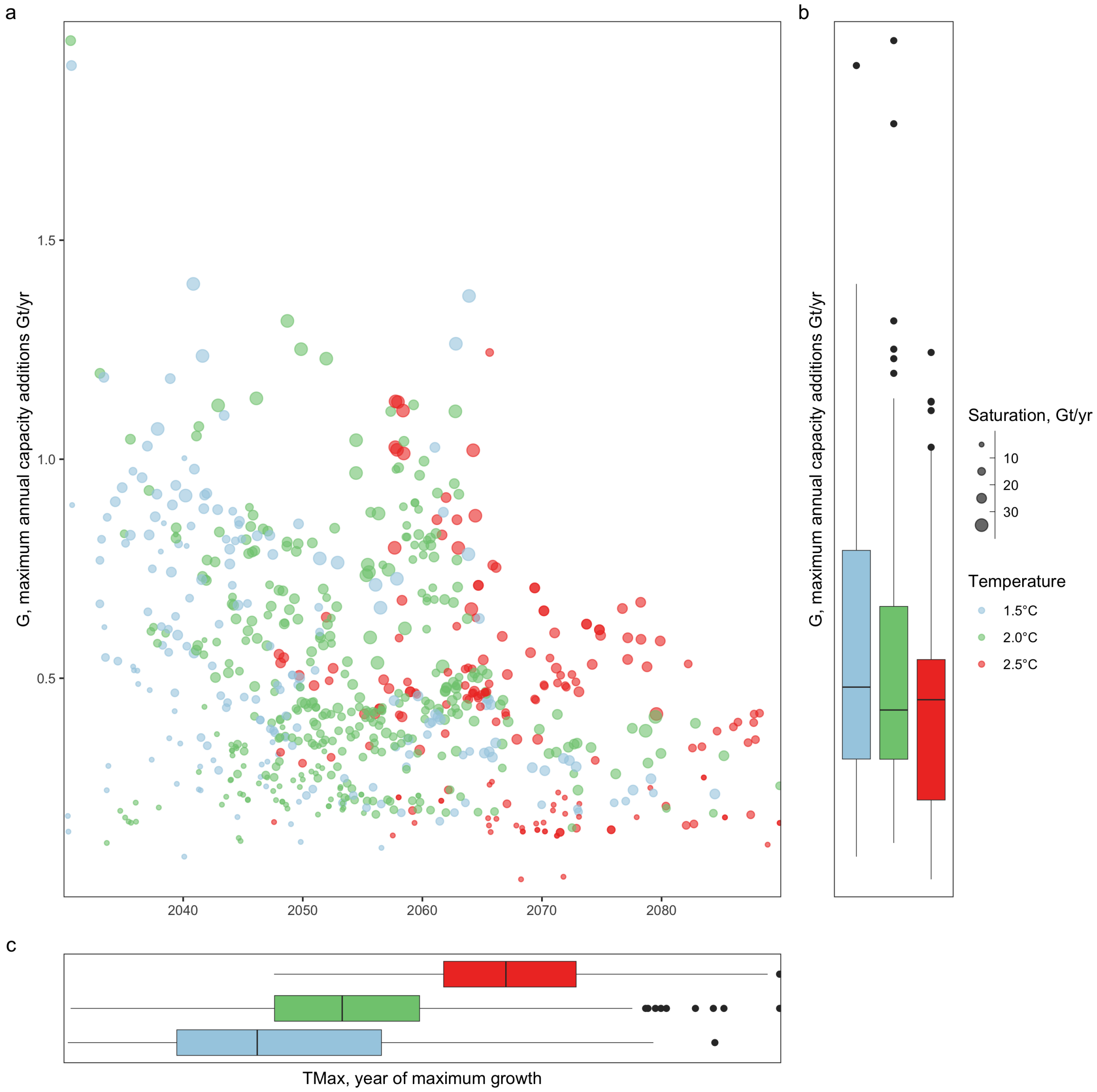


Fig. S5 | Illustration of our approach to estimate potential CCS market in the IPCC AR6 scenario ensemble (Methods). In this particular scenario, CCS technologies start the acceleration after significant emission reductions caused by other mitigation measures. CCS is then used to mitigate remaining CO_2 fossil- and process-based CO_2 emissions (blue) as well as to offset CO_2 emissions in hard-to-abate sectors via negative emission technologies, such as BECCS and DACCS (green) to bring the global economy to net-zero CO_2 emissions (in CCS-applicable sectors, black line) by 2090.

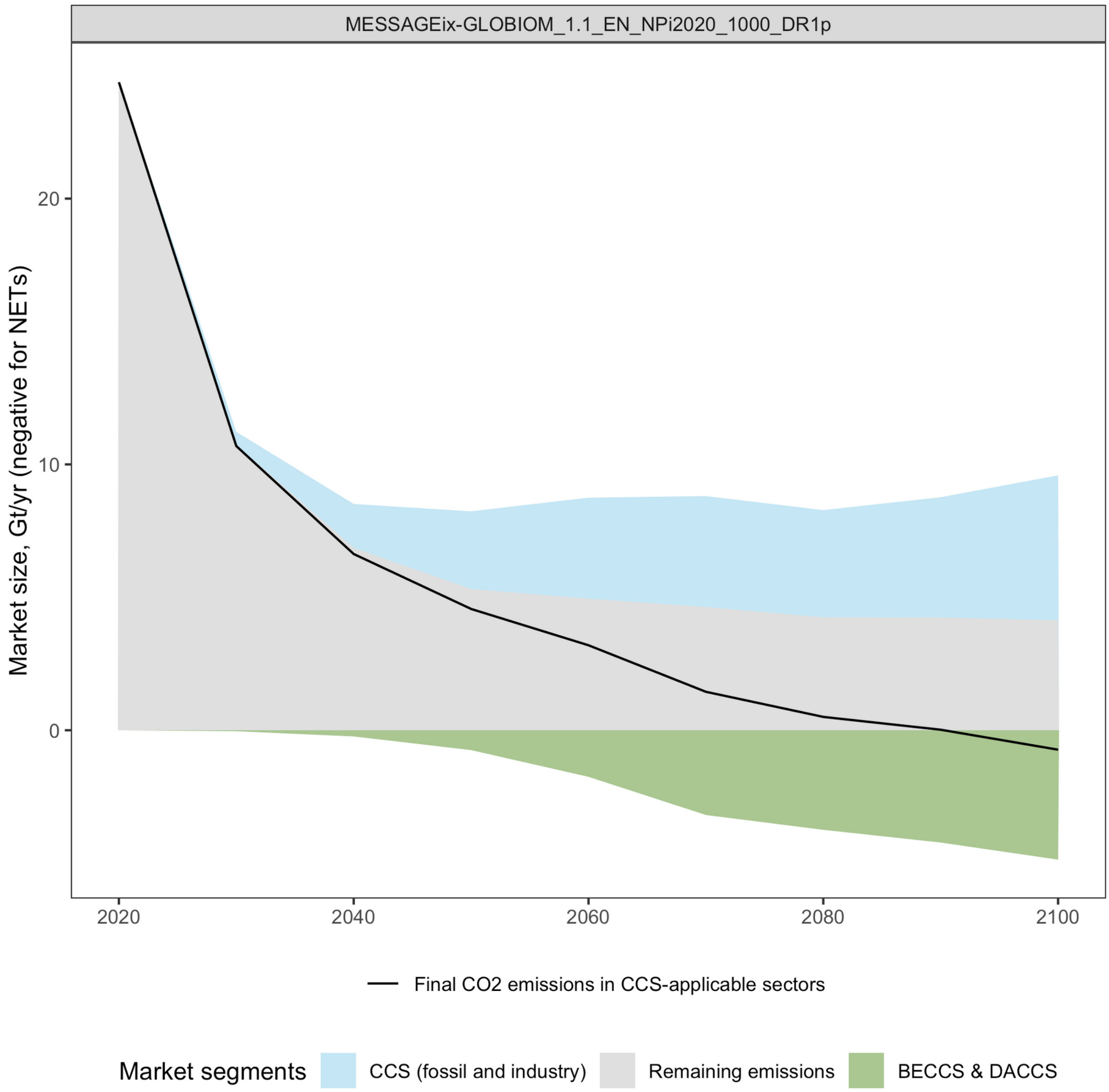
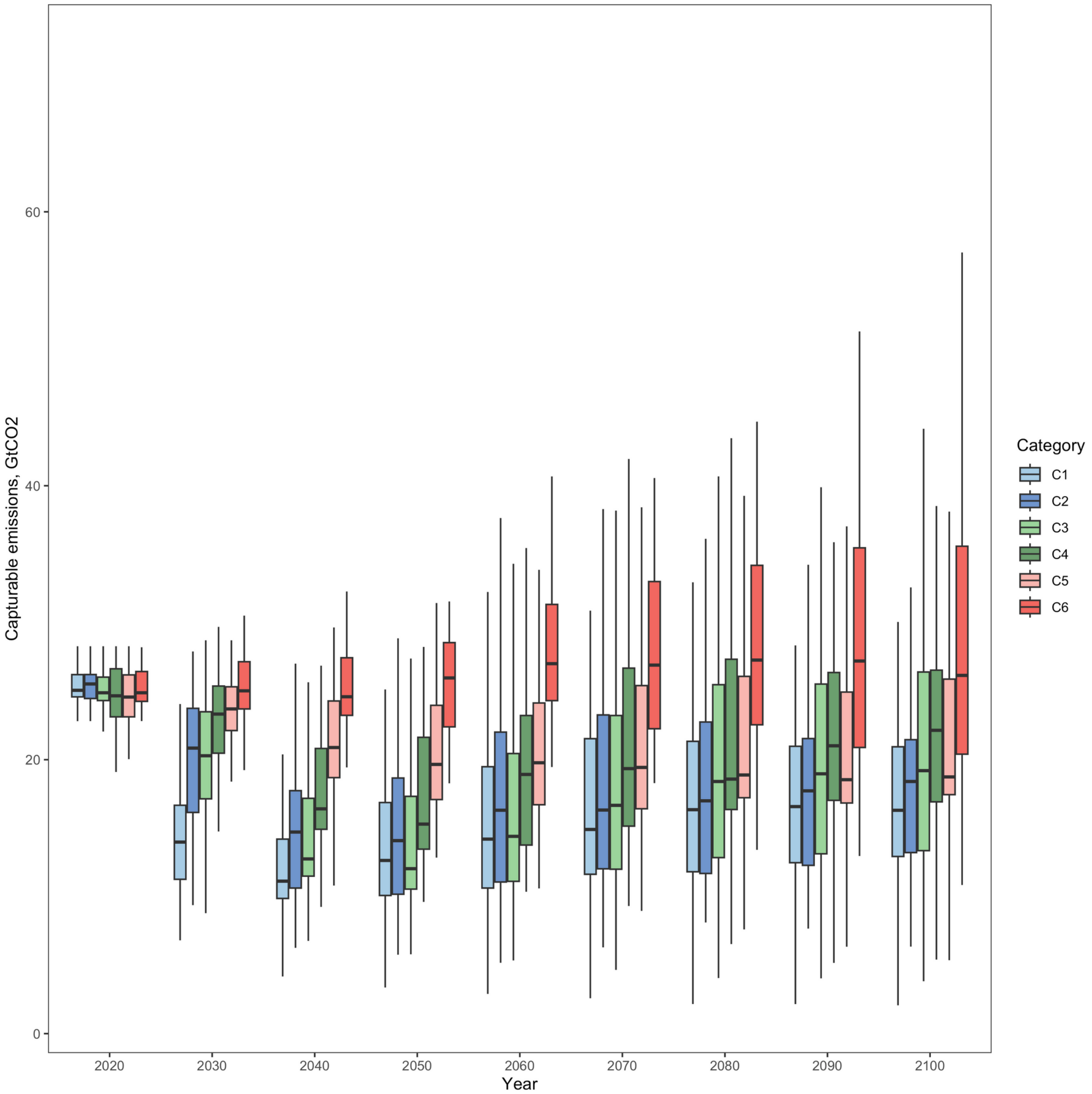


