One Earth, Volume *4*

Supplemental information

Historical precedents and feasibility of rapid coal and gas decline required for the 1.5°C target

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Supplemental figures

Figure S1. The development of unabated coal, natural gas, and oil in 1.5°C compatible scenarios.

The figure shows the development of total (with and without CCS) and unabated (without CCS) generation from fossil fuels in 1.5°C compatible scenarios at the global level; each line corresponds to a single scenario. Thick dashed lines correspond to the IEA's NZE2050 pathway[1].

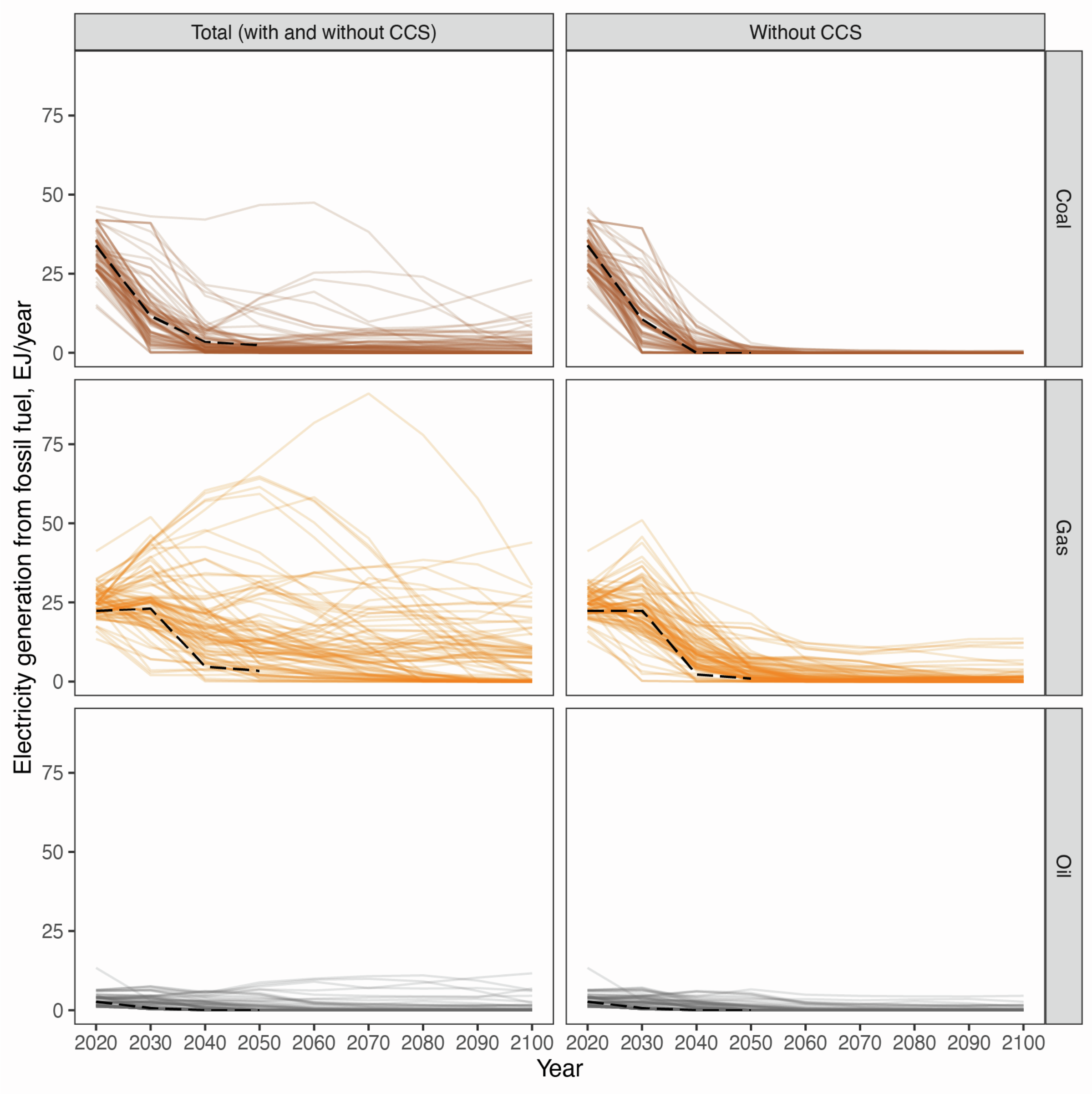


Figure S2. National and regional historical decline episodes.

The figure shows the relationship between the electricity system size (total electricity supply) and decline rate for historical fossil fuel decline episodes. Regional episodes are marked with orange and national episodes – with grey. The figure shows that the maximum decline rate for regional episodes is consistent with the maximum rate for national ones, continuing the same trend into the area of larger system sizes.

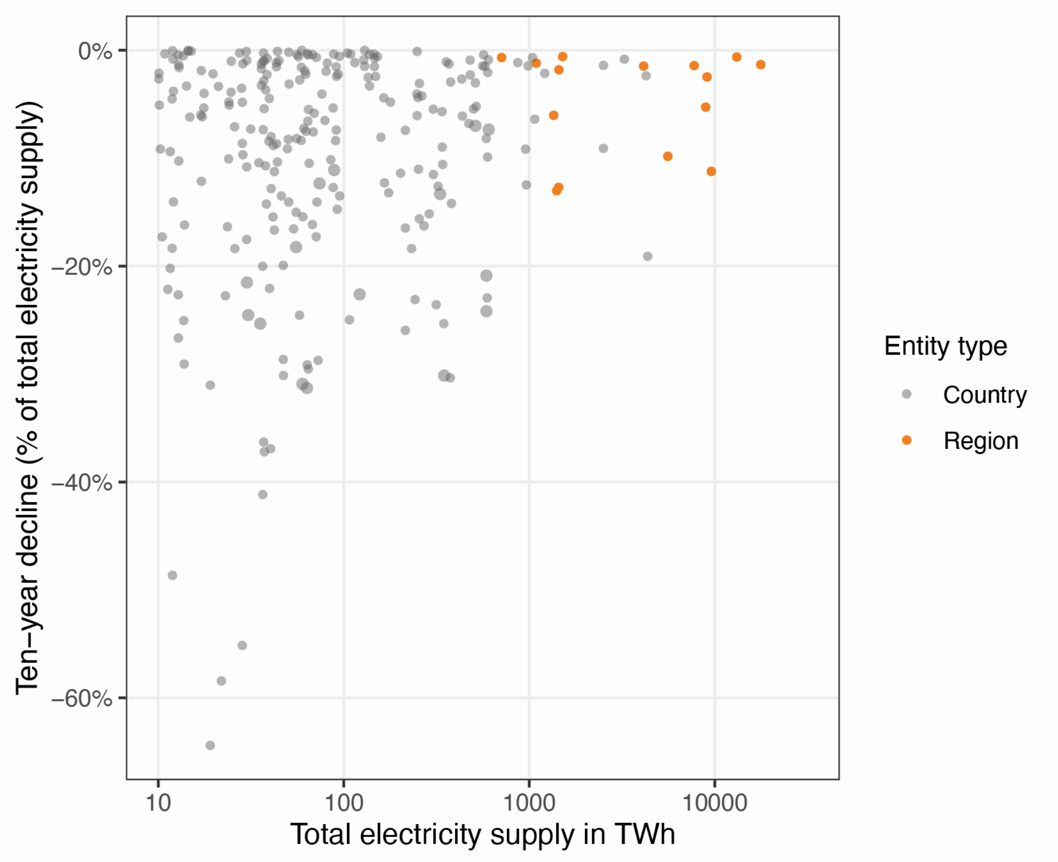


Figure S3. Historical decline episodes without and with regional episodes, compared to required coal and gas decline rates in 1.5°C-compatible scenarios.

Historical decline episodes are depicted with dots; for episodes with system size > 100 TWh/year and decline rate faster than 5%, primary substitution is marked with color. Coal phase-out pledges are depicted with triangles; medians and 80% ranges (so that 10% of individual scenario datapoints remain below and 10% – above the bar) for coal and gas decline rates in 1.5°C-compatible scenarios – with dots and bars. The line depicts the feasibility frontier of decline – the relationship between the highest observed decline rates and the size of the energy system – generated as a spline approximation of selected boundary datapoints produced with the ggplot package in Rstudio. The left pane shows only national episodes and a feasibility frontier based on these episodes. The datapoints in the right pane are equivalent to those in Figure 2A in the main text. The dashed line in the left pane is equivalent to the line in the right pane and shown for the ease of comparison.

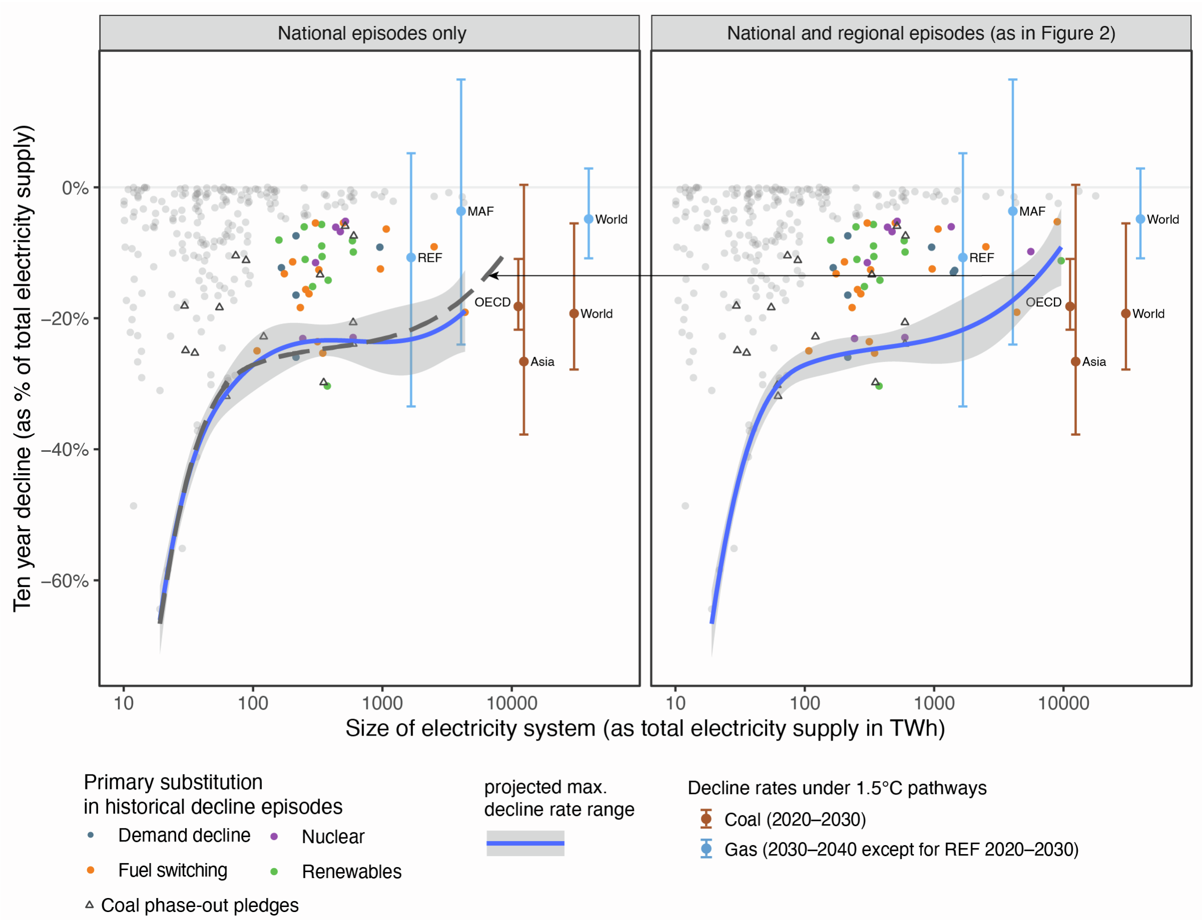


Figure S4. Historical decline episodes with and without adjustment for rebound, compared to required coal and gas decline rates in 1.5°C-compatible scenarios.

