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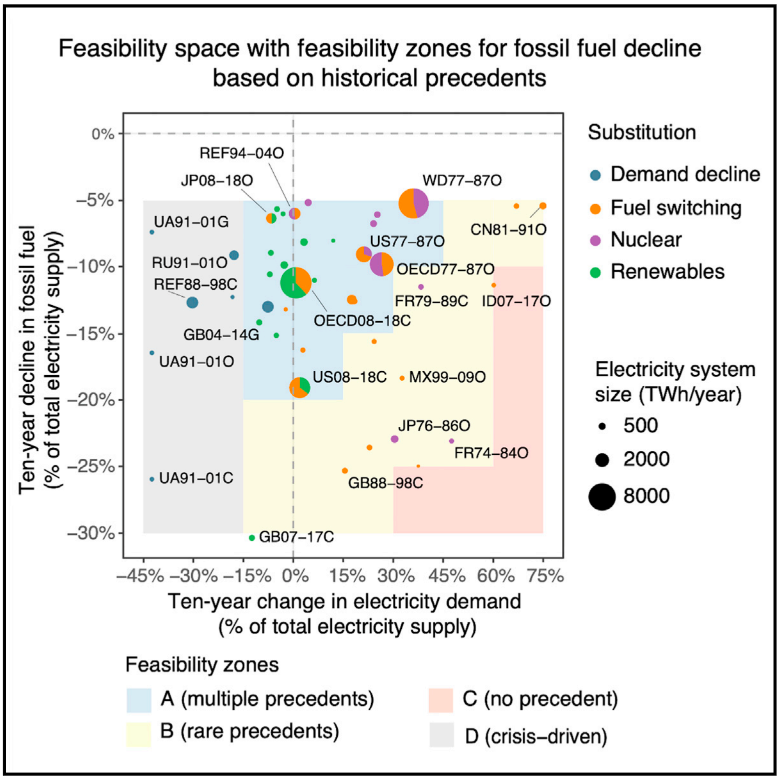
Historical precedents and feasibility of rapid coal and gas decline required for the 1.5°C target

Graphical abstract



Highlights

- We identify 43 notable cases of decline of fossil fuels use in electricity
- Faster decline occurs in smaller countries and with lower electricity demand growth
- Feasibility space is proposed as a new tool to map future scenarios onto precedents
- Decline of coal in Asia required for the 1.5°C target is historically unprecedented

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In brief

Reaching the 1.5°C target requires rapidly phasing out fossil fuels. We investigate whether such decline is feasible by analyzing its historical precedents. Historically, the fastest decline occurred in smaller electricity markets, under lower electricity demand growth, and in response to energy security concerns. There are no or rare historical precedents for the required coal decline in Asia (most scenarios) and OECD (one-half of scenarios), as well as gas decline in the Reforming Economies and Middle East and Africa (one-third to one-half of scenarios).

Vinichenko et al., 2021, One Earth *4*, 1477–1490
October 22, 2021
https://doi.org/10.1016/j.oneear.2021.09.012

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

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https://doi.org/10.1016/j.oneear.2021.09.012

SCIENCE FOR SOCIETY A major challenge in combatting climate change is stopping the use of fossil fuels such as coal in electricity generation. This is particularly challenging in Asia—the largest global region with rapidly growing electricity demand—where coal is widely used. Fast transitions to low-carbon power sources are needed, yet it is unclear whether historical precedents for such transitions exist. The most similar shifts away from fossil fuels occurred in the 1970s and 1980s, when rapidly growing Western countries replaced oil with nuclear power and coal. Other cases of rapid decline in large countries involved switching one fossil fuel to another or in post-socialist countries following the collapse of the Soviet Union. More recently, the Organisation for Economic Co-operation and Development (OECD) countries have been successfully replacing coal with renewables, but electricity demand growth is lower in these countries, and fossil fuel power plants are generally older. The findings from the study indicate that an unprecedented effort will be required to decarbonize Asia's energy sector and meet climate targets.

SUMMARY

To limit global warming to 1.5°C, fossil fuel use must rapidly decline, but historical precedents for such large-scale transitions are lacking. Here we identify 147 historical episodes and policy pledges of fossil fuel decline in 105 countries and global regions between 1960 and 2018. We analyze 43 cases in larger systems most relevant to climate scenarios. One-half of 1.5°C-compatible scenarios envision coal decline in Asia faster than in any of these cases. The remaining scenarios as well as many scenarios for coal and gas decline in other regions have precedents only where oil was replaced by coal, gas, or nuclear power in response to energy security threats. Achieving the 1.5°C target will be difficult in the absence of fossil fuel decline mechanisms that extend far beyond historical experience or current pledges.

INTRODUCTION

Mitigating dangerous climate change requires massive and rapid shifts in the global energy system. The nature, scale, and speed of the required changes are depicted in climate-energy-economy scenarios called climate mitigation pathways and systematically assembled by the Intergovernmental Panel on Climate Change (IPCC) for its reports.[3–6] The IPCC climate mitigation pathways inspire and inform multiple sectoral, regional, and national roadmaps and scenarios such as the International Energy Agency (IEA) Net Zero by 2050 Roadmap for the Energy Sector,[7] the European Union (EU) 2050 long-term strategy,[8] and China's vision for net zero emissions by 2060.[9] It thus becomes increasingly important to understand to which extent these strategies are feasible. To answer this question, a growing body of literature[10–13] assesses whether new low-carbon technologies and infrastructure can expand fast enough.[12–18] At the same time, the feasibility of a sufficiently rapid decline of carbon-intensive