Fig. S6 | Capturable emissions in the IPCC AR6 scenario ensemble, by decade and IPCC scenario category. This figure displays the size of potential CCS market (i.e. CO_2 emissions that can potentially be captured, in Gt) over time. Categories vary by global mean surface air temperature change by 2100: C1 scenarios stay below 1.5°C with no or limited overshoot with a 50% probability; C2 - below 1.5°C with high overshoot; C3 - likely below 2°C; C4 - below 2°C; C5 - below 2.5°C; C6 - below 3.0°C [2]. The figure shows that the size of potential CCS market varies depending on the temperature outcome: in less stringent scenarios the potential market remains stable or even grows (C6), whereas more stringent scenarios show a rapid drop in CO_2 emissions until the mid-century. The box-plots show the interquartile range (IQR) of the CCS market size in the scenario sample: the median (second quartile) as the centre, the 25th and 75th percentiles (first and third quartiles) as the bounds of box, and the whiskers drawn within the 1.5 IQR value.



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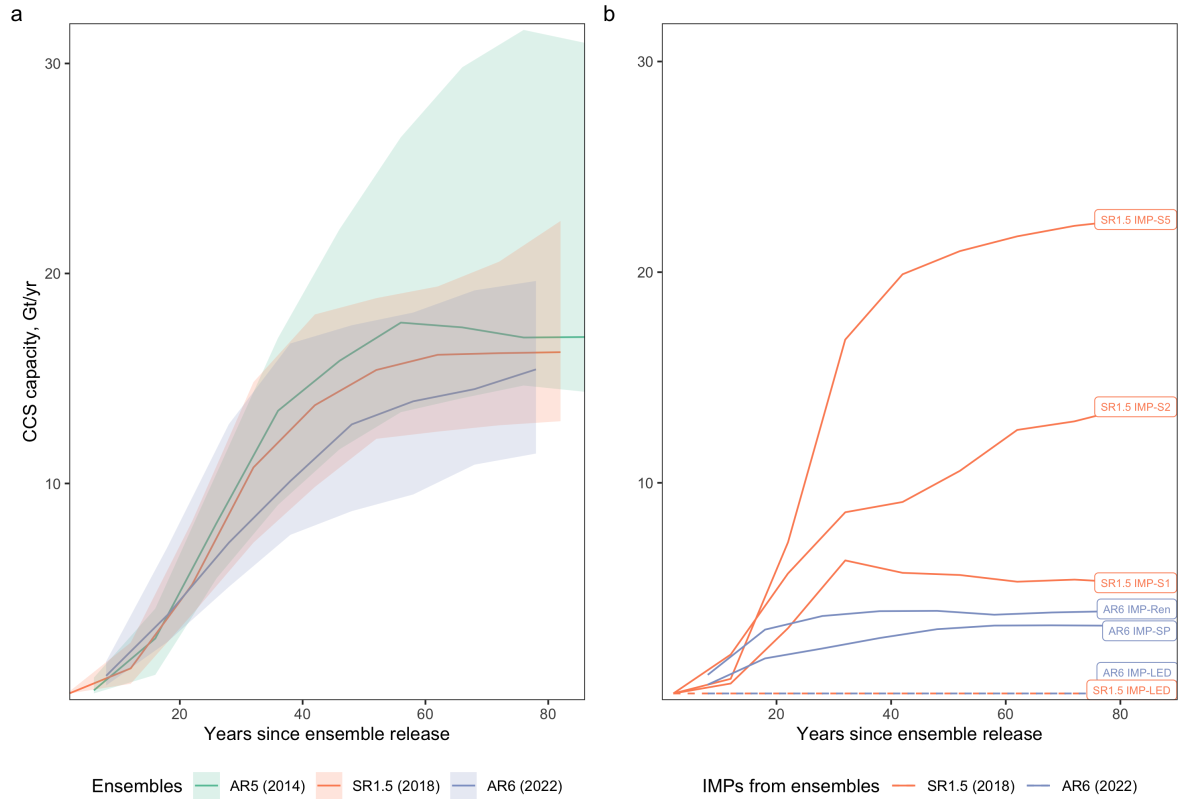


Fig. S8 | Gompertz and logistic curve fit of CCS deployment in Paris-compatible scenarios [1] consistent with our analytical approach to the feasibility of policy-driven technologies' deployment (i.e. "vetted", Methods).. Colored bars illustrate CCS applications, colored lines – growth curve fits (left y-axis). IMP-LED scenario is not displayed in this figure as it does not project any CCS capacity.