The left pane shows rebound-adjusted decline episodes (Experimental Procedures, Figure S15). The datapoints in the right pane, without adjustment for rebound, are equivalent to those in Figure 2A in the main text. Historical decline episodes are depicted with dots; for episodes with system size > 100 TWh/year and decline rate faster than 5%, primary substitution is marked with color. Coal phase-out pledges are depicted with triangles; medians and 80% ranges (so that 10% of individual scenario datapoints remain below and 10% – above the bar) for coal and gas decline rates in 1.5°C-compatible scenarios – with dots and bars. The line depicts the feasibility frontier of decline – the relationship between the highest observed decline rates and the size of the energy system – generated as a spline approximation of selected boundary datapoints produced with the ggplot package in Rstudio. The dashed line in the left pane is equivalent to the line in the right pane and shown for the ease of comparison.

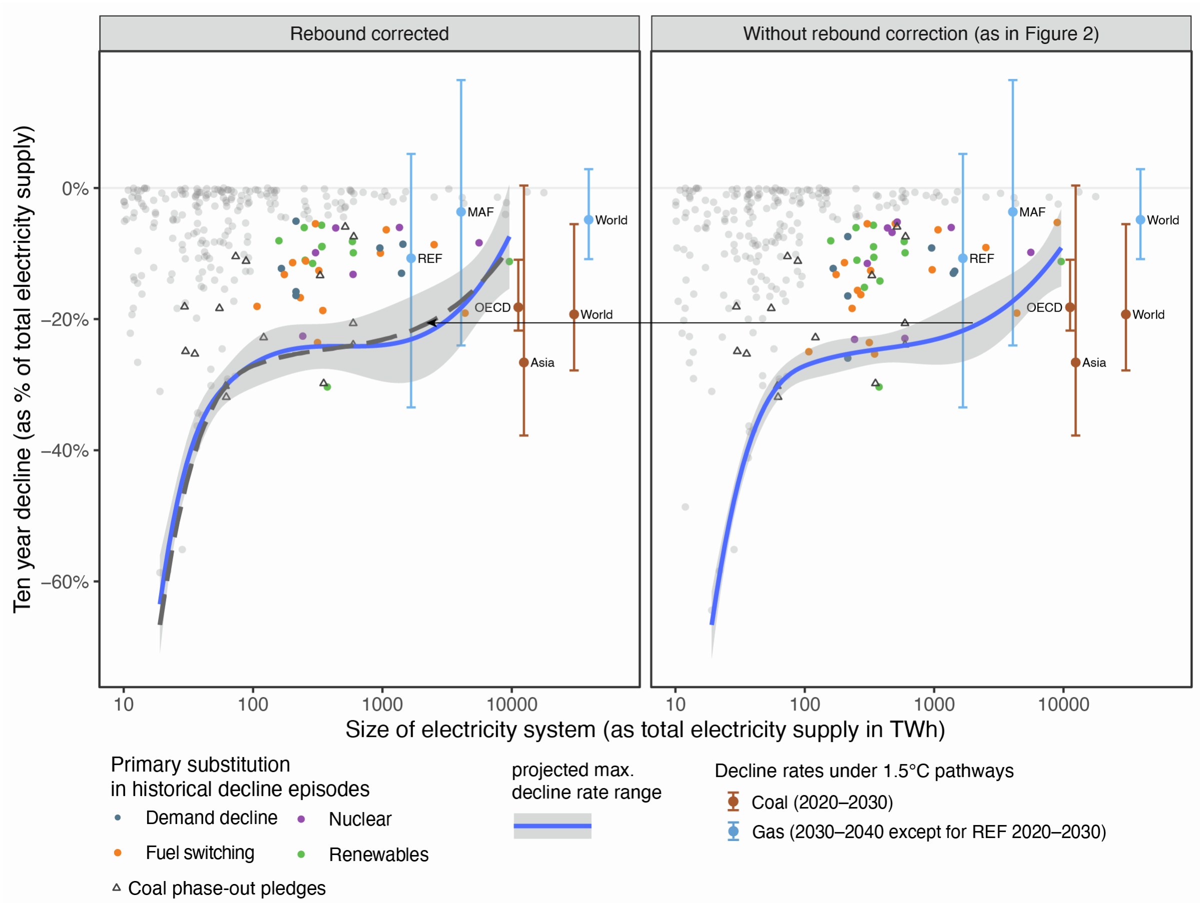


Figure S5. Historical decline episodes compared to required coal and gas decline rates in 1.5°C-compatible scenarios.

Panel (A) is equivalent to Figure 2A. Historical decline episodes are depicted with dots; for episodes with system size > 100 TWh/year and decline rate faster than 5%, primary substitution is marked with color. National coal phase-out pledges are depicted with triangles. The line depicts the feasibility frontier of decline – the relationship between the highest observed decline rates and the size of the energy system – generated as a spline approximation of selected boundary datapoints produced with the ggplot package in Rstudio. Panels (B) – (D) summarize decline rates in 1.5°C-compatible scenarios for coal, gas, and oil respectively. Dots show historical episodes with the electricity system size > 100 TWh/year; the daker dots are those colored in panel (A); the blue line is the feasibility frontier. Medians and 80% ranges (so that 10% of individual scenario datapoints remain below and 10% – above the bar) for each fuel/region combination are depicted with dots and bars. For each fuel/region combination, a period with the largest median decline rate is shown.

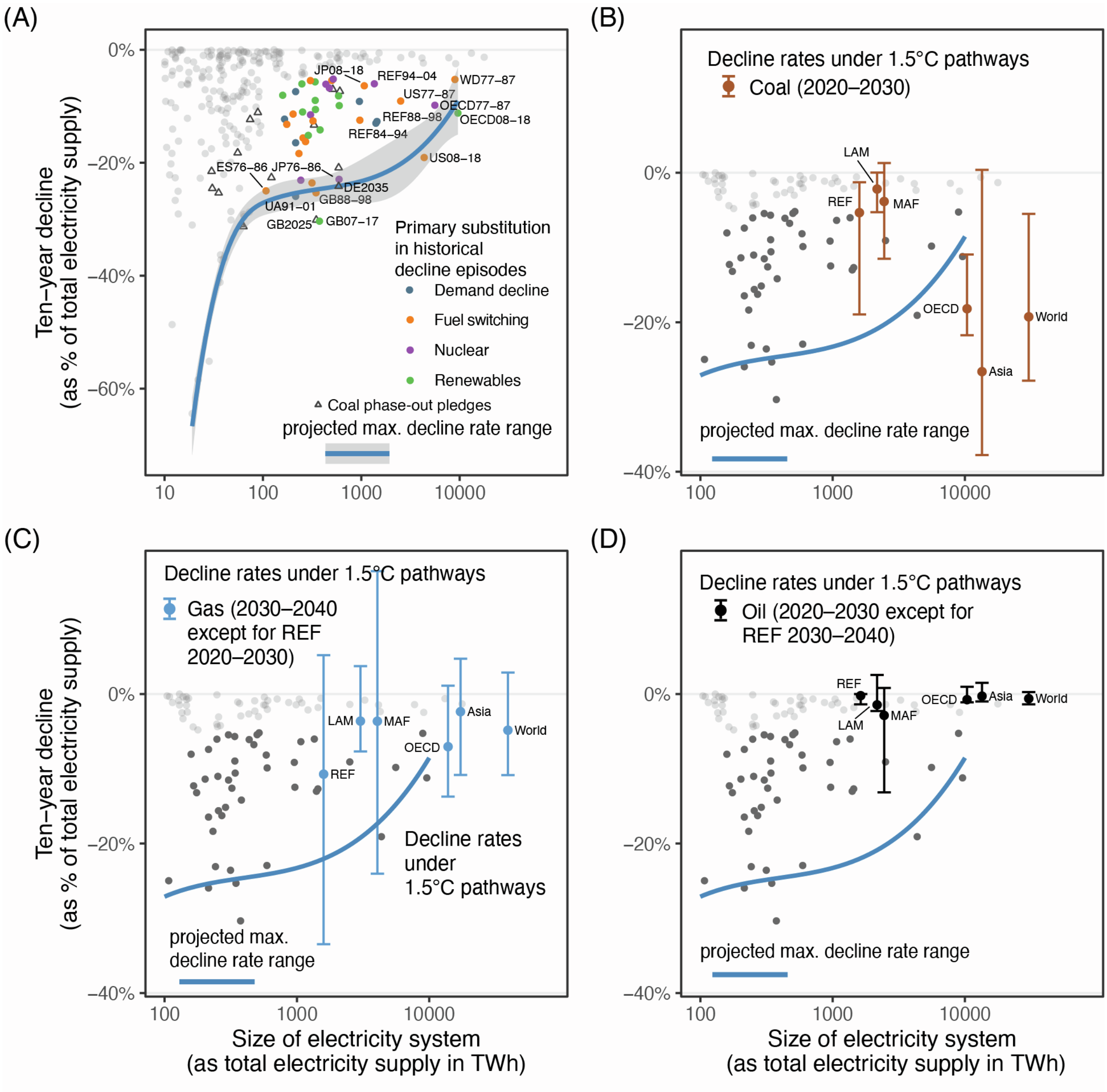


Figure S6. Fuel and technology substitution in selected historical decline episodes.

The figure shows historical fossil fuel decline episodes with the system size > 100 TWh/year and decline rate faster than 5% not shown in Figure 3. Change in each electricity source is calculated using the same method as fossil fuel decline (Experimental Procedures). Bars above zero – growing sources; below zero – declining sources. Numbers at the top of the bars – total electricity demand change over the period; at the bottom – decline in the fossil fuel defining the episode. The area of the circles above the bars show the electricity system size during the episode (mean of total electricity supply at the beginning and the end of the episode). Episodes are arranged according to the starting year. Episode coding: e.g. DE84–94C – Germany, 1984–1994, coal decline.

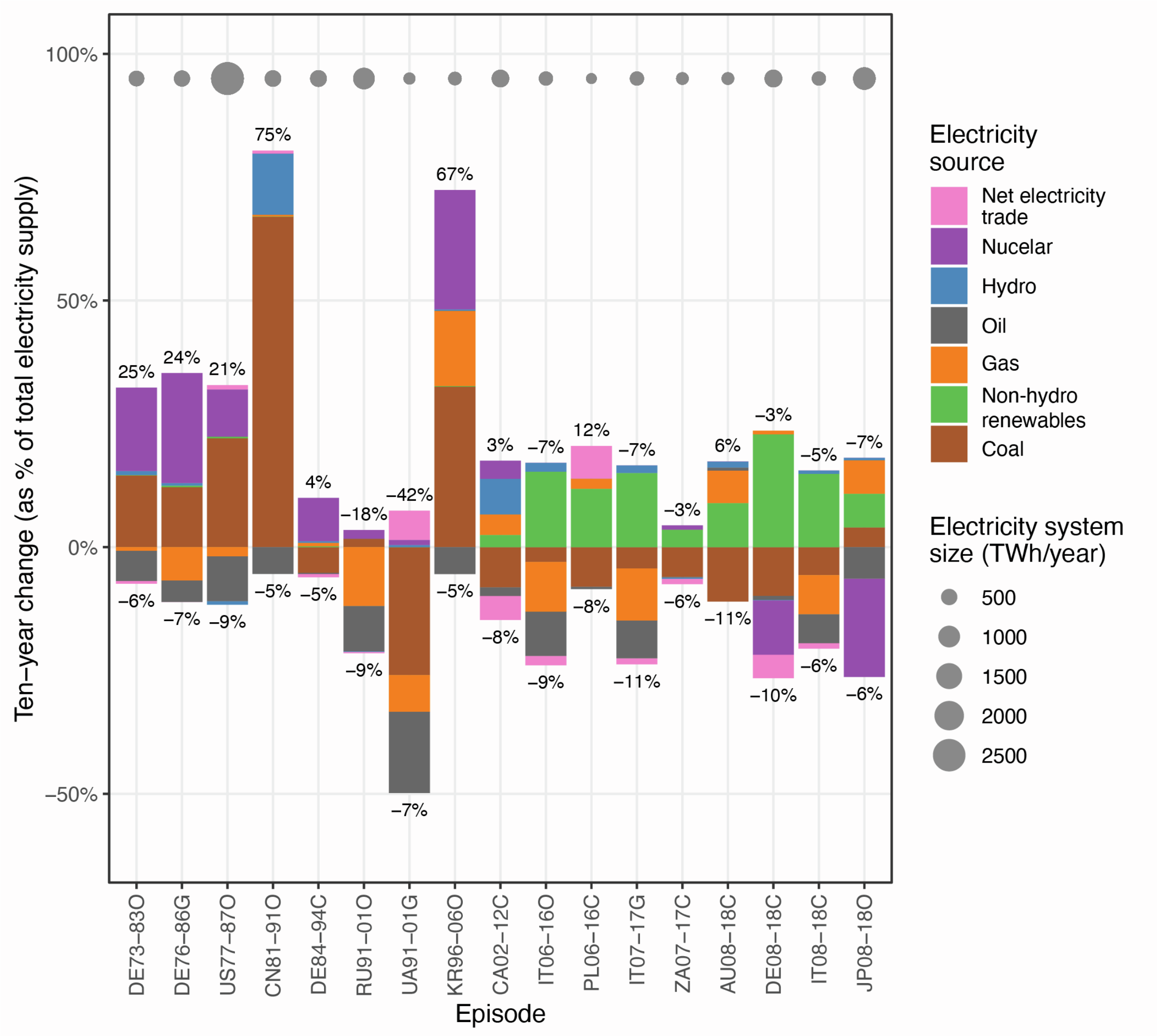


Figure S7. Fuel and technology substitution in selected climate mitigation scenarios.