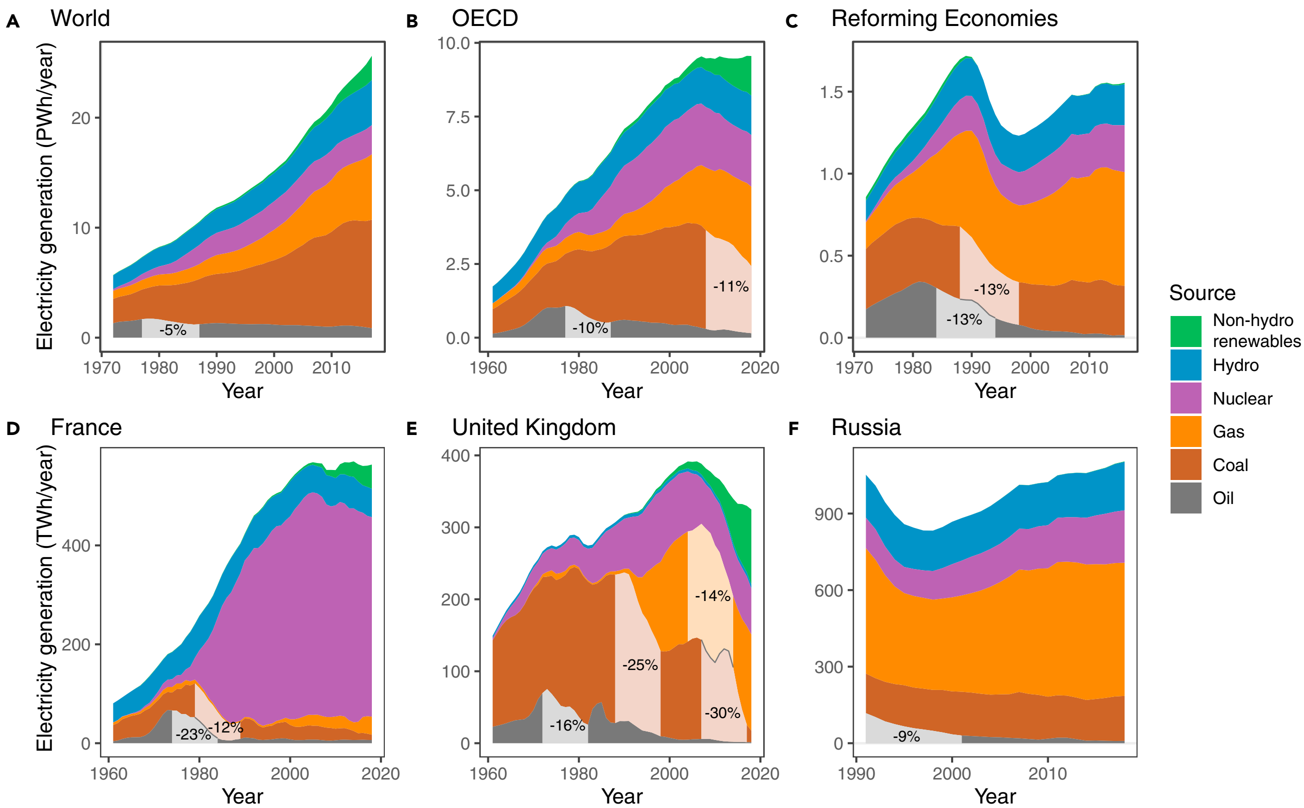

Figure 1. Illustrative episodes of decadal fossil fuel decline in electricity in the world, large regions, and countries

In each case, the declining episodes are highlighted in white with the 10-year decline rate (normalized to the size of the electricity system; see experimental procedures).

(A, B, D, and E) These panels illustrate oil decline episodes following the oil crises combined with rising electricity demand and the growth of nuclear, gas, and coal; (B) and (E) illustrate the recent decline in coal in the OECD and United Kingdom in the face of stagnant and falling demand replaced by growing renewables, and (E) also illustrates the decline of coal in the UK in the 1990s as a result of natural gas exploration in the North Sea. (C) and (F) illustrate decline episodes associated with the post-Soviet crisis and declining demand. Non-hydro renewables primarily include solar and wind power but also biomass.

technologies has not been assessed in the same systematic way. However, the effectiveness of climate mitigation directly depends on the rate of emission reductions, reflecting not the *expansion* of low-carbon technologies, but the *decline* of carbon-intensive ones.

Due to constantly rising energy demand, historically, new energy sources and technologies have often added to, rather than replaced, old ones,[19,20] even when alternatives were available (as illustrated in the case of the global electricity mix in Figure 1). Even as natural gas and nuclear became available, the use of coal continued to rise through the late twentieth and early twenty-first century. However, this global rise has masked decline in individual countries, where certain fuels or technologies were displaced by others that offered cheaper, better, or more desirable energy services[20] (Figure 1). For example, many countries eliminated oil in electricity production following the 1970s oil embargoes.[21,22] More recently, a group of countries (dominated by wealthier economies with older coal power fleets)[23] committed to phase out the use of unabated coal in power production.[24] Decline of fossil fuels in individual countries has often been a protracted process. For example, the decline of coal in the UK has taken more than half a century,[25] and coal phase-out in Germany, initiated in the 1980s,[26] is still likely to take decades.[23] This is because the flip side of the energy transition,[25] or exnovation,[27] presents a distinct challenge that can lead to stranded fossil fuel resources[28–30] and infrastructures[13,31–35] and resistance from affected workers and communities.[36–39]

In comparison, the IPCC 1.5°C-compatible pathways indicate that meeting climate targets requires rapid phase-out of fossil fuels (Figure S1), including shortening lifetimes of fossil electricity infrastructure to historically unprecedented levels.[35,40] Fossil fuels have to be phased out up to 50% faster if the deployment of carbon capture and storage (CCS) and negative emission technologies—a controversial component of most climate mitigation scenarios—is limited.[41]

In this paper, we ask whether there are historical precedents of fossil fuel decline envisioned in the IPCC 1.5°C-compatible scenarios. We find that many of these scenarios depict fossil fuel decline rates that are either unprecedented or only have precedents in historical responses to energy security threats, when oil was substituted by coal or nuclear power in energy systems much smaller than scenario macro-regions. This relates to coal decline in Asia in all scenarios (except one), coal decline in the Organisation for Economic Co-operation and Development (OECD) countries in more than one-half of scenarios, as well as

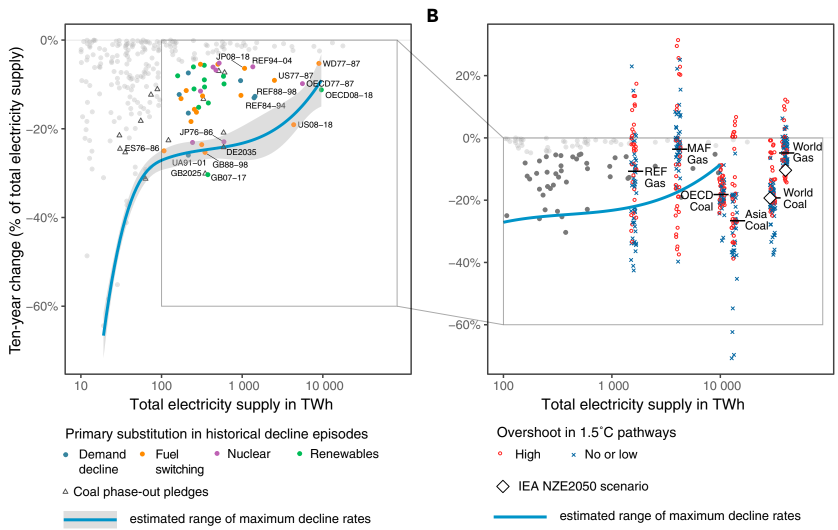

Figure 2. Historical decadal decline episodes as a function of system size and compared with required coal and gas decline rates in 1.5°C-compatible scenarios

(A) Historical decline episodes with the color indicating the primary type of substitution for episodes with faster decline rates (over 5%) in larger systems (>100 TWh) and national coal phase-out pledges depicted with triangles. The line estimates the historical relationship between the maximum observed decline rates and the size of the energy system (see experimental procedures). See Table S6 for country codes.