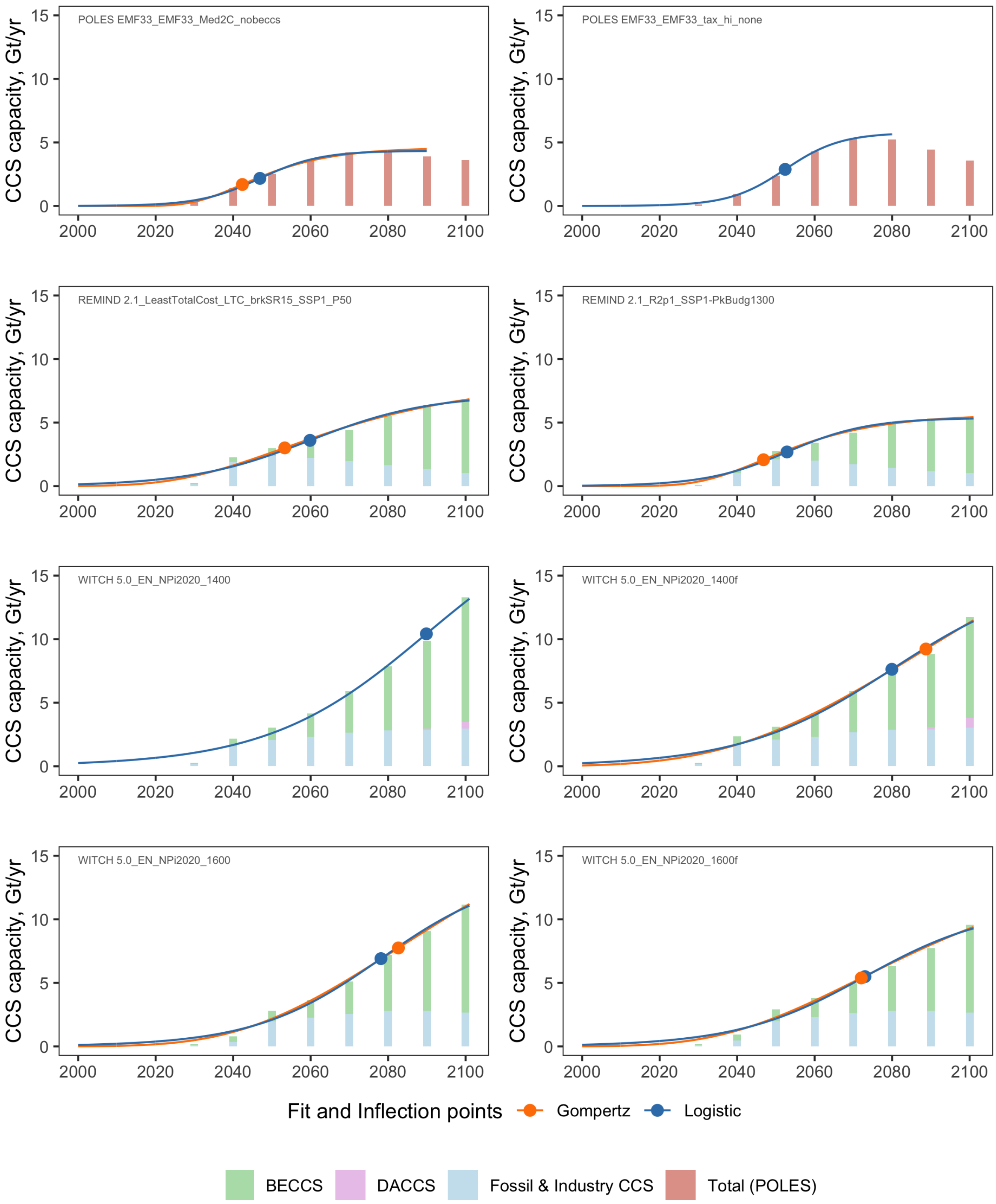


Fig. S9 | CCS market size over time in Paris-compatible scenarios [1] consistent with our analytical approach to the feasibility of policy-driven technologies' deployment (i.e. "vetted", Methods).

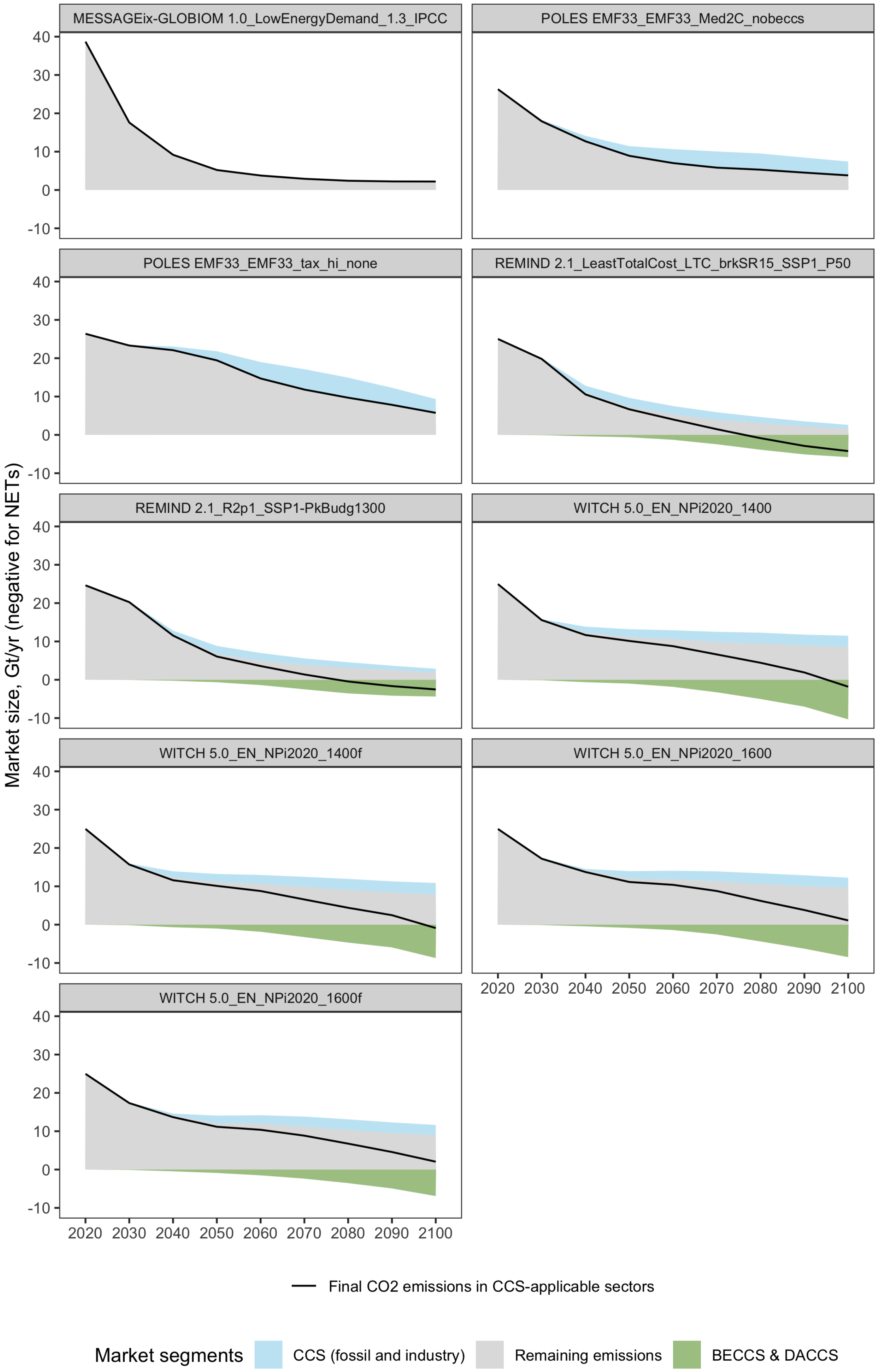
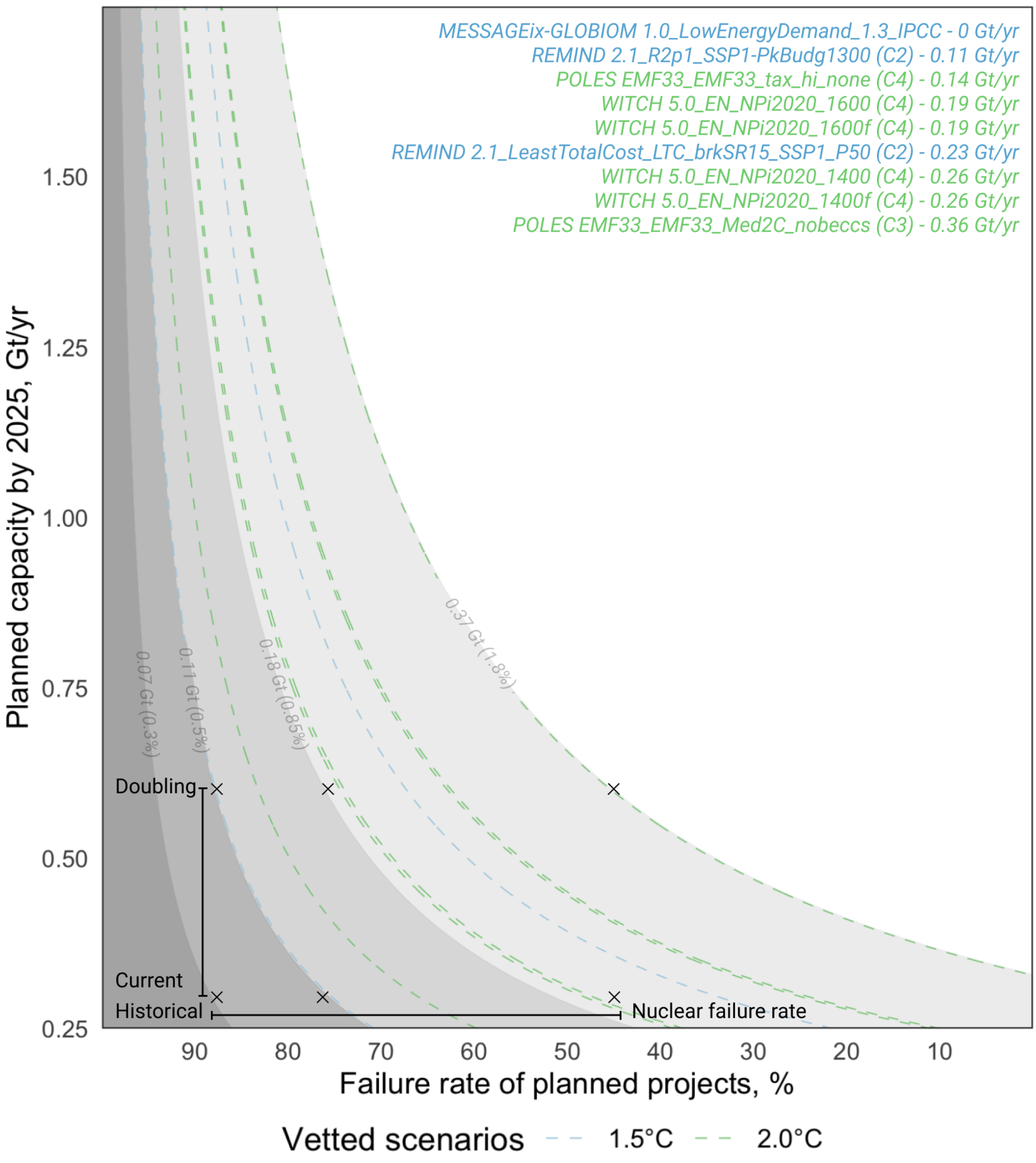