The figure shows changes in 2020–2030 for all regions in representative scenarios P1-P4 and the IEA's Net Zero Energy by 2050 Roadmap[1] (only global data are available for P1 and NZE2050)[2]. Change in each electricity source is calculated using the same method as fossil fuel decline (Experimental Procedures). Bars above zero – growing sources; below zero – declining sources. Numbers at the top of the bars – total electricity demand change over the period; at the bottom – change in gas (G) and coal (C).

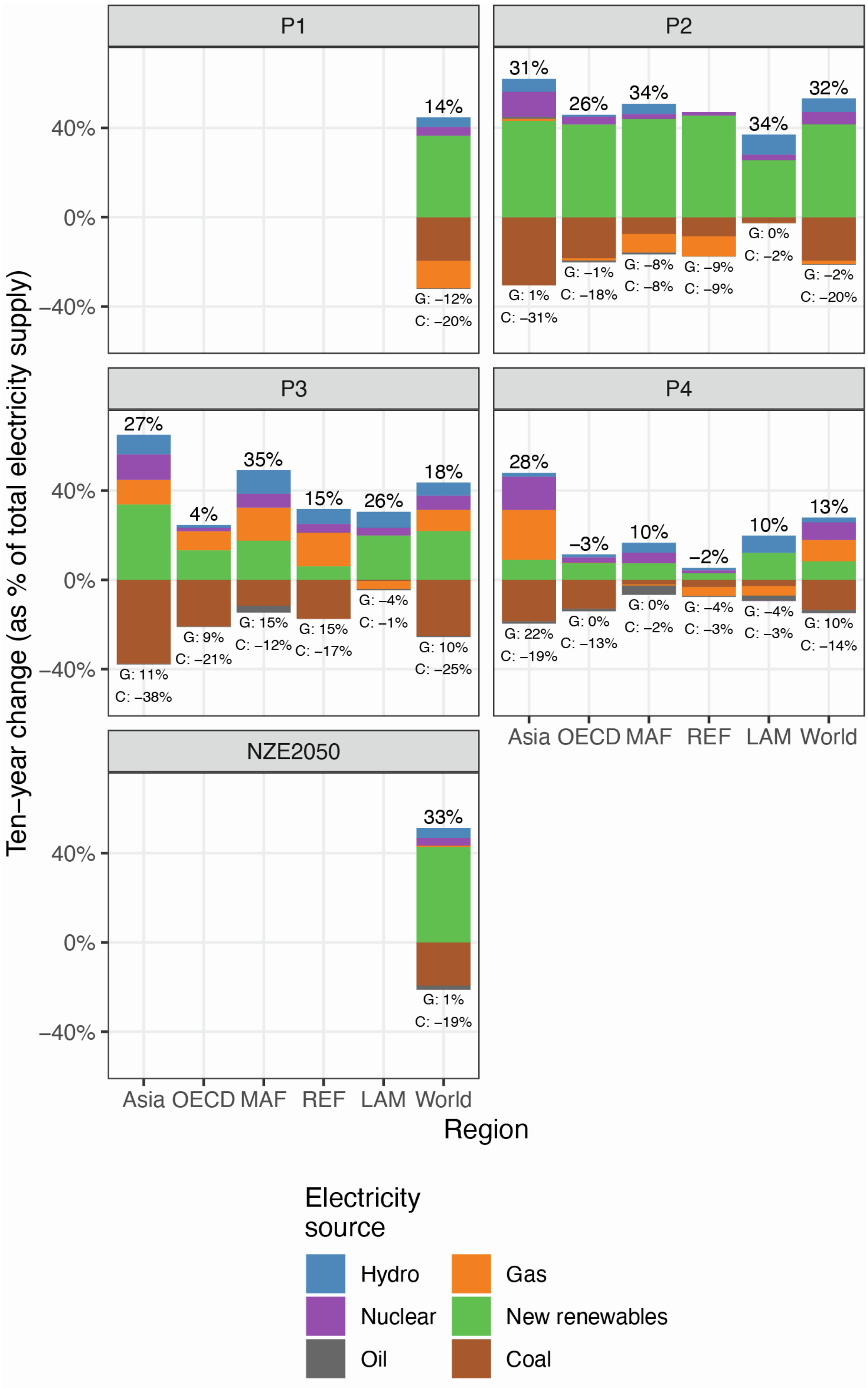


Figure S8. Building feasibility space for fossil fuel decline.

(A) Calculating weighted density scores. The axes X and Y represent ten-year change in fossil fuel and total electricity demand respectively. Dots show historical decline episodes used in the calculation (color – primary substitution classification; size – total electricity supply). Numbers – weighted density scores for bins calculated as a sum of system sizes (log-transformed) of episodes within the bin. (B) The principle of producing augmented feasibility scores. E.g. bins Y and Z also provide feasibility evidence for bin X (Experimental procedures). Therefore the augmented score for bin X is calculated by summing up weighted density scores within the quadrant demarcated by brown lines. (C) Defining feasibility zones. Numbers – augmented feasibility scores for bins calculated as illustrated in panel (B). n/d – augmented feasibility score is not determined (for areas which are classified as Zone D based on demand decline). Zone A: score > 10; Zone B: 10 >= score > 0; Zone C: score = 0; Zone D: demand decline > 15%.

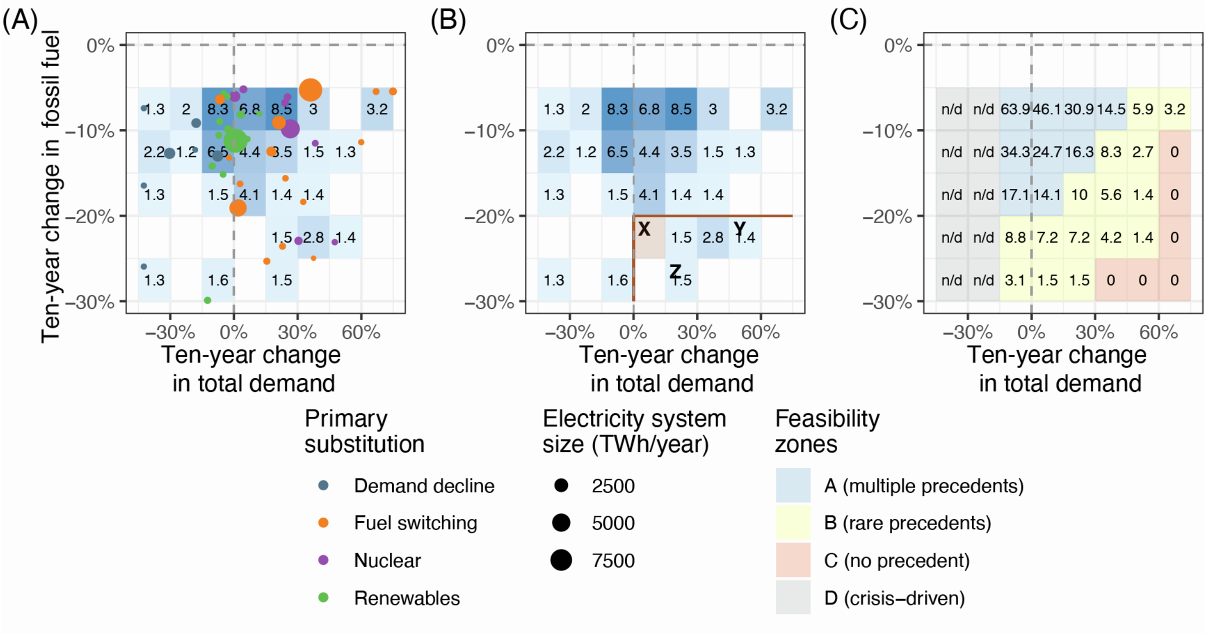


Figure S9. Decline rates for scenarios with high and low levels of CCS.

The figure shows the relationship between coal and gas decline rates (global and for selected regions) and the global generation from the respective fuel with CCS in 2050 (a proxy for the availability of CCS technologies). For each scenario, the maximum decline rate across the three decades (2020–30, 2030–40, and 2030–50) is shown. "High" level of CCS is defined as global generation with CCS > 5 EJ/year and > 10 EJ/year for coal and gas respectively. The bars show medians and full ranges of rates for high and low CCS levels.

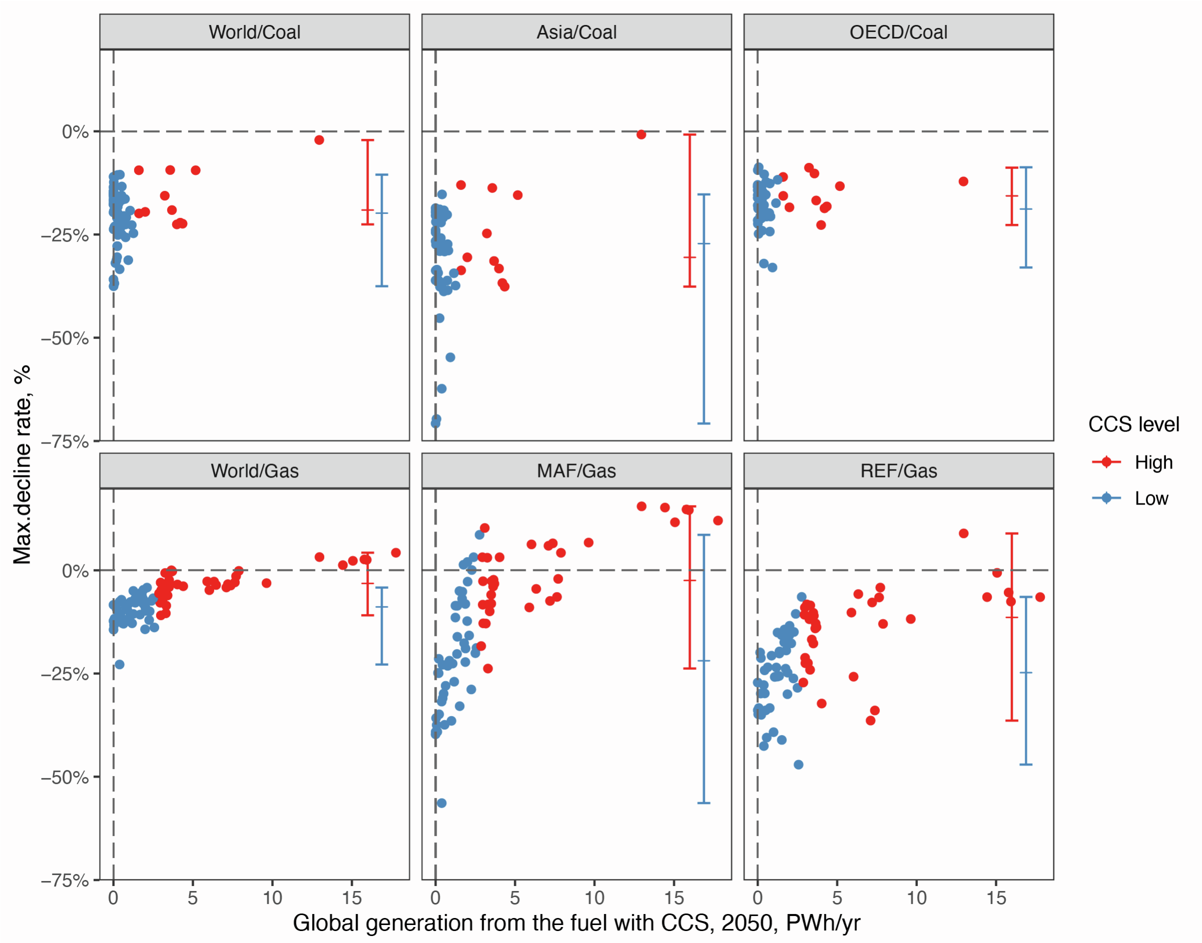


Figure S10. Ten-year decline and growth rates of oil, gas and coal observed in 1.5°C-compatible scenarios.