(B) The regions, fuels, and time periods with the highest decline rates in 1.5°C-compatible scenarios[5] (2020–2030 for natural gas in REF and coal in OECD, Asia, and the world; 2030–2040 for natural gas in MAF and the world). Colored dots show decadal change rates in individual pathways, with red circles depicting high overshoot, blue crosses (x) depicting low overshoot, and the median shown with a horizontal line. White diamonds show global decline rates for the IEA's NZE 2050 scenario. We show both negative and positive changes since the latter affect the median and IQR values for scenarios. Decline ranges for all regions and fuels are shown in Figure S5. Median electricity system size is used for each fuel/region combination.

gas decline in the Reforming Economies (REF), and also Middle East and Africa in one-third to one-half of scenarios. This signals both an enormous challenge of seeing through such rapid decline of fossil fuels and the need to learn from historical lessons when rapid declines were achieved on the national scale.

RESULTS

Method summary

To analyze the feasibility of decline of fossil fuels, we compare historical precedents of coal, oil, and natural gas decline in electricity production to the decline of these fuels needed to reach the 1.5°C climate target as envisioned in the IPCC 1.5°C-compatible pathways[5,2] as well as in the IEA Net-Zero Emissions by 2050 (NZE) scenario.[7] We focus on fossil fuel use in electricity since this sector is the first to decarbonize in cost-effective mitigation scenarios[3,42]. We also focus on the near term (2020–2050) when decline rates are the highest and most unabated fossil fuel use in electricity is phased out (Figure S1). Historically, we identify decadal episodes of decline between 1960 and 2018 using a sample of 105 countries (Table S1), as well as five major world regions (Table S2), and globally. We also consider recent national pledges to phase out coal.[23]

To compare these historical precedents with climate mitigation scenarios, we consider both the rate and the context of decline. We normalize the rate of decline to the overall size of the electricity system (total electricity supply) (experimental procedures). We control for three high-level contextual characteristics: the overall size of the electricity sector, the growth in electricity demand, and how the declining fossil fuel is substituted.

To analyze the feasibility of the decline required to meet climate targets, we use feasibility spaces, a conceptual tool designed to relate historical experience to future plans, projections, or scenarios.[43] Since we consider several contextual factors affecting the feasibility of decline, we construct two feasibility spaces: one, auxiliary, focused exclusively on the size of the electricity sector and the other focused on the electricity demand dynamics, which also considers the size of the system and the nature of substitution (experimental procedures).

Historical episodes of fossil fuel decline

No primary energy source has declined globally since the beginning of the industrial revolution.[44] However, we identify 245 decadal decline episodes in fuels used for electricity production in 105 individual countries with electricity production over 10 TWh/year (the level of Uruguay or Costa Rica today; Table S1) and global regions, which occurred between 1960 and 2018. In addition, several countries have recently pledged to phase out unabated coal as part of the Powering Past Coal Alliance[23] (Figure 2). In 147 of these episodes and pledges (further collectively called episodes), the decline in a fossil fuel as a share of total electricity supply was more than 5% over a decade (Figure 2). We focus on these cases because a slower decline does not signal a significant technological shift or policy effort. Rapid decline has been limited to small countries: out of 11 episodes with decline over 30%, 10 took place in countries with electricity production less than 50 TWh/year (as in Denmark between 2007 and 2017) (Table S3). In electricity systems between 100 and 1,000 TWh/year, decline is slower than 25% in almost all episodes, with the exception of 30% coal decline in the UK between 2007 and 2017 (Table S4). In major economies comparable in size with the global regions in scenarios (over 1,000 TWh/year), historical decline has rarely been faster than 10% except for the US, where coal declined 19% between 2008 and 2018. The highest rates observed in country groups such as the OECD (close to 10,000 TWh/year) are even slower, since they aggregate even more uneven changes in the countries comprising these groups (Figure 3). The most notable decline in these mega-systems is the decline of coal in the OECD from 2008 to 2018 (11%). Not surprisingly, worldwide declines of fossil fuels in electricity are rarer still, with the only notable episode when oil fell by 5% of electricity supply globally between 1977 and 1987 (Figure 1). The relationship between the size of the system and the maximum observed rate