Fig. S10 | Formative phase deployment (until 2030) of Paris-compatible scenarios [1] consistent with our analytical approach to the feasibility of policy-driven technologies' deployment (i.e. "vetted", Methods). IMP-LED scenario is not displayed in this figure as it does not project any CCS capacity.



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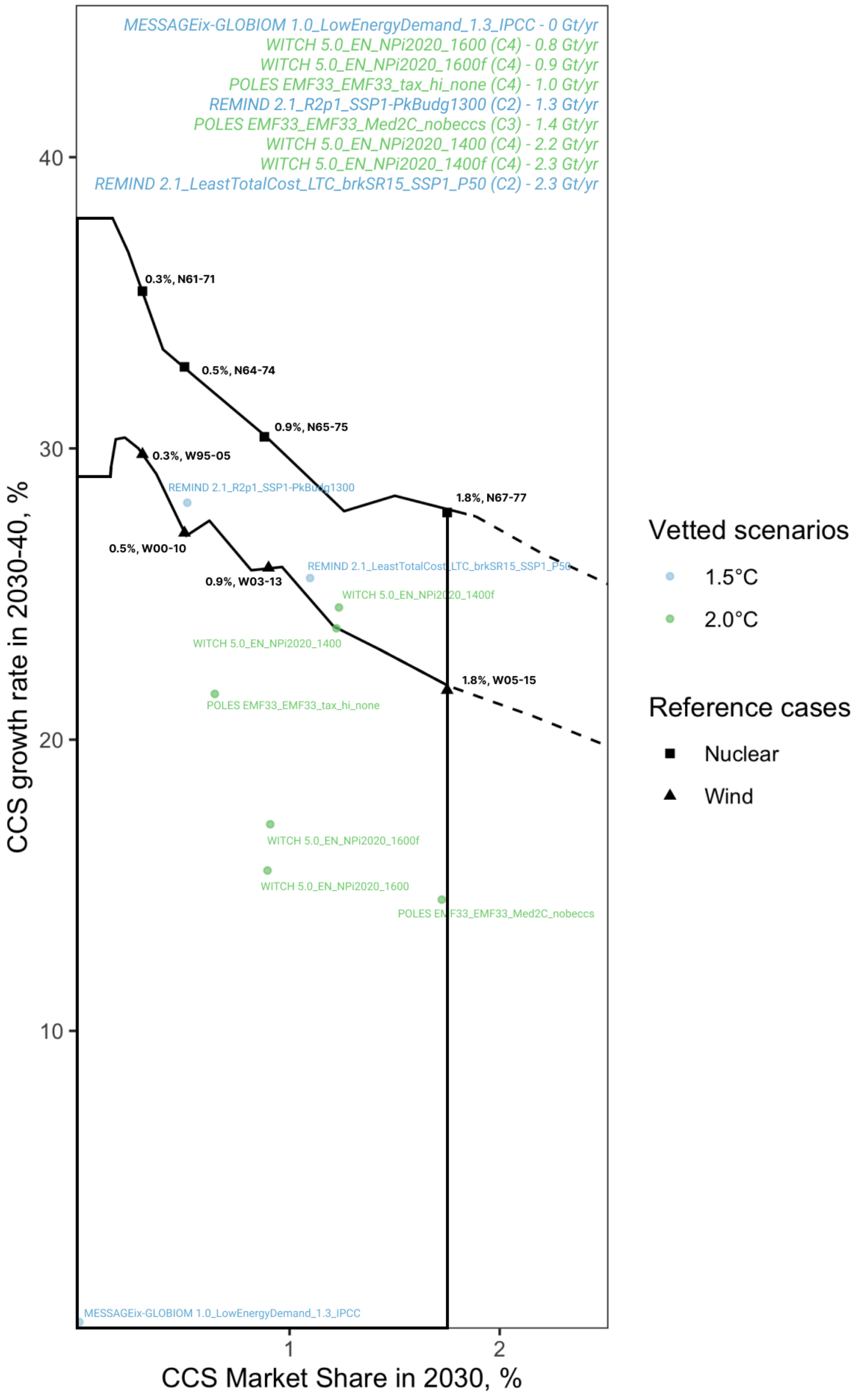