Each box and whiskers summarizes change (decline or growth) rates in the use of the given fossil fuel for electricity generation by decade and region across the range of 1.5°C-compatible scenarios. Thick horizontal lines represent median values; boxes – interquartile ranges; and vertical lines and dots – the entire range of rates. Slanted crosses for the World represent global decline rates in the IEA's NZE2050 Scenario[1].

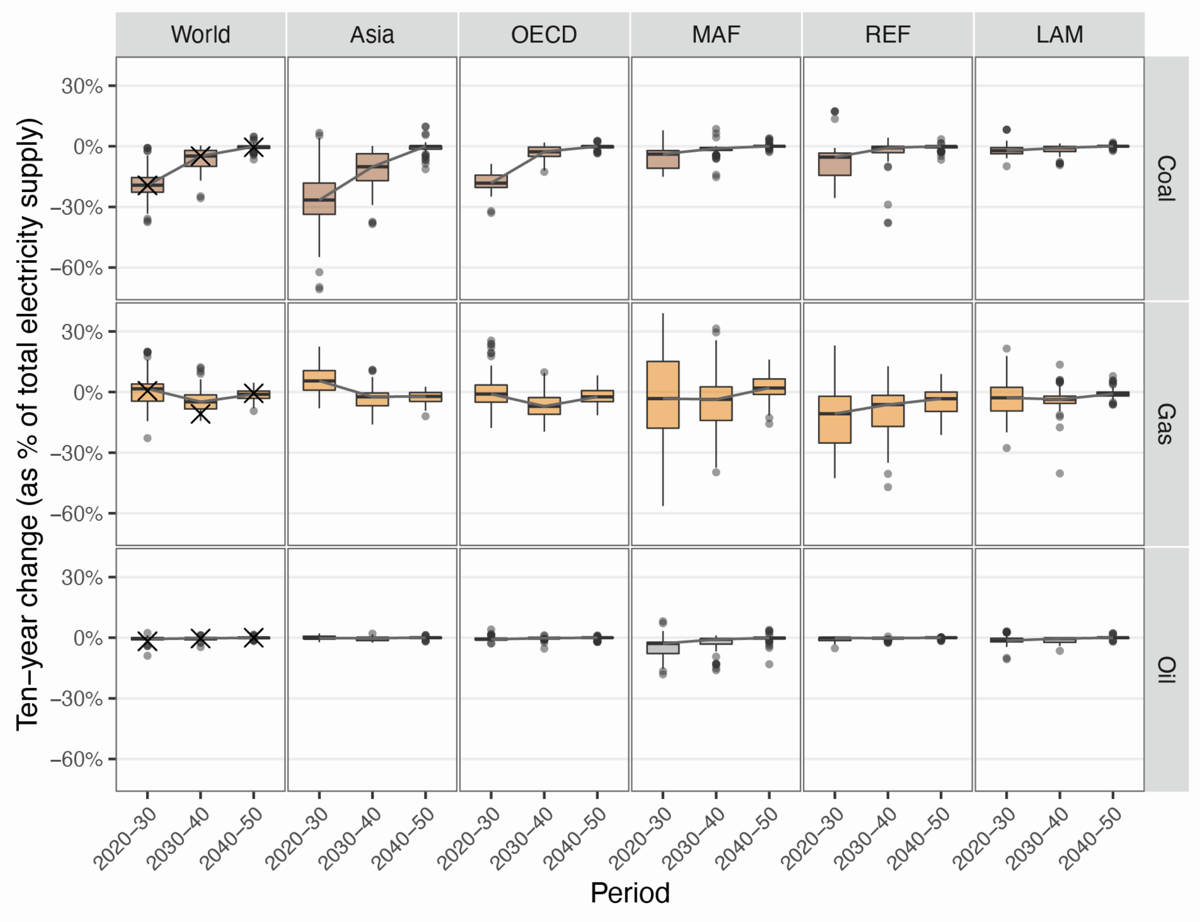


Figure S11. Decline rates in historical episodes and 1.5°C-compatible scenarios calculated for 10-year and 20-year periods.

The figure illustrates the effect of period length on decline rates in historical episodes and climate mitigation scenarios. Panel (A): decline rates in historical episodes. Crosses – 10-year episodes, dots – 20-year episodes. The lines depict the feasibility frontier of decline – the relationship between the highest observed decline rates and the size of the energy system – generated as a spline approximation of selected boundary datapoints produced with the ggplot package in Rstudio (dashed – based on 10-year episodes, solid – based on 20-year episodes). With a few exception, switching from 10 to 20-year period does not lead to significantly larger decline rates for episodes involving larger systems close to the frontier, which means that in most high-decline episodes the period of continuous decline is closer to 10 years. Panel (B): ranges of decline rates in 1.5°C-compatible scenarios. Grey dots represent 20-year historical decline episodes with system size > 100 TWh year. Colored dots and bars depict medians and 80% ranges (so that 10% of individual scenario datapoints remain below and 10% – above the bar) for coal and gas decline rates in 1.5°C-compatible scenarios for selected region/fuel combination. Bright colors depict 20-year periods; shaded – 10-year periods. For each region/fuel combination and period duration the period with the largest median decline rate between 2020 and 2050 was selected (10 years: coal – 2020–2030 for all regions, gas –2030–2040 for all regions except for REF 2020–2030; 20 years – 2020–2040 for all regions).

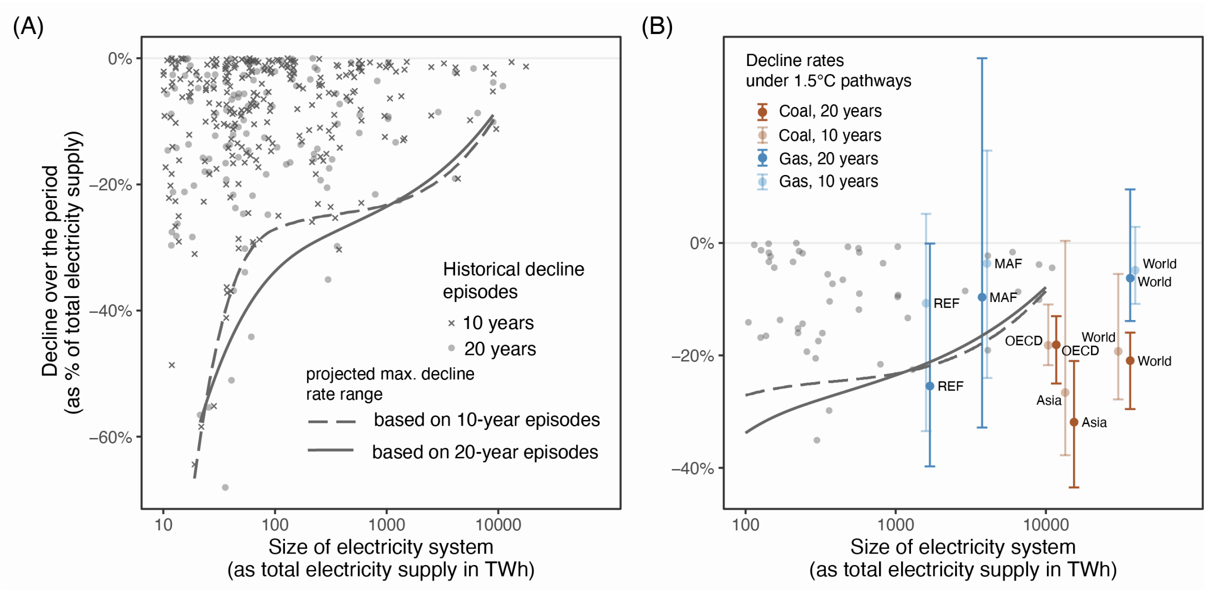


Figure S12. Fossil fuel decline rates in 1.5°C-compatible scenarios using 10-year and 20-year decline periods.

The figure summarizes coal and gas decline rates in 1.5°C-compatible scenarios calculated using 10-years (blue) and 20-year (orange) decline period. The dots and bars depict medians and 80% ranges (so that 10% of individual scenario datapoints remain below and 10% – above the bar). For each fuel/region combination a period with the largest median decline rate was selected (10 years: coal – 2020–2030 for all regions, gas – 2030–2040 for all regions except for REF 2020–2030; 20 years – 2020–2040 for all regions except for gas in Asia 2030–2050).

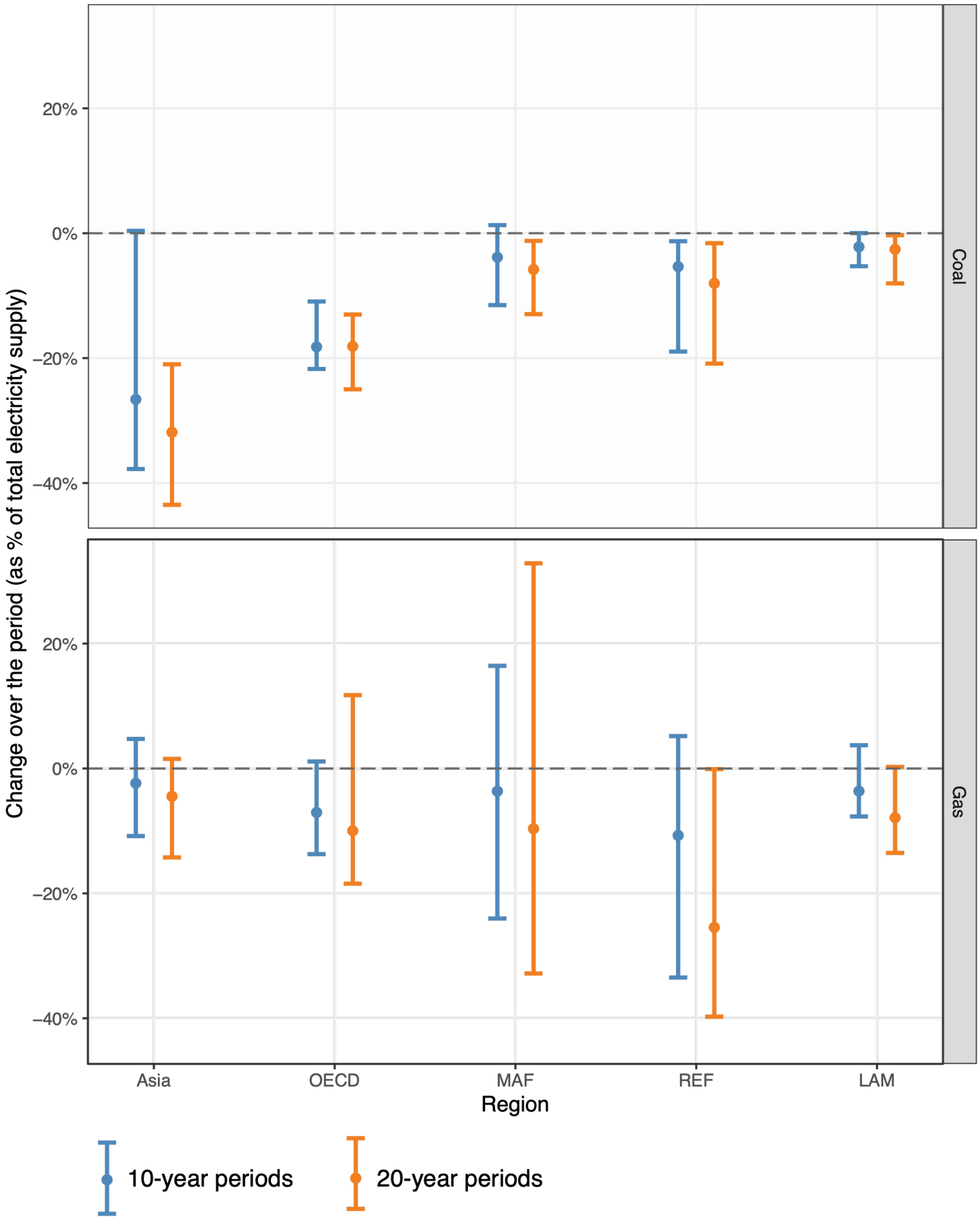


Figure S13. Changes in gas-fired generation in 1998-2008* and 2008–2018 years.**

Change is calculated using the same method as decline in fossil fuels (Experimental Procedures); the calculation was done for 105 countries with total electricity supply > 10 TWh/year in 2017 (Table S1). Countries with change (growth or decline) less than 5% in both decades are not shown. Countries in which gas-fired generation increased in both periods, are in the top-right quadrant; increased in the first decade and decreased in the second – in the bottom-right quadrant etc. Dot size represents electricity system size (total electricity supply) in 2008. Countries are colored according to their region (Table S2); country codes – Table S6.