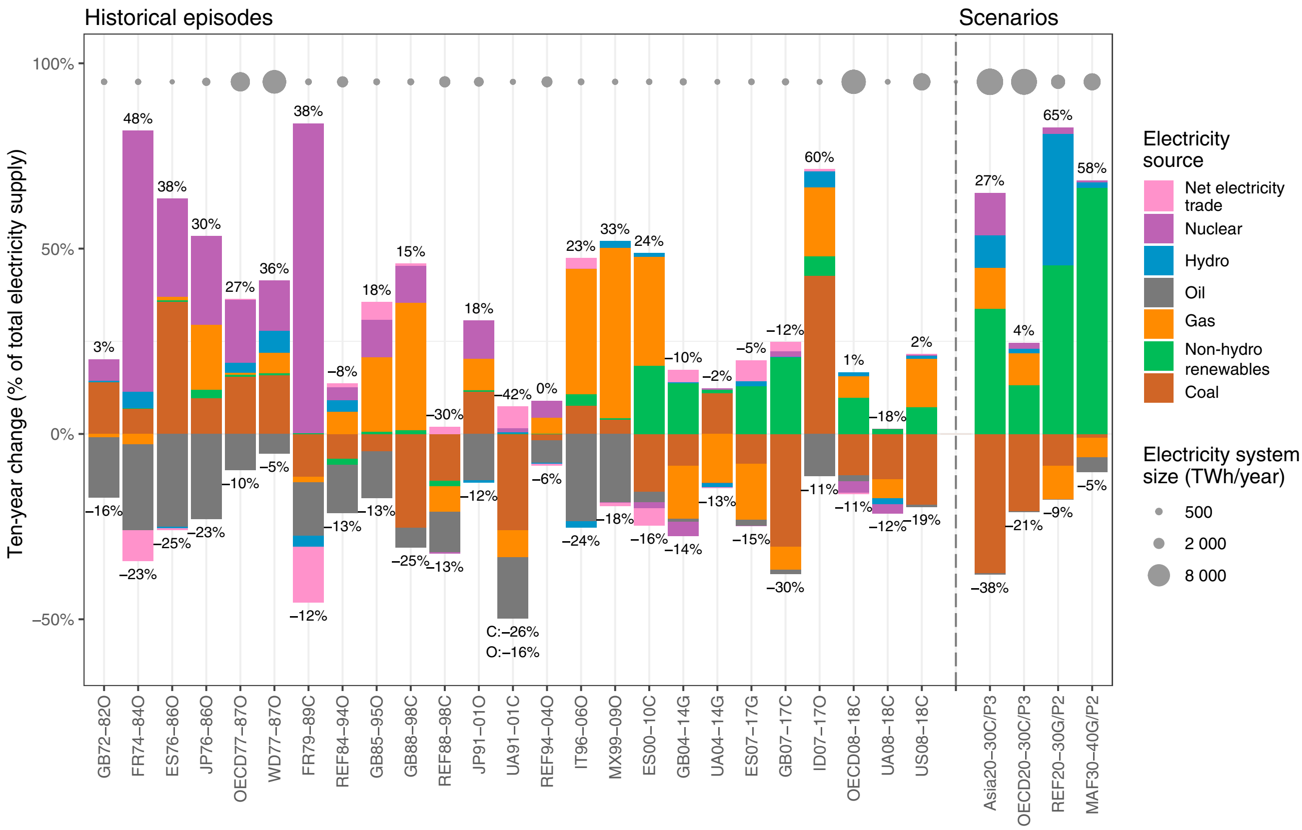

Figure 3. Fuel and technology substitution in the most significant historical decline episodes and selected climate change mitigation scenarios

Bars depict growth (above the horizontal axis) or decline (below the axis) of electricity sources and technologies in a particular period normalized to the total electricity supply averaged between the start and the end of the period (experimental procedures). Numbers at the bottom of the bars indicate the normalized decline rate in the fossil fuel defining the episode and numbers at the top of the bars indicate the normalized change in total electricity demand over the period. The circle above each bar shows the average electricity system size during the episode. Episodes are coded with their country code, period, and declining fuel: e.g., FR74–84O is France, 1974–1984, oil decline (see Table S6 for country codes). The figure shows the 25 fastest historical decline episodes in larger systems (total electricity supply >100 TWh/year); other significant historical episodes in larger systems are shown in Figure S6. Scenario bars show changes in selected regions and time periods for illustrative pathways P3 and P2. See Figure S7 for more scenarios and regions.

of decline holds for both individual countries, geographic macro-regions (such as Asia), and country groups (such as the OECD) (Figure S2). Rapid decline is less likely to occur in large electricity systems, which include a greater diversity of power plants, geographic regions, and socio-political interests. It is less likely for the drivers of decline (technology development, supply-demand dynamics, resource depletion, and regulations) to concurrently affect all elements of such heterogeneous systems. The rates of decline envisioned in the Powering Past Coal Alliance (PPCA) pledges are not out of the historically observed ranges for countries of similar sizes.

These observations allow us to estimate a historically probable frontier for fossil fuel decline rates based on the size of the electricity system (Figure 2). More cases of rapid decline in smaller systems are likely the result of their greater homogeneity and are not simply a statistical artifact resulting from more observations of such systems (experimental procedures; Note S1; Table S5). The relationship between the system size and maximum decline rate also holds if aggregated regions are excluded (Figure S3). These results are robust to adjusting for rebound, or an increase in the use of fossil fuels following their decline (Figure S4, experimental procedures).

To identify historical precedents relevant for comparison with climate mitigation scenarios, we select all episodes of decline at or faster than 5% per decade among countries with electricity production exceeding 100 TWh/year at the start of the episode (N = 37; Figure 3; Table S4). We do not consider decline in systems smaller than 100 TWh/year (approximately the size of Norway or the Netherlands in 2019) because they are more than 15 times smaller than the smallest global region in the climate mitigation scenarios and, given the clear relationship between the size of the system and the maximum decline rate (Figure 2), we consider them less informative for assessing the feasibility of decline needed for climate mitigation. To enable direct comparison with scenarios, we also analyze decline episodes at or faster than 5% globally and in the same five global regions that are analyzed in scenarios: Asia, OECD, Latin America (LAM), Reforming Economies (REF), and the Middle East and Africa (MAF). Overall, we analyze 37 national, five regional, and one global episode of decline (Figures 2 and 3; Table S4).