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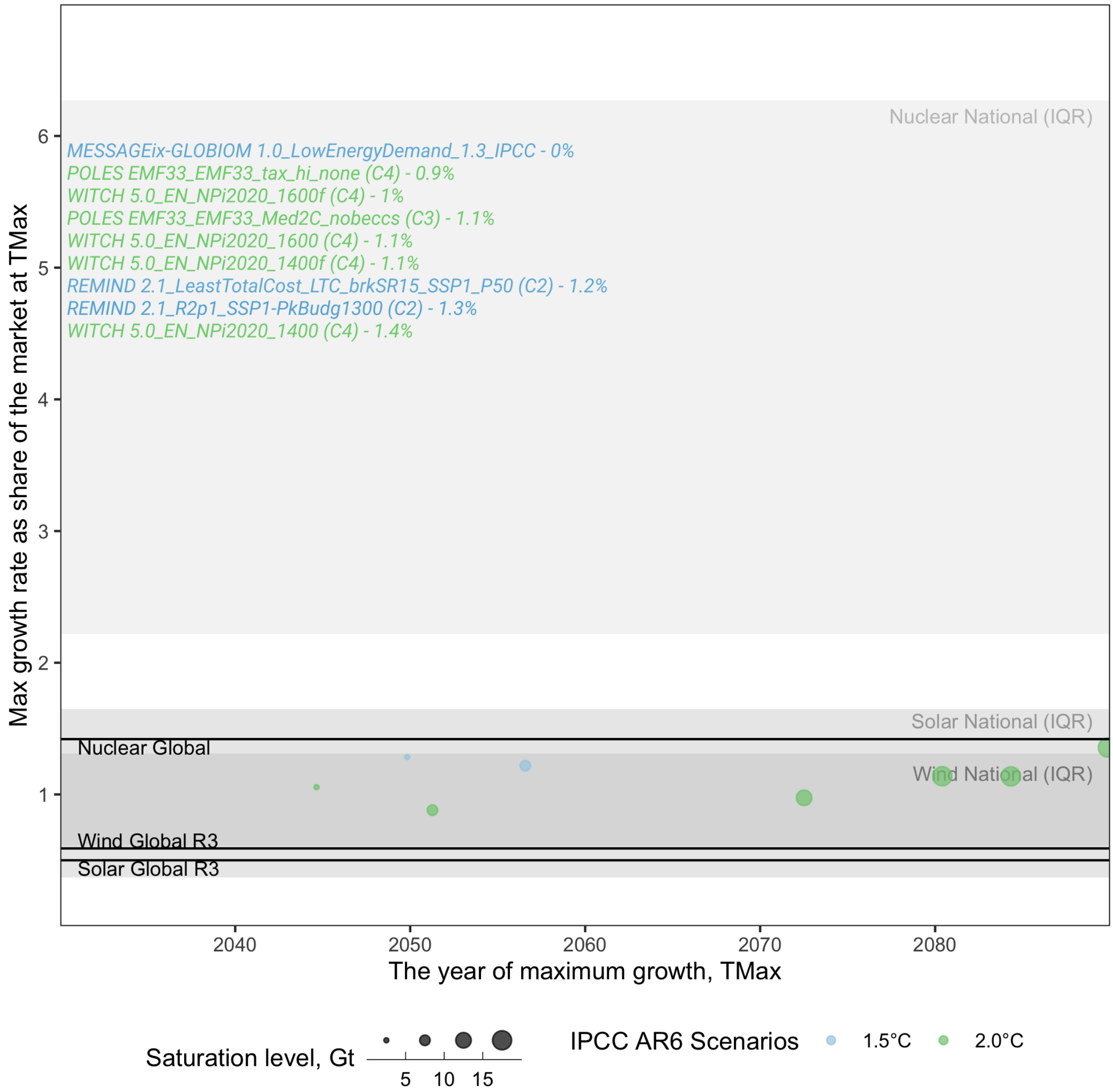

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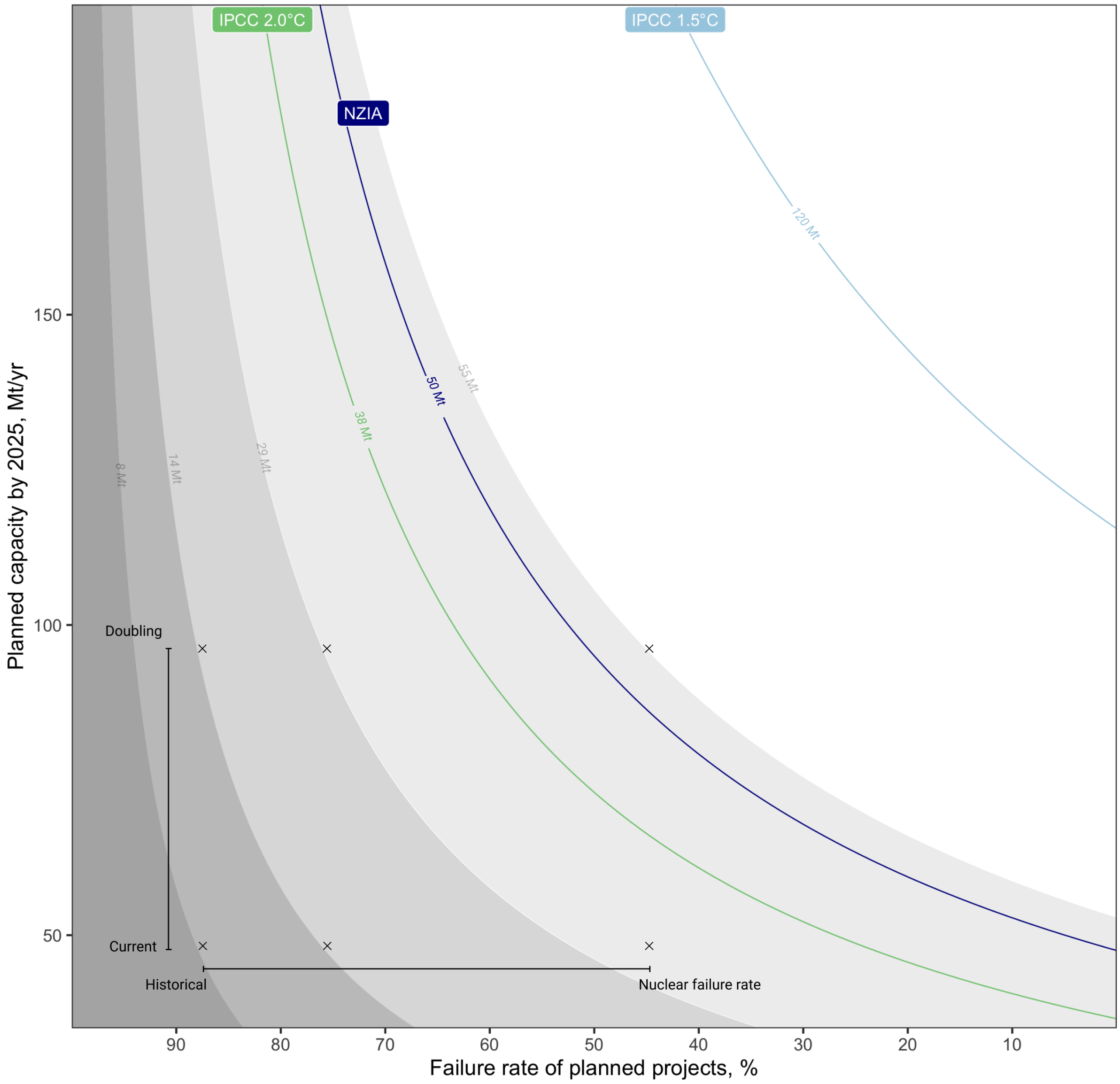
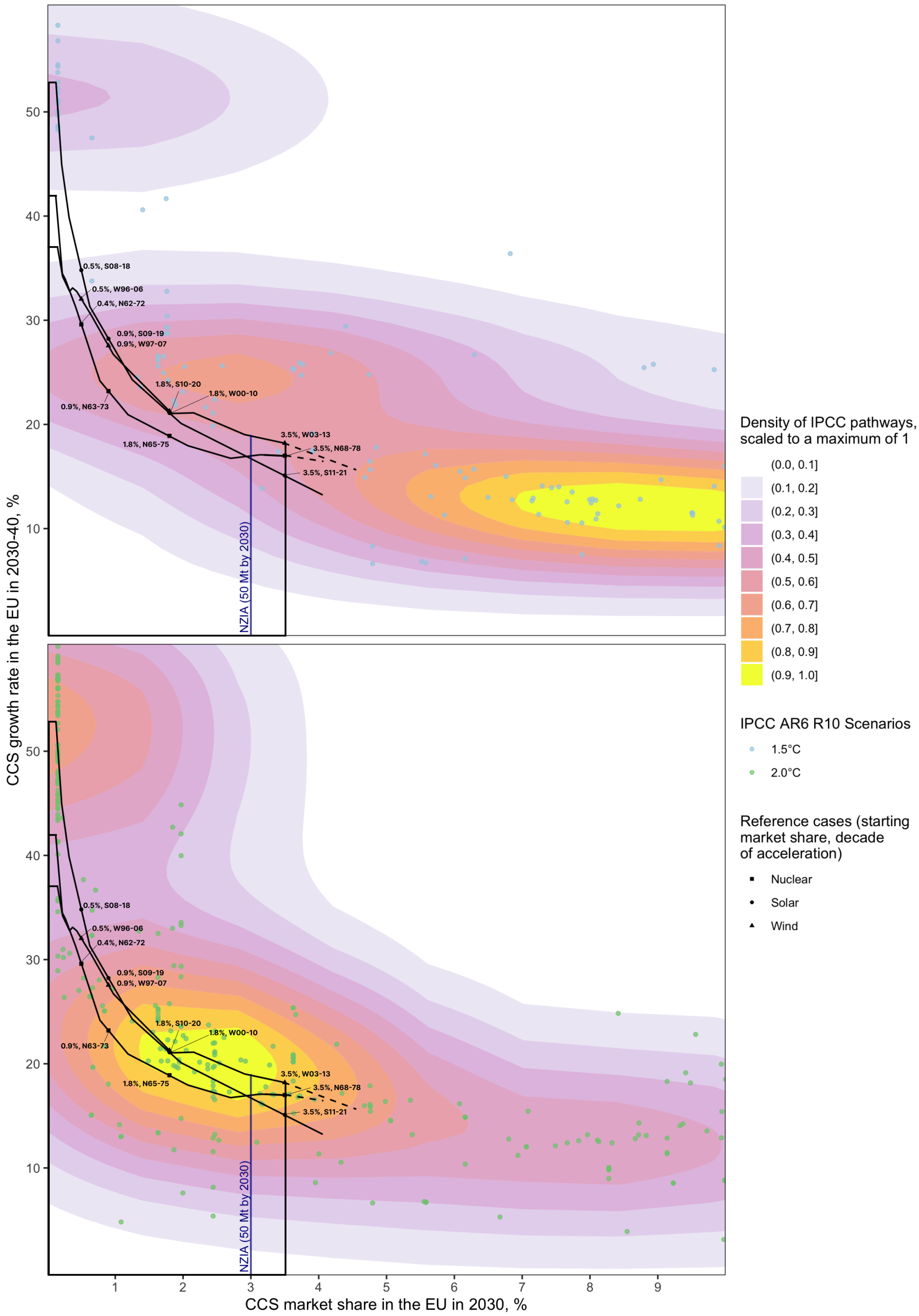