* Or 1997–2007, depending on the most recent datapoint available.

** Or 2007–2017, depending on the most recent datapoint available.

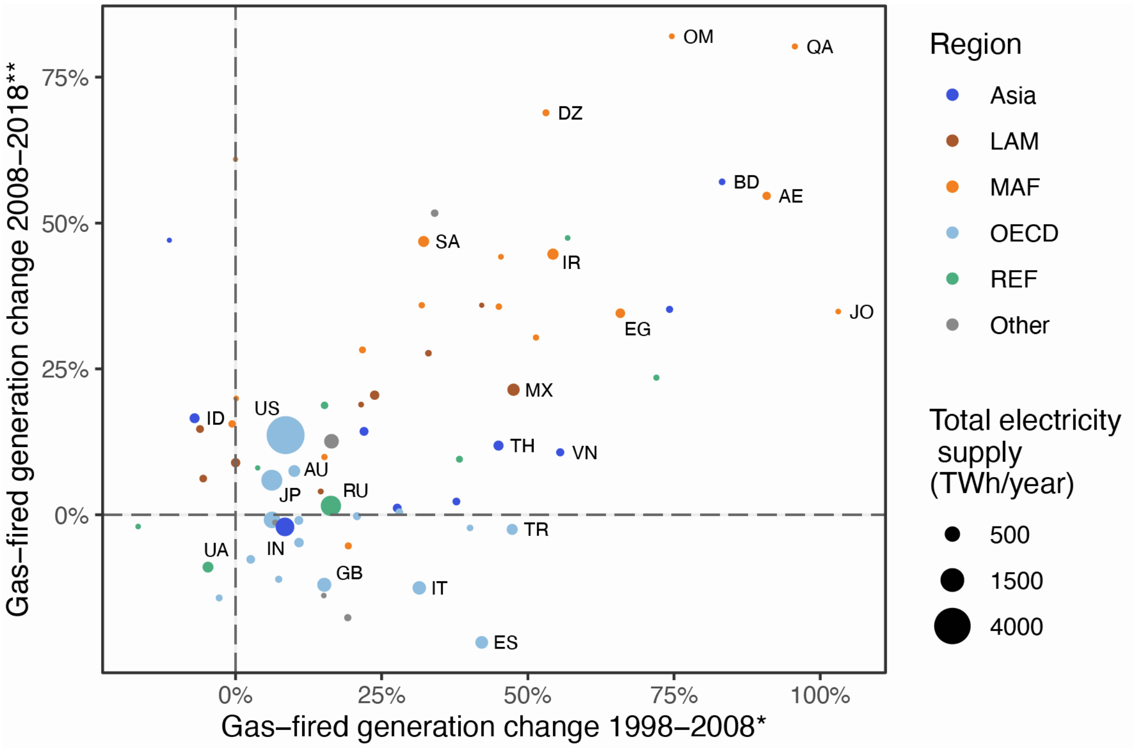


Figure S14. Measuring decline in fossil fuel generation.

The figure shows electricity generation from coal (brown) and all other sources combined (grey). S_{C0} and S_{C1} – generation from coal at the beginning and the end of the period respectively; T_0 and T_1 – total generation at the beginning and the end of the period respectively. Decline in coal is calculated as absolute decline ($S_{C1} – S_{C0}$) relative to the average "electricity system size" – total electricity supply, which in the absence of electricity imports or exports is equivalent to total generation ((T_0 + T_1)/2). In this example, 10-year decline rate calculated in this way is 10%. This is different from the decline in coal-fired generation relative to its original size (33%).

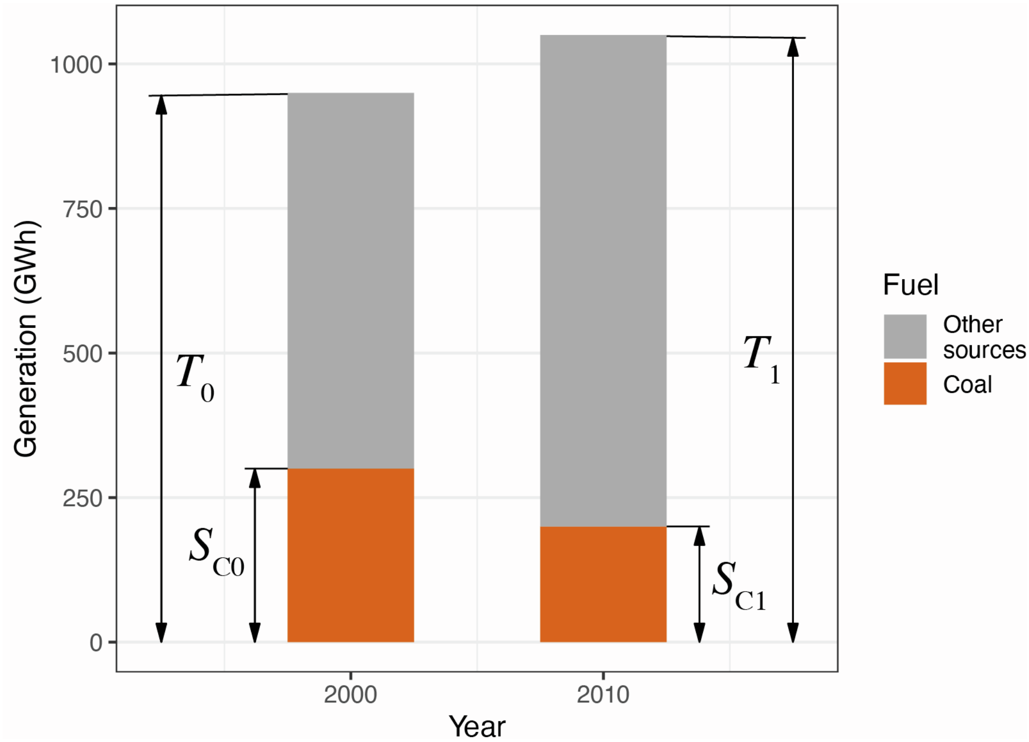


Figure S15. Sensitivity of the decline metric to the time-point of measuring electricity system size.

The figure compares the effect of different definitions of the electricity system size on fossil fuel decline and demand change rates. Colored circles – significant historical decline episodes (Table S4), color – primary substitution (Experimental Procedures), size of the circles – electricity system size in TWh/year. Grey hollow circles and crosses – coal decline and demand change in Asia (2020–2030) in 1.5˚C compatible scenarios, the most challenging combination of fuel, region, and period. Hollow circles – high-overshoot scenarios, crosses – low- or no-overshoot scenarios. The three panels reflect three different approaches to measuring the decline rate of fossil fuels and the change in electricity demand. In the first panel (Start), the absolute reduction in the use of fossil fuels and the absolute increase in electricity demand are denominated to the total electricity supply at the beginning of the period. In the second panel (Mean (start-end)) – the denominator is the average of total electricity supply at the beginning and the end of the period. This is the metric used in our main analysis. In the third panel (End) – the denominator is the total electricity supply at the end of the period. The change between these three ways of measurement affects historical and scenario datapoints in a similar way, so a relationship between historical episodes described in the article generally holds.

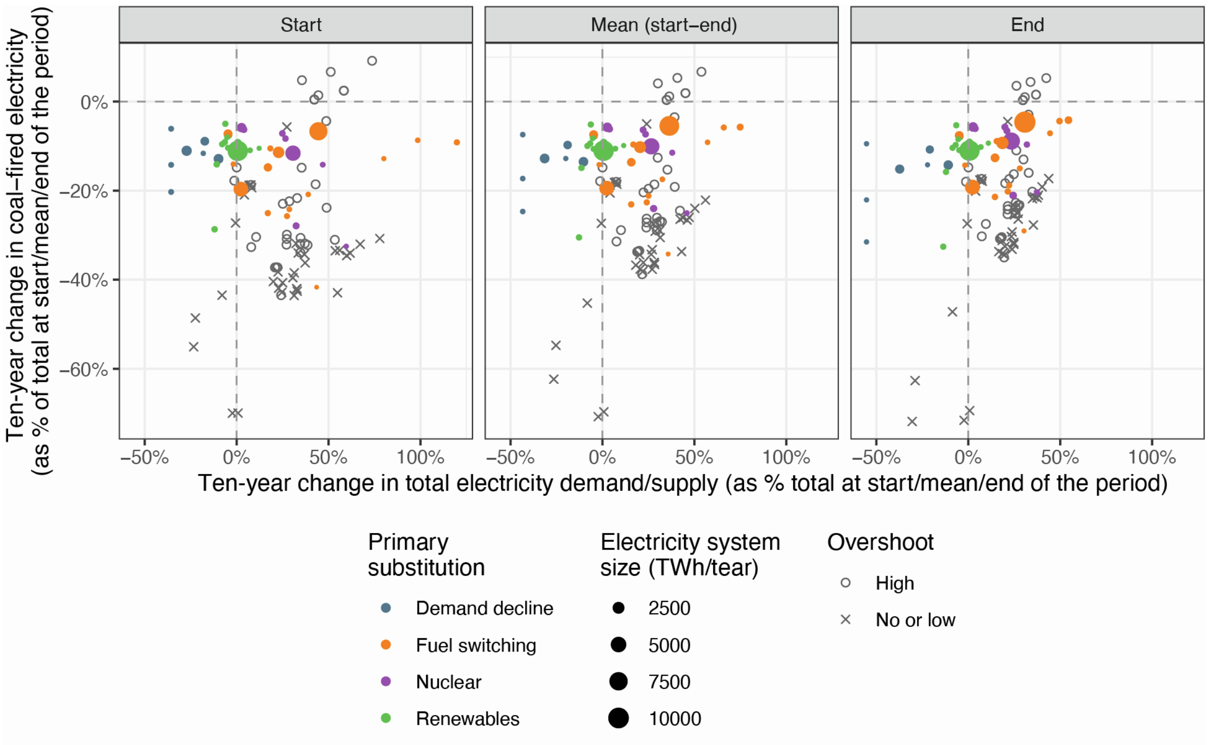


Figure S16. Adjusting decline rates for rebound.

If generation from the given source increases within 10 years after the end of the identified period, the maximum level achieved during that period (S_{i1}') is used instead of the level at the end of the period (S_{i1} – see Experimental Procedures and Figure S14) in calculating the amount of decline.