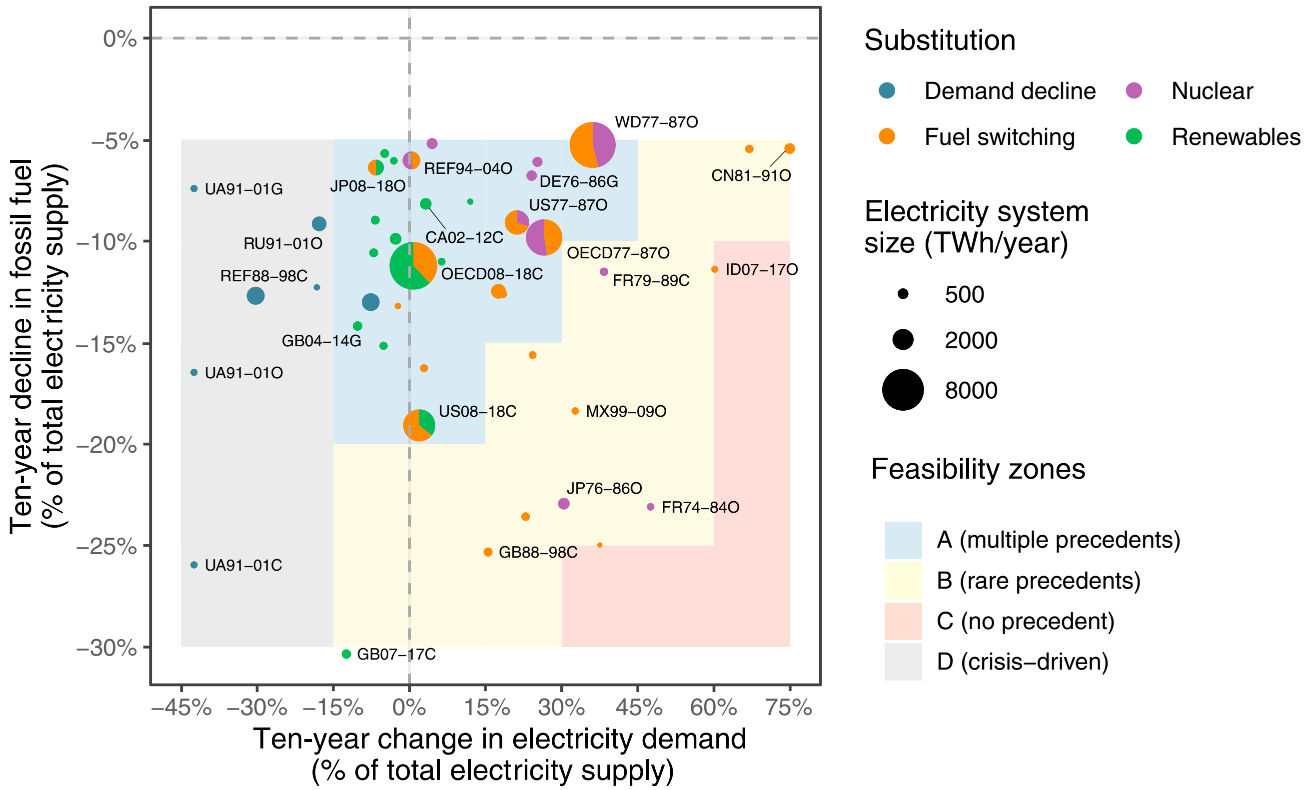

Figure 4. Feasibility space with feasibility zones for fossil fuel decline based on historical precedents of decline under different demand change in different system sizes

Historical episodes with 10-year decline rates faster than 5% in larger systems (>100 TWh/year) define the feasibility zones. For each episode, the total electricity system size (mean of beginning and end of the episode) is indicated by the area of the circle, and the primary substitution by color (for larger systems we also indicate the secondary substitution); see Table S4. Episodes are coded with their country code, period, and declining fuel. Zones A and B are defined by the density of historical precedents, zone C contains no historical precedents in larger systems, and zone D contains only decline episodes in post-Soviet countries following the collapse of the USSR (experimental procedures, Figure S8).

Decline of fossil fuels in these episodes was the result of fuel switching, technology substitution, or demand decline (Figures 3 and S6; Table S4; experimental procedures). Fuel switching occurs when the declining fossil fuel is substituted by another fossil fuel such that essentially the same infrastructure can be used, reducing the need for premature plant retirement, which potentially makes decline less challenging. The majority of fuel-switching episodes were triggered by concerns over fuel imports (particularly in the 1970s and 1980s following the oil crises), declining or, on the other hand, newly discovered domestic fuel reserves. The declining fuel in most fuel-switching episodes was oil, which is both a source of the most serious energy security concerns[45] and has ample uses outside of the power sector. In earlier fuel-switching cases, oil was swapped for coal: this included the global swap of oil for coal in 1977–1987. In later fuel-switching episodes, oil and coal were primarily substituted by natural gas, such as in the US following the shale gas revolution of the last decade (Figure 3) or in the UK's North Sea gas exploration, which spurred its coal decline in the 1990s.

The need for new power generation infrastructure can slow down decline, especially if this infrastructure is capital intensive, such as nuclear power plants, wind turbines, or solar panels. Nuclear power played a primary role in replacing oil and coal in France; oil, gas, and coal in Germany; and oil in Japan and the OECD region in the 1970s–1980s and a secondary role in replacing oil in the UK, Spain, and the world in the 1970s–1990s, and coal in the UK in the 1980s–1990s. In all these cases, nuclear power was expanded in response to concerns over security of imported or rapidly depleting domestic fossil fuels. Both fuel switching and nuclear substitution episodes generally occurred in parallel with strong electricity demand growth[46] (Table S4; Figure 4).

In the last two decades, fossil fuels in OECD countries were substituted with solar and wind power, which played a primary role in coal decline in the UK, Australia, Germany, and the OECD, oil in Japan, and gas in Spain and Italy, as well as contributing to coal decline in the US and Spain. Switching to decentralized and variable electricity sources such as modern renewables requires adjustments in the way electricity grids are operated, which may also slow down decline by adding an additional level of complexity. This occurred during increasing concerns over climate change and declining costs of solar and wind power technologies. In contrast to earlier episodes, electricity demand stagnated or declined during these episodes. Demand decline was sufficiently steep to play a primary role in oil and coal decrease only in connection with the dissolution of the Soviet

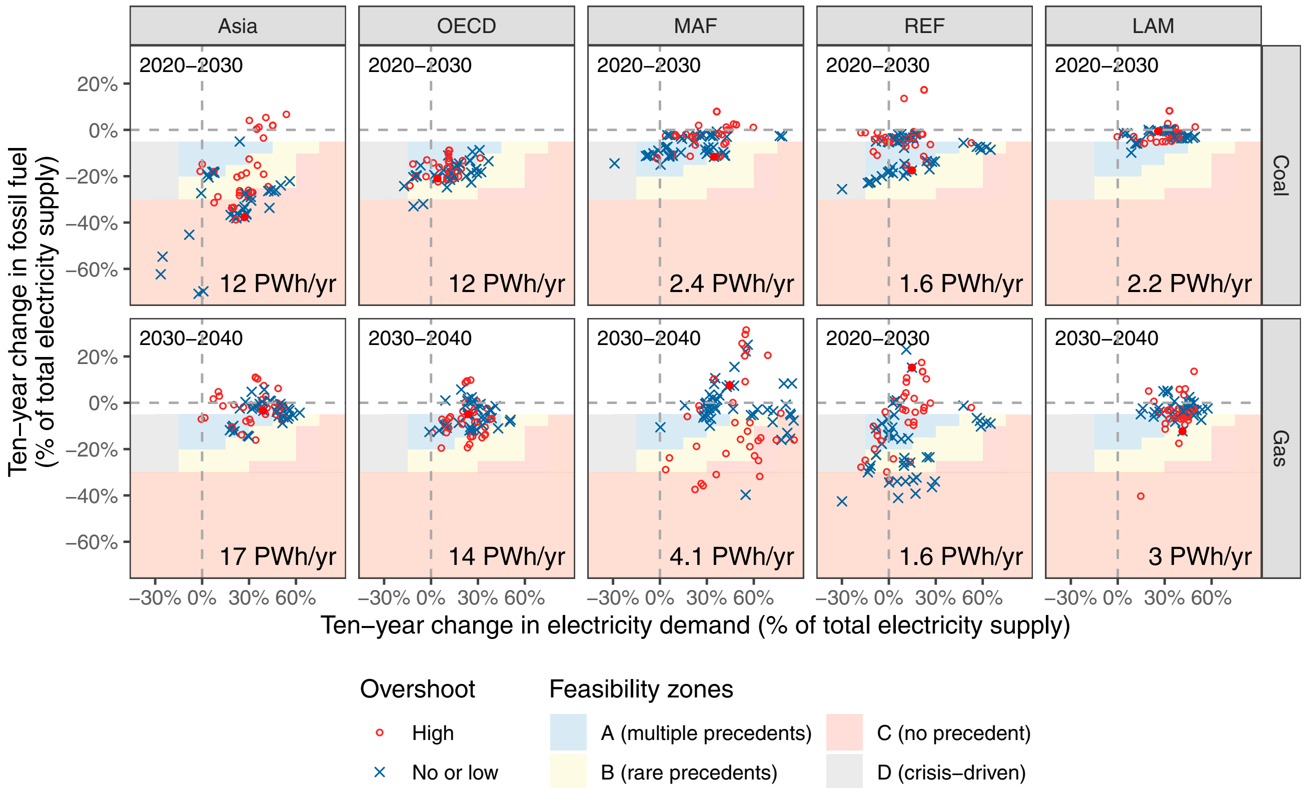

Figure 5. Ten-year decline rates and demand change in scenarios projected on the feasibility space defined by historical episodes