Fig. S14 | Feasibility space of CCS deployment at the acceleration phase in the EU in 2030-2040. The figure illustrates CCS growth rates at the acceleration phase in R10EUROPE region in the IPCC AR6 scenario ensemble consistent with 1.5°C (top) and 2°C (bottom) warming by the end of the century (2D-density map) [1, 2]. To understand the feasibility of Paris-compatible CCS acceleration in the EU, we construct a feasibility space based on the reference cases (black lines) of wind (1992-2014, [8]), solar (2005-2021, [9]) and nuclear (1959-1979, [10]) acceleration in EU28+UK as well as the market share gained by CCS by 2030 (i.e. at the formative phase). Nuclear power acceleration rate was calculated from a sample of countries that includes the former Yugoslavia. To analyse the feasible range of CCS deployment in the EU by 2040 provided that the NZIA target is adopted and met by 2030 (blue line), we compare it to scenarios and feasibility space. Note: IPCC R10EUROPE region includes more European countries than EU28+UK.



2 Supplementary Tables

Table S1 | Publicly available CSS project databases

Main Sources	Details	Type	URL	Activity
Carbon Capture and Sequestration Technology Program - MIT	Mostly commercial-scale projects	Online database	https://sequestration.mit.edu/	Inactive
National Energy technology Laboratory	Commercial-scale projects, limited information on capacity (mostly in MW), sector and storage type, and time	Offline database	https://netl.doe.gov/coal/carbon-storage/worldwide-ccs-database	Active
ZeroCO2.no	Mostly commercial-scale projects	Online/Offline database	http://www.zeroco2.no/projects/list-projects	Inactive
Global CCS Institute	Only operational and planned commercial-scale projects	Online database + Annual reports	https://co2re.co/	Active
Program on Energy and Sustainable Development at Stanford University	Announced and operational projects as of 2008	Publication	https://www.readcube.com/articles/10.2139%2Fssrn.1400118	Inactive
International Association of Oil and Gas producers	Recent projects in the US, Europe, and MEA	Report	https://32zn56499nov99m251h4e9t8-wpengine.netdna-ssl.com/bookstore/wp-content/uploads/sites/2/2021/03/Global-CCS-Projects-Map.pdf	Active
Scottish Carbon Capture and Storage database	Various projects, unclear about the frequency of updates	Online database	https://www.sccs.org.uk/expertise/global-ccs-map	Unclear
Zero Emission Platform (ZEP)	Only EU projects, unclear about the frequency of updates	Online database	https://zeroemissionsplatform.eu/about-ccs-ccu/css-ccu-projects/	Unclear
IEA CCUS Projects Database	Only operational and planned commercial-scale projects	Online/Offline database	https://www.iea.org/data-and-statistics/data-tools/ccus-projects-explorer	Active
Clean Air Task Force Interactive Map	Recent projects in the US, Europe, and MEA	Offline database	https://docs.google.com/spreadsheets/d/115hsADg3ymy3lKBy4PBQRXz_MBknptqlRtlfuv79XV8/edit#gid=1540463113	Active

Table S2 | Definitions of sectors in CCS Projects Database used in this study

Sector	Subsectors	IPCC Variable	Definition
Fossil Electricity	Coal Power, Natural Gas Power	Carbon Sequestration|CCS|Fossil|Energy|Supply|Electricity	total carbon dioxide emissions captured from fossil fuel use in electricity production (part of IPCC category 1A1a) and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers
Fossil Industry	Hydrogen (Coal), Hydrogen (Oil), Hydrogen (NG), CTL ("coal-to-liquids"), Ethylene	Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry + Carbon Sequestration|CCS|Fossil|Energy|Supply (excl. Electricity)	total carbon dioxide emissions captured from fossil fuel use outside of electricity production and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers
BECCS Electricity	Bioenergy, Waste	Carbon Sequestration|CCS|Biomass|Energy|Supply|Electricity	total carbon dioxide emissions captured from bioenergy use in electricity production (part of IPCC category 1A1a) and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers
BECCS Industry	Ethanol, Pulp and Paper	Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry + Carbon Sequestration|CCS|Fossil|Energy|Supply (excl. Electricity)	total carbon dioxide emissions captured from bioenergy use outside of electricity production and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers
Industry: Process	Cement, Iron and Steel	Carbon Sequestration|CCS|Industrial Processes	total carbon dioxide emissions captured from industrial processes (e.g., cement production, but not from fossil fuel burning) use and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers
NGP	Natural Gas Processing		fugitive emissions captured from the extraction and processing of the natural gas prior to its shipment and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean
DACCS	Direct Air Capture	Carbon Sequestration|Direct Air Capture	total carbon dioxide sequestered through direct air capture

Table S3 | Definitions of regions in CCS Projects Database used in this study

Region	Description	Countries
R10NORTH_AM	countries of North America; primarily the United States of America and Canada	Canada, Guam, United States of America
R10EUROPE	countries of Eastern and Western Europe (i.e., the EU28), can include Turkey	Austria, Belgium, Croatia, Denmark, France, Finland, Spain, Sweden, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Switzerland, Turkey, United Kingdom
R10PAC_OECD	countries of the Pacific OECD	Australia, Japan, New Caledonia, New Zealand, Samoa, Solomon Islands, Vanuatu
R10REF_ECON	countries from the Reforming Economies of Eastern Europe and the Former Soviet Union; primarily Russia	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
R10CHINA+	countries of centrally-planned Asia; primarily China	China (incl. Hong Kong), Cambodia, Korea (DPR), Laos (PDR), Mongolia, Viet Nam
R10INDIA+	countries of South Asia; primarily India	India, Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka,
R10REST_ASIA	other countries of Asia	(in not in India+/China+) Afghanistan, Bangladesh, Bhutan, Fiji, Maldives, Nepal, Pakistan, Sri Lanka, Cambodia, Korea (DPR), Laos (PDR), Mongolia, Viet Nam
R10AFRICA	countries of Sub-Saharan Africa	Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zaire, Zambia, Zimbabwe
R10MIDDLE_EAST	countries of the Middle East; Iran, Iraq, Israel, Saudi Arabia, Qatar, etc.	Iraq, Iran (Islamic Republic), Israel, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, United Arab Emirates
R10LATIN_AM	countries of Latin America and the Caribbean	Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela
R10ROWO	Rest of the World - to be used only if decent match with the 10 regions can otherwise not be achieved	

Table S4 | Median and IQR parameters of CCS capacity from Gompertz and logistic growth models. This table contains growth parameters of technologies which reached their maximum growth in their respective markets.