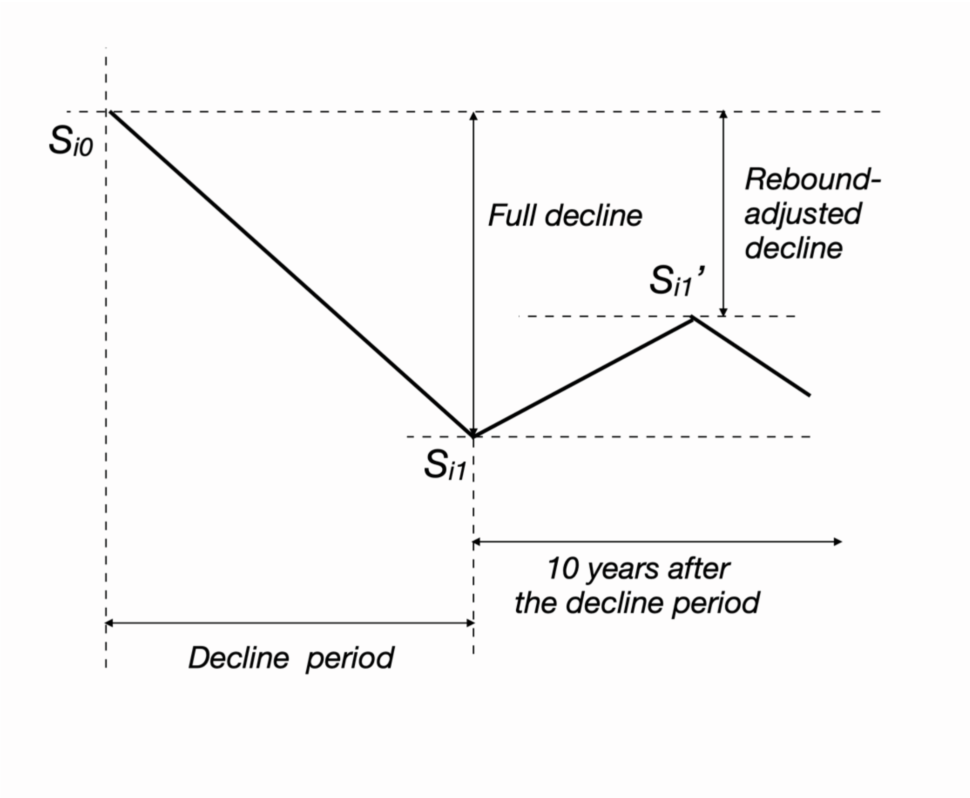
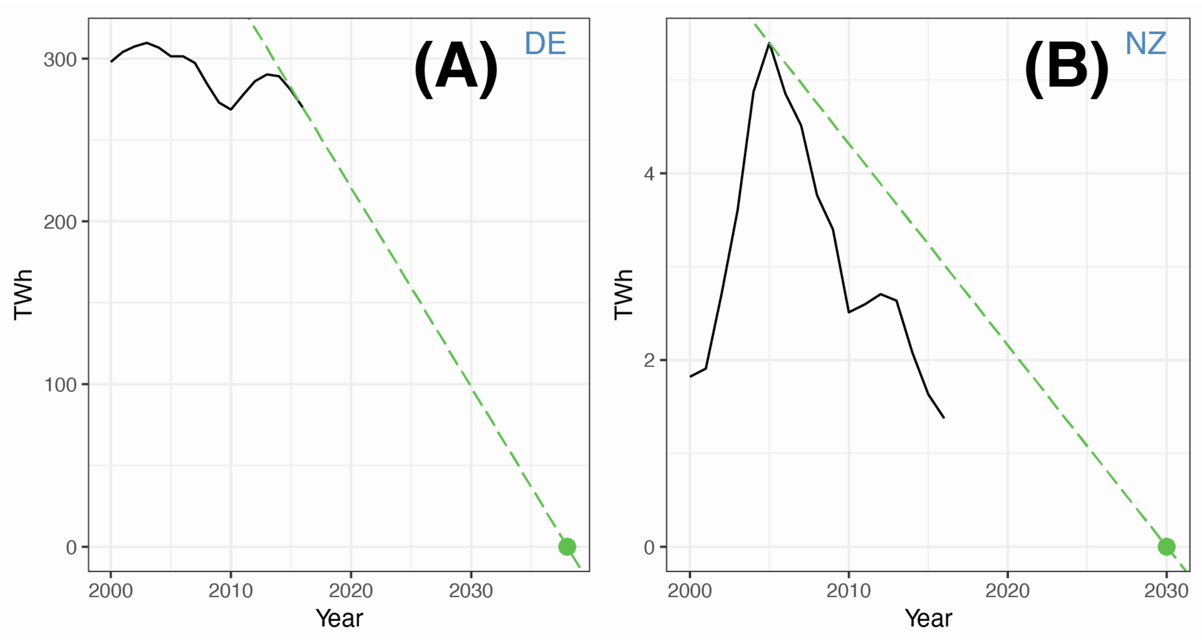


Figure S17. Examples of calculating decline rates based on phase-out pledges of Germany, phase-out year 2038 (A), and New Zealand (B)



Supplemental tables

Table S1. Years when countries entered our sample from exceeding the threshold of 10 TWh/year in terms of total electricity supply.

Asterisk (*) means the beginning of data series for the country; its total electricity supply could be above 10 TWh/year before that date.

Country	Year
Austria, Australia, Belgium, Canada, France, Germany, Italy, Japan, Netherlands, Norway, Poland, Sweden, Switzerland, Spain, United Kingdom, United States	1960*
Finland	1961
Hungary, New Zealand	1965
Denmark	1966
Argentina, Bulgaria, Brazil, China, Colombia, Czechia, Greece, India, Mexico, North Korea, Romania, Slovakia, South Africa, South Korea, Venezuela	1971*
Philippines, Turkey	1972
Iran	1973
Portugal	1974
Egypt	1975
Israel, Pakistan	1976
Thailand	1977
Chile, Saudi Arabia,	1978
Ireland, Iraq	1979
Malaysia, Peru	1980
Cuba, Kuwait	1981
Indonesia	1982
Algeria, United Arab Emirates	1983
Nigeria	1985
Singapore	1986
Syria	1989
Armenia, Azerbaijan, Belarus, Bosnia & Herzegovina, Croatia, Estonia, Georgia, Kyrgyzstan, Latvia, Lithuania, Libya, Moldova, Russia, Serbia, Slovenia, Tajikistan, Ukraine, Uzbekistan	1990*
Zimbabwe	1991

Country	Year
Morocco	1992
Bahrain, Vietnam	1993
Bangladesh	1995
Ecuador	1997
Dominican Republic, Lebanon	1998
Tunisia	2000
Oman	2002
Qatar	2002
Mozambique, Turkmenistan	2004
Jordan	2005
Iceland	2007
Sri Lanka	2008
Uruguay	2009
Paraguay	2010
Ghana, Zambia	2011
Costa Rica, Myanmar	2012
Guatemala, Sudan	2013
Panama, Trinidad & Tobago	2015
Angola, Ethiopia	2016
Democratic Republic of the Congo, Kenya	2017

Table S2. Definition of regions for the analysis of fossil fuel decline rates in future scenarios and historical decline rates.

Region	Definition in scenarios[4]	Definition in historical analysis of decline
Asia	Includes most Asian countries with the exception of the Middle East, Japan and Former Soviet Union states, e.g. China, India, Indonesia.	Includes non-OECD Asia according to the classification used in IEA World Energy Balances[3], e.g. China, India, Indonesia.
LAM (Latin America)	Includes the countries of Latin America and the Caribbean, e.g. Brazil, Argentina, Mexico.	Includes the countries of Latin America and the Caribbean, according to the classification used in IEA World Energy Balances[3], e.g. Brazil or Argentina, plus Mexico and Chile (which are included in OECD in IEA classification).
MAF (Middle East and Africa)	Includes the countries of the Middle East and Africa, e.g. Saudi Arabia, Nigeria, South Africa	Includes the countries of the Middle East and Africa, according to the classification used in IEA World Energy Balances[3], e.g. Saudi Arabia, Nigeria, South Africa.
OECD (Organisation for Economic Co-operation and Development)	Includes OECD member countries as of 1990, and European Union member states and candidates, e.g. the US, the UK, Japan, Australia, Poland, Bulgaria.	Includes OECD member countries as of 1990, e.g. the US, the UK, Japan, Australia. Unlike future scenarios, does not include “new” EU members, e.g. Poland or Bulgaria.
REF (Reforming economies)	Reforming Economies of Eastern Europe and the Former Soviet Union. Effectively includes 12 post-Soviet countries, e.g. Russia or Ukraine.	Former Soviet Union prior to 1990, post-Soviet republics since 1990. In addition to 12 countries in scenarios, also includes Lithuania, Latvia, and Estonia (for continuity with historical Soviet Union data).

Table S3. Fossil fuel decline episodes with rate beyond than 30% per decade.

The table lists all ten-year historical episodes of fossil fuel decline with decline rate above 30% per decade in countries with total electricity supply > 10 TWh/year. The episodes are arranged according to slower to faster decline rates. Country codes – Table S6. See Experimental Procedures for explanation of substitution classification. “Renewables” exclude hydro power. TES – total electricity supply.

Episode	Country	Period	Declining fuel	Decline (% of TES)	Demand change (% of TES)	Total electricity supply (TWh/year)	Primary substituting source (change, % of TES)	Secondary substituting source, (change, % of TES)
BE74-84O	BE	1974-1984	Oil	-30 %	28 %	47	Nuclear (56%)	Coal (15%)
GB07-17C	GB	2007-2017	Coal	-30 %	-12 %	375	Renewables (21%)	Demand (-12%)
KP07-17C	KP	2007-2017	Coal	-31 %	-35 %	19	Demand (-35%)	–
DK07-17C	DK	2007-2017	Coal	-36 %	-7 %	37	Renewables (28%)	Imports (19%)
BY91-01O	BY	1991-2001	Oil	-37 %	-35 %	40	Demand (-35%)	Gas (5%)
DK95-05C	DK	1995-2005	Coal	-37 %	4 %	37	Renewables (20%)	Gas (15%)
SG99-09O	SG	1999-2009	Oil	-41 %	37 %	37	Gas (76%)	–
IE79-89O	IE	1979-1989	Oil	-49 %	27 %	12	Coal (50%)	Gas (26%)
SY07-17O	SY	2007-2017	Oil	-55 %	-74 %	28	Demand (-74%)	–
DK72-82O	DK	1972-1982	Oil	-58 %	36 %	22	Coal (69%)	Imports (25%)
AZ99-09O	AZ	1999-2009	Oil	-64 %	3 %	19	Gas (67%)	–

Table S4. Significant historical episodes of fossil fuel decline.

The table lists all identified ten-year historical episodes of fossil fuel decline with decline rate above 5% and electricity system size > 100 TWh/year. Regional and national episodes are arranged according to decline rate. Region codes –Table S2, country codes – Table S6. See Experimental Procedures for explanation of substitution classification. ”Renewables” exclude hydro power. TES – total electricity supply.

Episode	Country/ region	Period	Declining fuel	Decline (% of TES)	Demand change (% of TES)	Total electricity supply (TWh/year)	Primary substituting source (change, % of TES)	Secondary substituting source (change, % of TES)
World								
WD77-87O	World	1977-1987	Oil	-5 %	36 %	8941	Coal (16%)	Nuclear (14%)
Regions								
REF84-94O	REF	1984-1994	Oil	-13 %	-8 %	1405	Demand (-8%)	Gas (6%)
REF88-98C	REF	1988-1998	Coal	-13 %	-30 %	1441	Demand (-30%)	–
OECD08-18C	OECD	2008-2018	Coal	-11 %	1 %	9591	Renewables (10%)	Gas (6%)
OECD77-87O	OECD	1977-1987	Oil	-10 %	27 %	5587	Nuclear (17%)	Coal (15%)
REF94-04O	REF	1994-2004	Oil	-6 %	0 %	1354	Nuclear (5%)	Gas (4%)
Countries								
GB07-17C	GB	2007-2017	Coal	-30 %	-12 %	375	Renewables (21%)	Demand (-12%)
UA91-01C	UA	1991-2001	Coal	-26 %	-42 %	215	Demand (-42%)	Imports (6%)
GB88-98C	GB	1988-1998	Coal	-25 %	15 %	346	Gas (34%)	Nuclear (10%)
ES76-86O	ES	1976-1986	Oil	-25 %	38 %	107	Coal (36%)	Nuclear (26%)
IT96-06O	IT	1996-2006	Oil	-24 %	23 %	315	Gas (34%)	Coal (8%)
FR74-84O	FR	1974-1984	Oil	-23 %	48 %	242	Nuclear (70%)	–
JP76-86O	JP	1976-1986	Oil	-23 %	30 %	593	Nuclear (24%)	Gas (18%)
US08-18C	US	2008-2018	Coal	-19 %	2 %	4352	Gas (13%)	Renewables (7%)
MX99-09O	MX	1999-2009	Oil	-18 %	33 %	232	Gas (46%)	–
UA91-01O	UA	1991-2001	Oil	-16 %	-42 %	215	Demand (-42%)	Imports (6%)
GB72-82O	GB	1972-1982	Oil	-16 %	3 %	271	Coal (14%)	Nuclear (6%)
ES00-10C	ES	2000-2010	Coal	-16 %	24 %	255	Gas (29%)	Renewables (18%)
ES07-17G	ES	2007-2017	Gas	-15 %	-5 %	289	Renewables (13%)	Imports (6%)
GB04-14G	GB	2004-2014	Gas	-14 %	-10 %	381	Renewables (14%)	Demand (-10%)
UA04-14G	UA	2004-2014	Gas	-13 %	-2 %	175	Coal (11%)	Demand (-2%)
GB85-95O	GB	1985-1995	Oil	-13 %	18 %	323	Gas (20%)	Nuclear (10%)
JP91-01O	JP	1991-2001	Oil	-12 %	18 %	965	Coal (11%)	Nuclear (10%)
UA08-18C	UA	2008-2018	Coal	-12 %	-18 %	166	Demand (-18%)	–
FR79-89C	FR	1979-1989	Coal	-12 %	38 %	304	Nuclear (84%)	–
ID07-17O	ID	2007-2017	Oil	-11 %	60 %	202	Coal (43%)	Gas (19%)
AU08-18C	AU	2008-2018	Coal	-11 %	6 %	253	Renewables (9%)	Gas (7%)
IT07-17G	IT	2007-2017	Gas	-11 %	-7 %	342	Renewables (15%)	Demand (-7%)
DE08-18C	DE	2008-2018	Coal	-10 %	-3 %	596	Renewables (23%)	Demand (-3%)
RU91-01O	RU	1991-2001	Oil	-9 %	-18 %	956	Demand (-18%)	–
US77-87O	US	1977-1987	Oil	-9 %	21 %	2510	Coal (22%)	Nuclear (10%)
IT06-16O	IT	2006-2016	Oil	-9 %	-7 %	340	Renewables (15%)	Demand (-7%)
CA02-12C	CA	2002-2012	Coal	-8 %	3 %	586	Hydro (7%)	Gas (4%)