Colored areas represent feasibility zones (experimental procedures, Figure S8). Each point represents changes in fossil fuel and electricity demand in an individual 1.5°C-compatible pathway for the respective fuel, region, and period. Point color and shape depict the pathway status in terms of overshoot.[6] Demand change is calculated using the same method as fossil fuel decline (experimental procedures). For each combination of fuel and region, the period with the largest median decline rate between 2020 and 2050 is presented and marked in the upper left corner. In the bottom right corner, the median system size for the respective region and period is shown. A datapoint for a single pathway is beyond the boundaries of the MAF/coal panel (WITCH-GLOBIOM 4.2/ADVANCE_2020_1.5C-2100 with a decrease in demand more than 40%).

Union, which led to the collapse of many energy-intensive industries[47] and took place when the entire electricity system in the REF region shrank by more than 25% between 1988 and 1998. More recent decline of coal in Ukraine reflected the armed conflict in Donbas, where most coal deposits are concentrated. Demand decline also contributed to the recent decrease of coal and gas in the UK.

Feasibility space for fossil fuel decline

To relate the empirical evidence to the future scenarios, we first construct a historical feasibility space (Figure 4) and then map 1.5°C pathways onto it (Figure 5). Feasibility spaces have been proposed and used to identify combinations of conditions that enable a given climate action in different contexts.[43] Previous studies have used feasibility spaces to establish a dynamic feasibility frontier, which separates conditions in which climate actions are feasible from those where it is not feasible.[23] Here, similar to Cherp et al.,[18] we further develop the feasibility space approach through feasibility zones based on the presence and significance of historical precedents that occurred under specific circumstances of demand growth, electricity system size, and the nature of technologies substituting fossil fuels. Electricity demand growth defines a key dimension of the feasibility space. Faster demand growth makes rapid decline of fossil fuels less likely because it requires more rapid expansion of substituting technologies, including investment, construction of infrastructure, and adjustment of markets and supply chains. When electricity demand is declining because of recessions, economic restructuring, advances in energy efficiency, or lifestyle changes, fossil fuels may also decline with little or no substitution required.

Figure 4 shows a feasibility space of fossil fuel decline based on the historical episodes of decline faster than 5% in systems larger than 100 TWh/year (37 national, five regional, and one global episode; Table S4). We identify four feasibility zones of decline characterized by differing frequency and nature of historical precedents (Figure 4). We define the first two zones (A and B) by using an algorithm that determines, for each combination of decline rate and demand change, the frequency of historical decline episodes with faster decline rates or higher demand growth, weighted by system size (Figure S8; experimental procedures).

- Zone A includes many historical episodes in electricity systems of all sizes and featuring all types of substitution, including by renewables. It covers moderate (slower than

−20%) fossil fuel decline under slow or moderate (slower than 15%) demand growth or up to −15% demand decline as well as slower rates of decline (−5 to −15%) under faster demand growth (15%–45%).

- Zone B includes significantly fewer episodes and only in countries with electricity systems smaller than 600 TWh/year (the largest being Japan in ca. 1980) and involving only fossil fuel switch or substitution by nuclear power, with one exception of coal decline in the UK in 2007–2017, which involved both demand decline and substitution by wind power (Figure 3). Zone B covers the same decline ranges as zone A under higher (up to 60% and 75%) demand growth as well as faster (−20% to −30%) fossil fuel decline.
- Zone C does not include any historical precedents of decadal fossil fuel decline between 1960 and 2018 in systems with electricity supply over 100 TWh/year.
- Finally, zone D covers fossil fuel decline rates up to −30% under demand decline faster than −15%. Historical episodes within zone D include only former Soviet countries where decline of fossil fuels was driven by the economic collapse of the 1990s.

1.5°C-compatible scenarios compared with historical cases of decline

Figure 5 shows the decadal decline rates of coal and gas in the global regions envisioned in the IPCC 1.5°C-compatible scenarios plotted against the electricity demand growth in the same scenarios and mapped onto the feasibility zones presented in Figure 4. Among all fossil fuels, coal would need to decline most rapidly to meet climate targets. Globally, coal is phased out by 2050 in about two-thirds of 1.5°C-compatible scenarios (Figure S1) with worldwide median decline rate of −19% in 2020–2030 (the same rate of coal decline is envisioned in the IEA NZE 2050 roadmap).[7] The median rate of coal decline is similar between scenarios with and without CCS (Figures S1 and S9). The most rapid decline would need to occur in Asia and the OECD regions where most of the coal generation capacity is concentrated (Figures 5 and S10; Table S7; Data S1).

For the purposes of this analysis, we distinguish between high and low overshoot scenarios. High-overshoot scenarios allow more emissions and a higher rise in greenhouse gas concentration, which is subsequently compensated by deploying more negative emission technologies (such as bioenergy with carbon capture and storage [BECCS], massive afforestation, or atmospheric carbon dioxide removal) in the second half of the century. Both high- and low-overshoot scenarios envision similarly fast coal decline in the OECD concentrated in 2020–2030 with a median rate of −18% (inter-quartile range [IQR], −14% to −20%). Historical precedents for fossil fuel decline and demand change envisioned in scenarios can be identified by mapping these rates onto the feasibility space (Figure 4) as illustrated in Figure 5 and summarized in Table S8 and Data S1. Out of 69 scenarios, 35 envision decline rates that are either unprecedented (zone C) or historically only observed in economies with electricity supply at least 20 times smaller than in the OECD region and involving fossil fuel switching or nuclear substitution following the oil crises (zone B). In contrast, in climate mitigation scenarios, coal in the OECD is primarily replaced by renewables (Figure S7). Nevertheless, about half of all scenarios envision decline of coal in the OECD with rates that have multiple precedents and diverse types of substitution (zone A). However, the OECD is larger than most countries and regions where historical decline was observed, so that the closest historical precedent of comparable size is the decline of coal in the OECD from 2008 to 2018 with a decline rate of −11% (Figure 2). This episode involved primary substitution by renewables, but was slower than the decline envisioned in about 90% of scenarios and occurred under 1% demand growth while the median demand growth in scenarios for the OECD from 2020 to 2030 is 12%.