	Gompertz				Logistic			
	TMax	G, Gt/yr	G_2020	G_TMax	TMax	G, Gt/yr	G_2020	G_TMax
Target cases								
CCS Global 1.5°C	2043 (2038-2054)	0.5 (0.3-0.8)	1.9% (1.2-3.1%)	3.4% (2.6-4.6%)	2048 (2041-2060)	0.5 (0.3-0.8)	2.0% (1.3-3.2%)	3.5% (2.8-4.5%)
CCS Global 2.0°C	2051 (2045-2058)	0.4 (0.3-0.7)	1.7% (1.3-2.5%)	2.8% (2.2-3.4%)	2056 (2050-2062)	0.4 (0.3-0.7)	1.8% (1.3-2.6%)	2.9% (2.4-3.4%)
CCS Global 2.5°C	2066 (2060-2073)	0.4 (0.2-0.5)	1.7% (0.9-2.2%)	2% (1.4-2.5%)	2069 (2064-2075)	0.5 (0.2-0.6)	1.9% (0.9-2.4%)	2.2% (1.4-2.7%)
Reference cases								
Nuclear Global	1982		1.5%		1985		1.4%	
Nuclear OECD	1980		2.3%		1983		2.2%	
Nuclear Japan	1982		2.9%		1985		2.6%	
Nuclear Korea	1992		5.5%		1996		3.6%	
Nuclear Spain	1984		6.6%		1985		5.5%	
Nuclear France	1983		10.5%		1985		8.9%	
Wind Brazil	2015		1.6%		2016		1.7%	
Wind Sweden	2018		1.6%		2016		1.6%	
Wind Spain	2005		1.6%		2007		1.7%	

TMax – the year when maximum growth is achieved; **G** – maximum annual capacity additions of CCS; **G_2020** – maximum growth rate of CCS normalised to the maximum market size in 2020; **G_TMax** – maximum growth rate of CCS normalised to the maximum market size at TMax. Figures in brackets show the the interquartile range (IQR).
For reference cases, we only show instances of national maximum growth in electricity markets larger than 100TWh and $G >1.6\%$. Only countries and regions where the maximum growth rate has been achieved are shown.

Table S5 | Median and IQR of CCS capacity variables in IPCC AR5 [3], SR1.5 [5, 6, 11], AR6, and AR6 IMP [1, 2] scenarios for reaching 1.5°C degree warming by the end of the century

Ensemble/IMP	t°C	Capacity 20 years since publication	G (Gt/yr/yr)	L (Gt/yr)	TMax*	dT
			Average values between Gmp and Log			
IPCC Scenario ensembles						
AR5 (2014)	1.5°C	4.7 (2.6-6.5)	0.7 (0.5-0.9)	22 (17-33)	31 (23-37)	41 (29-53)
SR1.5 (2018)	1.5°C	4.6 (3.0-6.9)	0.6 (0.4-0.8)	17 (13-25)	25 (21-32)	33 (25-47)
AR6 (2022)	1.5°C	4.5 (3.1-8.4)	0.5 (0.3-0.8)	17 (13-23)	24 (18-37)	37 (27-59)
SR1.5 (2018)	2.0°C	2.1 (0.3-4.0)	0.4 (0.2-0.7)	17 (8-25)	32 (23-43)	38 (28-55)
AR6 (2022)	2.0°C	2.9 (2.0-4.8)	0.4 (0.3-0.6)	17 (12-23)	32 (25-38)	40 (33-54)
AR6 (2022)	2.5°C	0.6 (0.3-2.1)	0.4 (0.2-0.5)	16 (11-24)	45 (38-52)	45 (35-62)
Illustrative Mitigation Pathways						
AR6-SP	1.5°C	1.8	0.1	3	19	39
AR6-Ren	1.5°C	3.2	0.2	3	12	17
AR6-LED	1.5°C	0	0	0	0	0
SR1.5-S1	1.5°C	2.6	0.4	8	23	25
SR1.5-S2	1.5°C	4.9	0.3	13	25	51
SR1.5-S5	1.5°C	5.9	1	22	25	23
SR1.5-LED	1.5°C	0	0	0	0	0
AR6-GS	2.0°C	2.1	0.2	12	41	60
AR6-Neg	2.0°C	3.7	0.3	11	22	36

**Number of years until TMax from the year of ensemble publication*

Table S6 | Summary of Paris-compatible scenarios [1] consistent with our analytical approach to the feasibility of policy-driven technologies' deployment (i.e. "vetted")

			Formative		*Acceleration*	*Stable growth*			
Model_Scenario	IPCC Category	Vetting group	CCS Capacity 2030, Mt/yr	CCS Market Share 2030, %	Growth rate 2030-40, %	Maximum annual growth G, Mt/yr/yr	G_TMax, %	TMax, yr	Saturation L, Gt/yr
REMIND 2.1_LeastTotalCost_LTC_brkSR15_SSP1_P50	C2 (1.5°C)	1	231	1,1%	26%	113	1,2%	2057	7,5
REMIND 2.1_R2p1_SSP1-PkBudg1300	C2 (1.5°C)	1	108	0,5%	28%	126	1,3%	2050	5
POLES EMF33_EMF33_Med2C_nobeccs	C3 (2.0°C)	1	363	1,7%	15%	135	1,1%	2045	4
POLES EMF33_EMF33_tax_hi_none	C4 (2.0°C)	1	136	0,6%	22%	189	0,9%	2051	5,5
WITCH 5.0_EN_NPi2020_1400	C4 (2.0°C)	2	258	1,2%	24%	254	1,4%	2090	20
WITCH 5.0_EN_NPi2020_1400f	C4 (2.0°C)	2	260	1,2%	25%	192	1,1%	2084	20
WITCH 5.0_EN_NPi2020_1600	C4 (2.0°C)	2	189	0,9%	16%	203	1,1%	2080	17
WITCH 5.0_EN_NPi2020_1600f	C4 (2.0°C)	2	191	0,9%	17%	159	1,0%	2073	12
MESSAGEix-GLOBIOM 1.0_LowEnergyDemand_1.3_IPCC	C1 (1.5°C)	3	0	0,0%	0%	0	0,0%	NA	0

Table S7 | Feasible ranges of CCS capacity in the EU in 2030 and 2040, estimated from reference cases for CCS deployment at the formative and acceleration phases, and compared to CCS capacity in the IPCC AR6 scenarios [1]. Columns illustrate different outcomes at the formative phase, whereas rows illustrate the compound annual growth rate (CAGR) for each 10-year reference period and the resulting CCS capacity by 2040. Reference case growth rates in the acceleration phase in the EU reported in this table are also illustrated in Fig. S14.

Formative phase (pre-2030) assumptions	88% failure & current plans	76% failure & current plans	45% failure & current plans	45% failure & doubling
CCS Capacity (2030), Mt/yr	8	14	29	55
Acceleration in 2030-2040				
Same as wind (EU)				
Growth rate	32.0%	27.6%	21.3%	18.2%
Capacity (2040), Mt/yr	128	160	200	293
Same as wind (China)				
Growth rate	47.4%	40.7%	31.3%	24.8%
Capacity (2040), Mt/yr	387	426	442	504
Same as nuclear (EU)				
Growth rate	29.6%	23.2%	18.9%	17%
Capacity (2040), Mt/yr	107	113	164	264
Same as nuclear (US)				
Growth rate	45.7%	41.8%	32.8%	24.9%
Capacity (2040), Mt/yr	345	460	495	508
Same as solar (EU)				
Growth rate	34.8%	28.2%	21.1%	15.1%
Capacity (2040), Mt/yr	159	168	197	224
IPCC 1.5°C Capacity, Mt/yr	**2030**: 118 (38-185); **2040**: 437 (288-654)			
IPCC 2°C Capacity, Mt/yr	**2030**: 39 (0-118); **2040**: 251 (174-400)			

3 Supplementary Notes

Supplementary Note 1: Inter-ensemble comparison of CCS deployment projections in the IPCC AR5, SR1.5, and AR6