Episode	Country/ region	Period	Declining fuel	Decline (% of TES)	Demand change (% of TES)	Total electricity supply (TWh/year)	Primary substituting source (change, % of TES)	Secondary substituting source (change, % of TES)
PL06-16C	PL	2006-2016	Coal	-8 %	12 %	159	Renewables (12%)	Imports (7%)
UA91-01G	UA	1991-2001	Gas	-7 %	-42 %	215	Demand (-42%)	Imports (6%)
DE76-86G	DE	1976-1986	Gas	-7 %	24 %	473	Nuclear (22%)	Coal (12%)
JP08-18O	JP	2008-2018	Oil	-6 %	-7 %	1071	Gas (7%)	Renewables (7%)
DE73-83O	DE	1973-1983	Oil	-6 %	25 %	436	Nuclear (17%)	Coal (15%)
ZA07-17C	ZA	2007-2017	Coal	-6 %	-3 %	249	Renewables (4%)	Demand (-3%)
IT08-18C	IT	2008-2018	Coal	-6 %	-5 %	339	Renewables (15%)	Demand (-5%)
KR96-06O	KR	1996-2006	Oil	-5 %	67 %	304	Coal (33%)	Nuclear (24%)
CN81-91O	CN	1981-1991	Oil	-5 %	75 %	500	Coal (67%)	Hydro (12%)
DE84-94C	DE	1984-1994	Coal	-5 %	4 %	518	Nuclear (9%)	–

Table S5. Frequency of fast decline rates in smaller and larger entities (including regions).

The frequency of decline episodes exceeding a given decline rate threshold for different "small" and "large" entities . "Small entities" in each case are defined as below a given threshold in terms of total electricity supply, whereas "large entities" are defined as above a given threshold. The Anderson–Darling test shows the probability that two observed samples come from the same probability distribution (Experimental Procedures). The binomial p-value shows the probability of obtaining the empirical results for large entities assuming the large entities have the same probability of exceeding the decline rate threshold as small entities (Experimental Procedures).

Threshold between small and large entities TWh/year	**Number of small entity observations (% of all observations)**	**Number of large entity observations (% of all observations)**	**Frequency of fast decline rates**			**Ratio between frequencies of decline rates exceeding the threshold in small and large entities**	**Anderson-Darling *p*-value**	**Binomial *p*-value**
			decline rate faster than	**…in small entities**	**…in large entities**			
100	153 (62%)	92 (38%)	-20%	16%	8%	2	0.045	0.02
			-25%	11%	3%	3	0.045	0.01
			-30%	7%	1%	6	0.045	0.02
200	173 (71%)	72 (29%)	-20%	15%	9%	1.7	0.02	*0.10*
			-25%	10%	4%	2	0.02	*0.07*
			-30%	6%	2%	4	0.02	*0.07*
300	189 (77%)	56 (23%)	-20%	14%	7%	2	0.047	*0.08*
			-25%	10%	4%	3	0.047	*0.09*
			-30%	5%	2%	3	0.047	*0.20*

Table S6. Country codes used in the article.

Code	Country
AE	United Arab Emirates
AO	Angola
AR	Argentina
AT	Austria
AU	Australia
AZ	Azerbaijan
BA	Bosnia & Herzegovina
BD	Bangladesh
BE	Belgium
BG	Bulgaria
BH	Bahrain
BR	Brazil
BY	Belarus
CA	Canada
CH	Switzerland
CL	Chile
CN	China
CO	Colombia
CR	Costa Rica
CU	Cuba
CZ	Czechia
DE	Germany
DK	Denmark
DO	Dominican Republic
DZ	Algeria
EC	Ecuador
EG	Egypt
ES	Spain
ET	Ethiopia
FI	Finland
FR	France
GB	United Kingdom
GE	Georgia
GH	Ghana

Code	Country
GR	Greece
GT	Guatemala
HR	Croatia
HU	Hungary
ID	Indonesia
IE	Ireland
IL	Israel
IN	India
IQ	Iraq
IR	Iran
IS	Iceland
IT	Italy
JO	Jordan
JP	Japan
KE	Kenya
KG	Kyrgyzstan
KP	North Korea
KR	South Korea
KW	Kuwait
KZ	Kazakhstan
LB	Lebanon
LK	Sri Lanka
LT	Lithuania
LY	Libya
MA	Morocco
MM	Myanmar
MX	Mexico
MY	Malaysia
MZ	Mozambique
NG	Nigeria
NL	Netherlands
NO	Norway
NZ	New Zealand

Code	Country
OM	Oman
PA	Panama
PE	Peru
PH	Philippines
PK	Pakistan
PL	Poland
PT	Portugal
PY	Paraguay
QA	Qatar
RO	Romania
RS	Serbia
RU	Russia
SA	Saudi Arabia
SD	Sudan
SE	Sweden
SG	Singapore
SI	Slovenia
SK	Slovakia
SY	Syria
TH	Thailand
TJ	Tajikistan
TM	Turkmenistan
TN	Tunisia
TR	Turkey
TT	Trinidad & Tobago
UA	Ukraine
US	United States
UY	Uruguay
UZ	Uzbekistan
VE	Venezuela
VN	Vietnam
ZA	South Africa
ZM	Zambia

Table S7. Ten-year change rates for fossil fuel-fired electricity generation in 1.5°C-compatible scenarios.

The table summarizes fossil fuel change rates for each period and region across 1.5°C-compatible scenarios. Min – minimum value; Q1 – first quartile; Median – median value; Q3 – third quartile; Max – maximum value.

Region	2020–2030					2030–2040					2040–2050				
	Min	Q1	Median	Q3	Max	Min	Q1	Median	Q3	Max	Min	Q1	Median	Q3	Max
Coal															
World	-38 %	-23 %	-19 %	-15 %	-0.8 %	-26 %	-10 %	-5 %	-2 %	0.3 %	-7 %	-1 %	-0.2 %	0 %	5 %
OECD	-33 %	-20 %	-18 %	-14 %	-9 %	-13 %	-5 %	-3 %	-0.4 %	2 %	-4 %	-0.8 %	0 %	0.1 %	3 %
Asia	-71 %	-34 %	-27 %	-18 %	7 %	-39 %	-17 %	-10 %	-4 %	0.1 %	-11 %	-1 %	0 %	0 %	10 %
Middle East and Africa	-15 %	-11 %	-4 %	-2 %	8 %	-15 %	-2 %	-1 %	-0.6 %	9%	-3 %	-0.2 %	0 %	0 %	4 %
Reforming economies	-26 %	-14 %	-5 %	-3 %	17 %	-38 %	-3 %	-0.7 %	0 %	4 %	-7 %	-0.8 %	0 %	0 %	4 %
Latin America	-10 %	-4 %	-2 %	-0.6 %	8 %	-9 %	-3 %	-0.8 %	-0.1 %	1 %	-2 %	-0.1 %	0 %	0 %	2 %
Gas															
World	-23 %	-5 %	2 %	4 %	20 %	-14 %	-8 %	-5 %	-1 %	12 %	-9 %	-3 %	-1 %	0.5 %	5 %
OECD	-18 %	-5 %	-1 %	4 %	26 %	-20 %	-11 %	-7 %	-3 %	10 %	-11 %	-5 %	-2 %	0.7 %	8.2 %
Asia	-8 %	1 %	6 %	11 %	22 %	-16 %	-7 %	-2 %	-0.5 %	11 %	-12 %	-5 %	-2 %	-0.2 %	3 %
Middle East and Africa	-56 %	-18 %	-3 %	15 %	39 %	-40 %	-14 %	-4 %	3 %	31 %	-16 %	-1 %	2 %	7 %	16 %
Reforming economies	-43 %	-25 %	-11 %	-2 %	23 %	-47 %	-17 %	-6 %	-2 %	13 %	-21 %	-10 %	-3 %	0 %	9 %
Latin America	-28 %	-9 %	-3 %	2 %	22 %	-40 %	-6 %	-4 %	-2 %	14 %	-6 %	-2 %	-0.9 %	0 %	8 %
Oil															
World	-9 %	-1 %	-0.6 %	0.1 %	2 %	-5 %	-1 %	-0.3 %	-0.2 %	1 %	-2 %	-0.4 %	-0.1 %	0 %	2 %
OECD	-3 %	-1 %	-0.8 %	-0.2 %	4 %	-5 %	-0.3 %	-0.2 %	-0.1 %	1 %	-2 %	-0.1 %	0 %	0 %	1 %
Asia	-2 %	-0.5 %	-0.3 %	0.8 %	2 %	-2 %	-1 %	-0.2 %	-0.1 %	2 %	-2 %	-0.2 %	0 %	0 %	1 %
Middle East and Africa	-98 %	-8 %	-3 %	-2 %	8 %	-16 %	-3 %	-0.8 %	-0.4 %	1 %	-13 %	-0.5 %	-0.1 %	0 %	4 %
Reforming economies	-5 %	-2 %	-0.1 %	0 %	0.6 %	-3 %	-0.4 %	-0.2 %	-0.1 %	0.6 %	-2 %	0 %	0 %	0 %	0.3 %
Latin America	-11 %	-2 %	-2 %	-0.2 %	3 %	-7 %	-2 %	-0.4 %	-0.4 %	0.1 %	-2 %	-0.3 %	0 %	0 %	2 %

Table S8. Summary feasibility scores for 1.5°C-compatible scenarios.

Summary feasibility scores are determined for each fuel/region combination in each scenario by choosing the least feasible score among three decades (2020-30, 2030-40, and 2040-50); the period to which the score applies is shown in the table (if there are several such periods, only the first one is shown). This table includes only selected region/fuel combinations with the largest median decline rate (see Data S1 for all region/period combinations). The overall feasibility score for a given scenario is determined by choosing the least feasible score across all fuel/period/region combinations. No overall score is determined for POLES EMF33 scenarios since they do not include critical regions (Asia and OECD). Zone A – multiple historical precedents; B – rate precedents; C – no precedents; D – crisis-driven decline. NA – no data for the region in the scenario. Blank cell – fossil fuel decline rate slower than 5% per decade; in comparing different scores, it is considered the most feasible. In comparing different scores, zone D is considered less feasible than zones A and B, but more feasible than zone C. See Experimental Procedures and Figure S8 for more details. Source of scenario data: [4].