Coal decline in Asia is faster than in the OECD but also encompasses a wider range of rates across the scenarios. In this region, there is earlier and faster decline in low-temperature overshoot scenarios and later and somewhat slower decline in high-temperature overshoot scenarios, which in most cases require more extensive use of negative emission technologies. In most of the low-overshoot scenarios, coal decline is concentrated in 2020–2030, where the median decline rate is −31% (IQR, −37% to −25%). The only low-overshoot scenarios that envision coal decline in Asia in 2020–2030 with more frequent precedents (zone A) feature the introduction of an economy-wide and worldwide carbon tax in 2020 that suppresses demand growth;[48] these scenarios also require faster coal decline in 2030–2040, rarely seen historically (zone B). Thus, two-thirds of low-overshoot scenarios require coal decline in Asia that do not have any historical precedents (zone C), and the remaining one-third requires decline with only rare historical precedents (zone B) (Figure 5; Tables 1 and S8). In high-overshoot scenarios, coal decline in Asia spans 2020–2030 (median decline rate −19%) and 2030–2040 (median decline rate −15%). About one-third (10) of these scenarios envision unprecedented decline rates in one of these periods (zone C) and all but one of the remaining scenarios envision the rates with only rare historical precedents (zone B) (Table 1; Figure 5; Table S8). In summary, all climate mitigation scenarios require coal decline in Asia that is either unprecedented or only has precedents in countries with at least 20 times smaller electricity supply and where fossil fuels were substituted by other fossil fuels or nuclear power. Similarly to the world as a whole, median decline rates of coal in OECD and Asia are almost not affected by the availability of CCS (Figure S9), since most scenarios envision that coal decline would need to occur faster than the CCS technology can be sufficiently widely deployed.

Decline of coal in Asia has one significant precedent in a region of similar size: the recent decline of coal in the OECD (the electricity supply in Asia will be similar to OECD in 2020–2030 and about 40% larger in 2030–2040). The recent decline rate of coal in the OECD (−11%) was almost three times lower than the median rate of decline envisioned in low-overshoot scenarios in Asia (−31%), and about two times lower than in high-overshoot scenarios (−19%). Furthermore, the OECD decline occurred under demand growth of 1%, whereas climate mitigation scenarios envision median decadal demand growth in Asia of 27%. The age of coal power plants at the start of the OECD decline was 31 years,[49] while the average age of power plants in Asia in 2020 is 12 years.[50] Finally, many other economic and socio-political conditions in the OECD can make it difficult to

Table 1. Decline of fossil fuels in scenarios in relation to feasibility zones determined by historical episodes of decline

					Number of scenarios with decline				
Fuel region	Period	Overshoot	Total electricity supply (PWh/year)	Decline (10 year): median (IQR)	No or trivial	Zone A (frequent precedents)	Zone B (rare precedents)	Zone C (no precedents)	Total
Coal OECD	2020–2030	low and high	12	−18% (−20% to −14%)	0	33	33	2	69*
Coal Asia	2020–2030	low	12	−31% (−37% to −25%)	0	6**	6	23	35
Coal Asia	2020–2030	high	12	−19% (−27% to −1%)	10	3	14	7	34
Coal Asia	2030–2040	high	17	−15% (−19% to −10%)	3	5	23	3	34
Gas REF	2020–2030	low	1.6	−16% (−28% to −9%)	7	12	15	11	45
Gas REF	2030–2040	high	1.6	−17% (−21% to −6%)	8	6	14	4	34***
Gas MAF	2020–2030	low	2.4	−8% (−20% to +3%)	20	11	5	9	45
Gas MAF	2030–2040	high	4.1	−14% (−23% to 0%)	13	1	9	11	34

Notes: The table summarizes the average fossil fuel decline rates as well as the number of scenarios in which fossil fuel decline rates fall into different feasibility zones. It covers regions, periods, and scenario types (high or low overshoot) where fossil fuel decline rates in a significant number of scenarios have no or rare historical precedents (see Data S1). (*) The sum also includes one scenario in zone D (crises-driven decline); (**) low-overshoot scenarios with economy and worldwide imposition of carbon tax in 2020[48] that require coal decline in Asia in zone B in 2030–2040; (***) the sum also includes two scenarios in zone D.

replicate/exceed the decline rates observed in 2008–2018 to Asia.

Decline of natural gas in climate mitigation scenarios is not as coordinated and universal as decline of coal because, in some pathways, gas is a "bridge fuel" to a low-carbon future[51] (Figures S1 and S10). Globally, the median rate of gas decline across scenarios is fastest in 2030–2040 (5%; Figure 2). The IEA NZE scenario[7] envisions no gas decline in 2020–2030, but a twice as fast decline (11%) in 2030–2040. At the same time, many scenarios envision more rapid decline of gas in gas-producing regions of MAF and REF (former Soviet Union, Russia being the largest member of this group). Low-overshoot scenarios envision the fastest decline (−16%, IQR −28% to −9%) of gas in REF in 2020–2030 with two-thirds of the pathways having no or rare precedents (zones C or B) in either 2020–2030 or 2030–2040. High-overshoot scenarios envision moderate decline in 2020–2030 followed by faster decline in 2030–2040 (median −17%, IQR −21% to −6%) with close to two-thirds of pathways having no precedents or only rare precedents (including cases of rapid demand decline following the collapse of the USSR). About one-third of scenarios do not envision unprecedented rates of gas decline in the REF region. Among the low-overshoot scenarios whose gas decline rates in REF have many historical precedents (zone A), the majority envision economy-wide and worldwide carbon tax imposed in 2020[48] (Table S8).

Scenarios envision similar patterns of natural gas decline in MAF. In low-overshoot scenarios, gas declines by −14% (−20% to +3%) in 2020–2030, with unprecedented or rarely seen rates in about one-third of scenarios (Table 1). In high-overshoot scenarios, gas grows on average by 15% (−8% to +24%) in 2020–2030 and then declines by −14% in 2030–2040 (−23% to 0%), with unprecedented rates in about one-third of scenarios. Altogether, one-third of scenarios envision unprecedented (zone C) gas decline rates in MAF, and in one-fifth of scenarios rates have rare precedents (zone B) (Tables 1 and S8; Figure 5). In both MAF and REF, the size of electricity systems in 2020–2040 (1.6 PWh/year in REF and 2.4–4.1 PWh/year in MAF) is closer to that of the largest countries such as the US or Japan or historical regions with decline precedents (Figure 2), which enables more direct comparison of scenarios with historical episodes than in the case of Asia and the OECD. In scenarios where CCS is available, decline rates for gas in both regions, especially in MAF, are less ambitious (Figure S9).