In order to examine whether more recent generations of IPCC scenario ensembles have changed their reliance on CCS for achieving temperature targets, we compare CCS deployment in AR5, SR1.5 and AR6 scenario ensembles, focusing on pathways compatible with the 1.5°C target. In this exercise, it is important to highlight that the most stringent scenario categories in the AR5, SR1.5, and AR6 scenarios are, in fact, not equally stringent: as we explain in Methods, AR6 sample achieves lower temperatures with higher probability by 2100 than AR5. To compare near-term CCS deployment (20 years) in these three scenario ensembles, we aligned them by the time from the year the scenario ensemble was published and used linear interpolation of CCS deployment projections in each scenario to calculate CCS capacity in 2034 for AR5 (2014), 2038 for SR1.5 (2018), and 2042 for AR6 (2022) (Fig. S7, Table S5). The three groups of scenarios envision remarkably similar CCS growth trajectories until stable growth phase – 4.7 Gt/yr (IQR 2.6-6.5) in AR5 and 4.5 Gt/yr (IQR 3.1-8.4) in AR6 are achieved within 20 years since ensemble release (i.e. 2034 for AR5 and 2042 for AR6). However, the maximum growth rate and the maximum eventual capacity of CCS have declined by 29% and 23% respectively between the median of AR5 and the median of AR6 scenarios. The reduction between SR1.5 and AR6 is generally lower, but is particularly noticeable between the two sets of Illustrative Mitigation Pathways (IMPs) – a number of scenarios "representing critical mitigation strategies discussed in the assessment" [2]. The first such set of IMPs in SR1.5 [5, 6] had a much bigger role for CCS technologies in all but one mitigation strategy than its descendant – the AR6 set [1, 2] (Fig. S7). The only exception is the IMP-LED scenario which does not project any CCS capacity – this scenario was first introduced in SR1.5 and updated in AR6. Therefore, the IPCC scenarios rely on CCS to a similar extent in the short-term and less in a long-term, although depicting similar deployment trajectories (Table S5) – with an overall duration of CCS technology deployment cycle of some 30-50 years.

Supplementary Note 2: Summary of vetted scenarios

Using the three feasibility spaces for CCS deployment at the formative, acceleration and stable growth phases, we identify IPCC AR6 scenarios with feasible CCS deployment trajectories throughout the century (Methods). Out of 218 1.5°C- and 423 2°C-compatible scenarios in the most recent scenario ensemble, we find only three 1.5°C and six 2°C scenarios that are consistent with historical evidence from selected reference cases and current market interest in CCS (Table S6). Interestingly, these scenarios display two contrasting trajectories for feasible global CCS deployment to meet the Paris target (Fig. S8), and another one which does not deploy any CCS.

The first group of scenarios (which includes two 1.5°C and two 2°C scenarios) displays a deployment trajectory that requires a 108-363 Mt/yr capacity to be implemented at the formative phase by 2030 (0.5-1.7% market share). The lower bound of this range corresponds to a subsector-adjusted failure rate (76%) and no additional plans until 2025, whereas the upper bound would require a 45% failure rate and doubling of current plans by 2025. In the following decade, two 1.5°C scenarios envisage acceleration of CCS deployment inline with historical observations for global wind power deployment, whereas two 2°C scenarios show acceleration of much lower ambition than observed historically for wind or nuclear power. Later on, this group of scenarios is characterised by 0.11-0.19 Gt/yr maximum annual capacity additions (0.9-1.3% when normalised to market size at $TMax$) achieved by the mid-century and saturation by around 2070 at 4-7.5 $GtCO_2$/yr. A relatively short deployment duration of this group of scenarios is reminiscent of the global diffusion of nuclear power. These maximum growth metrics are significantly lower than the IQR range for all scenarios in their respective temperature groups S4, both in absolute values and when normalised to the market size. In this group, reaching 1.5°C (two REMIND scenarios) requires both BECCS expanding and fossil CCS saturation by 2040. In contrast, a similar CCS deployment trajectory with no BECCS (POLES "No BECCS" scenario) only leads to 2°C.

The second group of scenarios (which includes four 2°C scenarios) displays a deployment trajectory that requires a 190-260 Mt/yr capacity to be implemented at the formative phase by 2030 (0.9-1.2% market share), however higher maximum growth rates than in the first group. These maximum growth rates are still modest (0.16-0.25 Gt/yr) compared to the IQR for this temperature group (0.3-0.6 Gt/yr). Long-term CCS capacity consists largely from BECCS additions as fossil fuel-based CCS saturates at about 3 Gt/yr. BECCS plays an important role in offsetting CO_2 emissions which, in these scenarios, do not decline as rapidly as in scenarios in the first group (Fig. S9. Moreover, two scenarios in these group project DACCS uptake to start in 2090 and reach at least 0.5 Gt/yr by 2100. This results in the late timing of maximum growth achievement and high saturation levels. It is important to highlight that all four scenarios which follow this trajectory are produced by the same Integrated Assessment Model, WITCH 5.0.

Finally, the last group – depicting no CCS deployment (Fig. S9) – is represented by one scenario (IMP-LED) which foresees rapid energy demand changes to meet the 1.5°C target without overshoot. The positions of these scenarios relative to the three feasibility spaces at the formative, acceleration, and growth phases are illustrated in Fig. S10, Fig. S11, and Fig. S12.

Supplementary Note 3: Application of the proposed method to analyse the feasibility of policy-driven technologies' deployment at the regional scale (EU Net Zero Industry Act CCS Target)

Policy-driven technologies are often associated with technology targets and market plans. We show how such plans can be used in conjunction with empirically-derived failure rates to capture erratic deployment patterns of emerging technologies in the formative phase. In this Supplementary Note, we show how this approach can assist in understanding the feasibility of policy targets in the formative and acceleration phases. This Supplementary Note also serves as an example of how this approach can be used at the regional scale.

In the European Union, the aspiration for CCS deployment is driven primarily by the EU Hydrogen Strategy (EC 2020) and the Innovation Fund, which have already provided support for CCS projects across a number of subsectors, with a particular emphasis on blue hydrogen (40% of planned 48 Mt capacity). The recent (March 2023) call by the European Commission for a 50 Mt annual CCS capacity by 2030 was proposed in the Net Zero Industry Act (NZIA) [7]. Clearly, the capacity of planned projects will need to increase in order to allow some space for potential failures and meet this target. With the EU CCUS Strategy due this year, it is plausible that planned project capacity will continue to grow which would make the second wave of interest in CCS significantly bigger than the previous one (which was already outpaced in the EU in 2021). With the 2030 target proposed, the recently published initiative of the European Commission aims to assess the role of CCS technologies in EU decarbonisation efforts further – in 2040. As our approach is well-fit for this question, we address it by constructing feasibility spaces of CCS deployment at the formative (until 2030) and acceleration phases (until 2040) specifically for the European Union. This allows us to, first, analyse the recently proposed EU NZIA target (50 Mt/yr capacity by 2030) and, second, understand what could be realistically achieved in the following decade provided that the target is adopted and met. For the formative phase (2020-2030), as in our global analysis, we consider the currently planned capacity (48 Mt) and its doubling by 2025, and the same reference cases for failure rates (historical 88%, subsector-adjusted 76%, and nuclear 45%).

In this decade, we see that the achievement of the proposed 50 Mt target would lead to CCS capacity higher than the 2°C median by 2030. Currently planned 2030 capacity stands at 48 Mt, therefore reaching the NZIA target will require improvements in failure rates beyond the historical (88%) and subsector-adjusted (76%), even if planned capacity doubles by 2025 (Fig. S13).

For the feasibility space at the acceleration phase of CCS deployment in the EU, we use reference cases of wind (1992-2014, [8]), solar (2005-2021, [9]) and nuclear (1959-1979, [10]) power acceleration in the EU starting from the same level of market penetration that can be achieved at the formative phase (0.5-3.5%), including the outcome of potentially meeting the NZIA target (50 Mt/yr, blue vertical line). For CCS acceleration in scenarios, we use IPCC AR6 scenarios for R10 regions that divide the globe into ten regions. Note: NZIA target only covers EU states, whereas IPCC R10EUROPE region includes the UK and some other non-EU countries.

We find only a few 1.5°C scenarios that are inline with the proposed 50 Mt/yr target by 2030. However, meeting the NZIA target would be in line with reaching a range of 2°C scenarios. What does it mean for the 2040 target? Here we use EU-based reference cases as they are the longest periods of rapid acceleration comparable to what is needed for CCS. Staying on the 2°C trajectory will require the growth rate at the acceleration phase of around 17-18% in 2030-2040 (highest density zone in the 2D-density plot), which would be comparable to the historical acceleration of wind and nuclear power in the EU and would lead to the operational CCS capacity of ca. 280 Mt/ye by 2040 (Fig. S14, Table S7).

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