Model	Scenario	Overshoot	Coal/Asia	Coal/OECD	Gas/MAF	Gas/REF	Overall
AIM/CGE 2.0	ADVANCE_2020_1.5C-2100	No or low	C (20-30)	B (20-30)	C (30-40)	B (30-40)	C
AIM/CGE 2.0	SSP1-19	No or low	C (20-30)	B (20-30)	B (30-40)	B (20-30)	C
AIM/CGE 2.0	SSP2-19	No or low	C (20-30)	B (20-30)	A (20-30)	B (20-30)	C
AIM/CGE 2.1	CD-LINKS_NPi2020_400	No or low	C (20-30)	B (20-30)			C
AIM/CGE 2.1	EMF33_WB2C_cost100	High	C (20-30)	B (20-30)		B (30-40)	C
AIM/CGE 2.1	TERL_15D_LowCarbonTransportPolicy	No or low	C (20-30)	B (20-30)	A (20-30)	B (20-30)	C
AIM/CGE 2.1	TERL_15D_NoTransportPolicy	No or low	C (20-30)	B (20-30)	C (30-40)	B (20-30)	C
GCAM 4.2	SSP1-19	No or low	B (30-40)	A (20-30)		A (40-50)	B
GCAM 4.2	SSP2-19	High	B (30-40)	A (20-30)		A (30-40)	B
GCAM 4.2	SSP5-19	High		B (20-30)		A (30-40)	B
IMAGE 3.0.1	ADVANCE_2020_1.5C-2100	High	B (30-40)	A (20-30)	A (20-30)	A (20-30)	B
IMAGE 3.0.1	CD-LINKS_NPi2020_400	High	B (30-40)	B (20-30)	A (20-30)	A (20-30)	B
IMAGE 3.0.1	IMA15-AGInt	No or low	B (30-40)	A (20-30)		A (40-50)	B
IMAGE 3.0.1	IMA15-Def	No or low	B (30-40)	A (20-30)		A (40-50)	B
IMAGE 3.0.1	IMA15-Eff	No or low	B (30-40)	B (20-30)	A (30-40)	A (20-30)	B
IMAGE 3.0.1	IMA15-LiStCh	No or low	B (30-40)	A (20-30)		A (40-50)	B
IMAGE 3.0.1	IMA15-LoNCO2	High	B (30-40)	A (20-30)		A (40-50)	B
IMAGE 3.0.1	IMA15-Pop	No or low	B (30-40)	A (20-30)		A (40-50)	B
IMAGE 3.0.1	IMA15-RenElec	High	B (20-30)	B (20-30)		A (40-50)	B
IMAGE 3.0.1	IMA15-TOT	No or low	B (20-30)	A (20-30)		A (20-30)	B
IMAGE 3.0.1	SSP1-19	No or low	B (20-30)	D (20-30)		B (40-50)	D
MERGE-ETL 6.0	DAC15_50	No or low	C (20-30)	B (20-30)	C (30-40)	B (20-30)	C
MESSAGE-GLOBIOM 1.0	ADVANCE_2020_1.5C-2100	No or low	C (20-30)	A (20-30)		C (20-30)	C
MESSAGE-GLOBIOM 1.0	ADVANCE_2030_Price1.5C	High	C (30-40)	A (20-30)	B (30-40)	C (30-40)	C
MESSAGE-GLOBIOM 1.0	EMF33_1.5C_cost100	No or low	C (20-30)	B (20-30)		C (20-30)	C
MESSAGE-GLOBIOM 1.0	EMF33_1.5C_full	No or low	C (20-30)	B (20-30)		C (20-30)	C
MESSAGE-GLOBIOM 1.0	EMF33_WB2C_cost100	High	B (20-30)	B (20-30)		A (40-50)	B
MESSAGE-GLOBIOM 1.0	EMF33_WB2C_full	High	B (20-30)	A (20-30)		A (40-50)	B
MESSAGE-GLOBIOM 1.0	EMF33_WB2C_limbio	High	C (20-30)	B (20-30)		A (40-50)	C
MESSAGE-GLOBIOM 1.0	EMF33_WB2C_nofuel	High	B (20-30)	B (20-30)			B
MESSAGE-GLOBIOM 1.0	SSP1-19	No or low	C (20-30)	B (20-30)			C

Model	Scenario	Overshoot	Coal/Asia	Coal/OECD	Gas/MAF	Gas/REF	Overall
MESSAGE-GLOBIOM 1.0	SSP2-19	No or low	C (20-30)	B (20-30)		B (30-40)	C
MESSAGEix-GLOBIOM 1.0	CD-LINKS_NPi2020_400	High	B (20-30)	A (20-30)		A (40-50)	B
POLES ADVANCE	ADVANCE_2020_1.5C-2100	No or low	C (20-30)	A (20-30)	A (30-40)	A (30-40)	C
POLES ADVANCE	ADVANCE_2020_WB2C	High	B (20-30)	A (20-30)		A (30-40)	B
POLES ADVANCE	ADVANCE_2030_1.5C-2100	High	C (30-40)	A (30-40)	B (30-40)	D (30-40)	C
POLES ADVANCE	ADVANCE_2030_Price1.5C	High	C (30-40)	A (30-40)	B (30-40)	D (30-40)	C
POLES ADVANCE	ADVANCE_2030_WB2C	High	B (30-40)	A (20-30)	A (30-40)	A (30-40)	B
POLES EMF33	EMF33_1.5C_cost100	No or low	NA	NA	B (20-30)	B (20-30)	NA
POLES EMF33	EMF33_1.5C_full	No or low	NA	NA	A (20-30)	B (20-30)	NA
POLES EMF33	EMF33_1.5C_limbio	No or low	NA	NA	C (20-30)	C (20-30)	NA
POLES EMF33	EMF33_1.5C_nofuel	No or low	NA	NA	B (20-30)	C (20-30)	NA
POLES EMF33	EMF33_WB2C_cost100	No or low	NA	NA		A (20-30)	NA
POLES EMF33	EMF33_WB2C_full	No or low	NA	NA		A (20-30)	NA
POLES EMF33	EMF33_WB2C_limbio	No or low	NA	NA	A (20-30)	A (20-30)	NA
POLES EMF33	EMF33_WB2C_nobeccs	No or low	NA	NA	A (20-30)	B (20-30)	NA
POLES EMF33	EMF33_WB2C_nofuel	No or low	NA	NA		A (20-30)	NA
POLES EMF33	EMF33_WB2C_none	No or low	NA	NA	A (20-30)	B (20-30)	NA
REMIND 1.7	ADVANCE_2020_1.5C-2100	High	C (20-30)	B (20-30)	C (30-40)	C (20-30)	C
REMIND 1.7	ADVANCE_2030_1.5C-2100	High	B (30-40)	B (20-30)	C (40-50)	C (30-40)	C
REMIND 1.7	ADVANCE_2030_Price1.5C	High	B (30-40)	B (20-30)	C (40-50)	C (30-40)	C
REMIND 1.7	CEMICS-1.5-CDR12	No or low	B (20-30)	B (20-30)	C (20-30)	C (20-30)	C
REMIND 1.7	CEMICS-1.5-CDR20	High	B (20-30)	B (20-30)	C (30-40)	B (20-30)	C
REMIND 1.7	CEMICS-1.5-CDR8	No or low	C (20-30)	B (20-30)	C (20-30)	C (20-30)	C
REMIND-MAgPIE 1.5	SSP1-19	High	B (20-30)	A (20-30)	C (30-40)	B (30-40)	C
REMIND-MAgPIE 1.5	SSP2-19	High	B (20-30)	A (20-30)	C (30-40)	B (30-40)	C
REMIND-MAgPIE 1.5	SSP5-19	High	B (20-30)	A (20-30)	B (30-40)	B (40-50)	B
REMIND-MAgPIE 1.7-3.0	CD-LINKS_NPi2020_400	High	B (20-30)	A (20-30)	C (30-40)	B (20-30)	C
REMIND-MAgPIE 1.7-3.0	EMF33_1.5C_cost100	High	C (20-30)	B (20-30)	B (30-40)	D (20-30)	C
REMIND-MAgPIE 1.7-3.0	EMF33_1.5C_full	High	C (20-30)	B (20-30)	B (30-40)	B (30-40)	C
REMIND-MAgPIE 1.7-3.0	EMF33_1.5C_nofuel	High	C (20-30)	B (20-30)	C (30-40)	D (20-30)	C
REMIND-MAgPIE 1.7-3.0	PEP_1p5C_full_eff	High	C (20-30)	A (20-30)	C (30-40)	B (20-30)	C
REMIND-MAgPIE 1.7-3.0	PEP_1p5C_full_goodpractice	High	B (30-40)	A (20-30)	C (40-50)	B (30-40)	C
REMIND-MAgPIE 1.7-3.0	PEP_1p5C_full_NDC	High	B (30-40)	A (20-30)	C (40-50)	C (30-40)	C
REMIND-MAgPIE 1.7-3.0	PEP_1p5C_full_netzero	High	B (20-30)	A (20-30)	B (30-40)	B (30-40)	B
REMIND-MAgPIE 1.7-3.0	PEP_1p5C_red_eff	No or low	B (20-30)	A (20-30)	C (20-30)	C (20-30)	C
REMIND-MAgPIE 1.7-3.0	SMP_1p5C_Def	No or low	C (20-30)	A (20-30)	B (20-30)	B (20-30)	C
REMIND-MAgPIE 1.7-3.0	SMP_1p5C_early	No or low	B (20-30)	A (20-30)	C (20-30)	C (20-30)	C
REMIND-MAgPIE 1.7-3.0	SMP_1p5C_lifesty	No or low	C (20-30)	B (20-30)	B (20-30)	B (30-40)	C
REMIND-MAgPIE 1.7-3.0	SMP_1p5C_regul	No or low	C (20-30)	A (20-30)	C (20-30)	C (20-30)	C
REMIND-MAgPIE 1.7-3.0	SMP_1p5C_Sust	No or low	B (20-30)	A (20-30)	C (20-30)	C (20-30)	C
REMIND-MAgPIE 1.7-3.0	SMP_2C_lifesty	High	B (20-30)	A (20-30)	B (30-40)	B (30-40)	B

Model	Scenario	Overshoot	Coal/Asia	Coal/OECD	Gas/MAF	Gas/REF	Overall
REMIND-MAgPIE 1.7-3.0	SMP_2C_regul	High	B (20-30)	B (20-30)	B (30-40)	B (30-40)	B
REMIND-MAgPIE 1.7-3.0	SMP_2C_Sust	No or low	C (20-30)	B (20-30)	B (20-30)	B (30-40)	C
WITCH-GLOBIOM 3.1	SSP1-19	No or low	C (20-30)	B (20-30)	C (20-30)	B (20-30)	C
WITCH-GLOBIOM 3.1	SSP4-19	No or low	C (20-30)	B (20-30)	C (20-30)	B (20-30)	C
WITCH-GLOBIOM 4.2	ADVANCE_2020_1.5C-2100	No or low	C (20-30)	A (20-30)		B (20-30)	C
WITCH-GLOBIOM 4.4	CD-LINKS_NPi2020_1000	No or low	C (20-30)	C (20-30)	A (20-30)	A (20-30)	C
WITCH-GLOBIOM 4.4	CD-LINKS_NPi2020_400	No or low	C (20-30)	C (20-30)	A (20-30)	B (20-30)	C

Table S9. Characteristics of regional gas-powered fleets.

The table summarizes data for 105 countries with the largest electricity systems (Table S1) according to their regions. See Experimental Procedures for the procedure of calculating average plant age. Data as of 2017, source: [5].

Region	Total installed capacity, GW	Installed gas-fired capacity, GW	Gas-fired capacity in the pipeline (planned and in construction), GW	Average age of gas-fired plants, weighted by capacity, years	Share of gas in total installed capacity	Ratio of pipeline to installed capacity (gas-fired plants)
ASIA	2065	150	112	13	7 %	74 %
LAM	403	73	35	17	18 %	47 %
MAF	514	244	134	14	48 %	55 %
OECD	2507	601	169	20	24 %	28 %
REF	390	152	21	32	39 %	14 %

Supplemental notes

Note S1. Comparing the distribution of decline rates in smaller and larger electricity systems.

The relationship between system size and decline rate is not because there are more observations of smaller systems and thus a greater likelihood of observing outlier cases of rapid decline but rather an inherent characteristic of smaller and larger systems. For example, in systems smaller than 100 TWh/year the frequency of decline episodes with rates exceeding 20% is twice as high, exceeding 25% – three times higher, and exceeding 30% – six times higher than in systems larger than 100 TWh/year (Table S5). A similar difference is observed comparing the systems under and above 200 TWh/year and 300 TWh/year. Using non-parametric Anderson–Darling test[6] (Experimental Procedures), we also determine that it is highly statistically improbable (p-values between 0.02-0.05) that these larger and smaller systems have the same underlying distributions of probabilities of decline (Table S5, Experimental Procedures). Finally, we find that the lower occurrence of faster decline rates for the systems larger than 100 TWh/year are unlikely due to chance (p-values 0.01-0.03), though for systems larger than 200 TWh/year and 300 TWh/year, the evidence is weaker (p-values generally around 0.1) possibly due to a smaller subsample of larger systems (Table S5, Experimental Procedures).

Supplemental References

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