Climate mitigation scenarios also envision decline of coal and gas in the remaining regions; however, the rates of decline in most scenarios have multiple historical precedents (Figure 5; Table S8). Finally, the use of oil in electricity production is already limited and thus requires rapid decline in climate mitigation pathways. Oil accounts for 3% of global electricity supply, 43% of which is concentrated in the MAF,[1] which is the only region where moderate decline occurs both in 2020–2030 and 2030–2040 (Figure S10; Table S7).

We conduct a sensitivity analysis, which considers 20- instead of 10-year decline periods (Figure S11). Historical 20-year decline episodes generally have similar or slower decline to 10-year episodes, because many of the 10-year episodes are preceded or followed by growth (Figure 1). In the particular case of the most recent 10-year episodes (such as decline of coal in OECD in 2008–2018), we simply are not able to observe their potential continuation into the future. In contrast, in climate mitigation scenarios, fossil fuels rarely grow, which means that decline is almost always faster when measured over 20 years. In particular, this is true with respect to coal in Asia and gas in REF and MAF (Figure S12). This means that the gap between historical precedents and what is depicted in scenarios is even higher when the decline of fossil fuels is measured over 20 years.

DISCUSSION

This paper contributes to understanding whether and where the feasibility of reducing the use of fossil fuels in electricity poses a challenge to meeting climate targets. Earlier research concluded that limiting temperature overshoot would require faster reductions in CO_2 and fossil fuel use.[41,52] Our analysis identifies whether there have been historical precedents for such decline. We show that, historically, decline of fossil fuels has been slower in larger countries and regions and under strong demand growth. The fastest decline in the past primarily involved substitution of one fossil fuel by another fossil fuel (e.g., the replacement of coal or oil with natural gas) or nuclear power. Many climate change mitigation scenarios envision decline of coal in Asia and OECD and gas in the REF and MAF regions that is notably different from these historical patterns. In interpreting these results it is important to keep in mind the limitations of comparing historical cases with future scenarios. These limitations reflect the obvious fact that the future is always different from the past, including in ways potentially significant for fossil fuel decline, such as the emergence of new technologies, policies, and public attitudes. Furthermore, from our vantage point at present, it is hard or even impossible to foresee some of these developments. This, however, does not mean that comparing the actual past with desirable futures is futile. On the contrary, such comparison helps to better understand the nature and scale of future challenges; i.e., in our case, where future fossil fuel decline should be most different from the past and also which historical episodes provide the most relevant lessons for future decline.

Most importantly, we find that half of the IPCC climate mitigation pathways—including both high and low overshoot—envision coal decline in Asia that does not have any historical precedents, and the other half envision decline that only has precedents in economies with electricity demand at least 20 times smaller and involving fossil fuel switching or substitution of fossil fuels by nuclear power following the oil crises. Such rates will be difficult to achieve in Asia, where the coal power plant fleet is young[35,40] and linked to domestic coal extraction. There were hopes that the coronavirus pandemic (COVID-19) would slow or even reverse the expansion of coal in Asia; however, in 2020, China increased the permitting rate for new coal plants, and in the rest of Asia there has been little change to coal power planning.[53] China has recently announced a halt to overseas coal financing[54] and a net zero target by 2060,[9] but it does not necessarily imply phasing out coal faster than historically observed rates. In a recent analysis of electricity markets, the IEA expects coal power capacity in China to rise until 2025 before eventually plateauing and foresees similar trends in other Asian countries.[55] The difficulties of phasing out coal in Asia are also signaled by Indonesia's recent announcement to use coal well into the 2050s[56] as well as the failure of G20 countries[57] to agree on a rapid coal phase-out in the run-up to COP26.

Beyond Asia, many IPCC climate mitigation pathways envision fossil fuel decline rates with frequent historical precedents; however, coal decline in the OECD and natural gas decline in major gas exporting regions (REF and MAF) have rare or no precedents in a substantial proportion of 1.5°C scenarios.

More than half of 1.5°C scenarios envision coal decline in the OECD that has rare precedents. However, coal power in OECD countries already dropped by a third (corresponding to 11% of the total electricity supply) from 2008 to 2018, and this drop was accelerated during the COVID-19 pandemic in 2020.[58] While this decline rate is only compatible with about 10% of 1.5°C scenarios, more rapid declines in the US from 2008 to 2018 (−19%), the UK from 2007 to 2017 (−30%), and Germany's coal exit pledge (−24%) indicate that faster rates are possible even in larger OECD countries. Given the aging power plant fleets in OECD economies and their track record of transitions away from coal,[23,25,26] it may be possible to scale up these decline rates to the OECD region as a whole, as envisioned in most 1.5°C scenarios.

Finally, many IPCC 1.5°C-compatible scenarios envision gas decline rates that are either unprecedented or have rare precedents in REF (two-thirds of 1.5°C scenarios) and MAF (one-half of 1.5°C scenarios). While many low-overshoot scenarios require unprecedented rates already in 2020–2030, many high-overshoot scenarios envision the initial growth of gas as a bridge fuel followed by fast decline in 2030–2040. Achieving unprecedented rates of gas decline in either REF or MAF seems challenging given both regions' vast natural gas resources and slow progress in deploying modern renewables. An additional problem in MAF may be young power plants due to the recent rapid growth of gas power generation (Figure S13; Table S9).

Historical precedents of fossil fuel decline offer several lessons for addressing these future challenges. The first lesson is that past decline of fossil fuels was driven by technological innovations. Some of the faster decline episodes involving switching from coal to natural gas required not only new resource discoveries but also innovations in extraction (such as offshore, fracking) and transportation (such as liquefied natural gas [LNG]). However, fossil fuel switching cannot be a long-term climate solution: the natural gas sector has been responsible for the largest growth in CO_2 emissions over the last decade.[59] Even faster rates of fossil fuel decline were achieved in the 1970s–1980s from substituting oil with nuclear power, a low-carbon technology that can lead to emission reductions. However, nuclear power is currently in decline, at least in most countries that historically led its expansion.[60] More recently, cost decline and other advances in solar and wind power led to these technologies displacing coal and, in some cases, gas. Even though the rate of this displacement may accelerate in the future, it has so far been slower than what is required in the majority of scenarios for the OECD and all scenarios in Asia.[18] Moreover, displacing coal with renewables has been limited to OECD countries with slow or shrinking electricity demand (Figure 4). Beyond renewables and nuclear, some climate mitigation scenarios[61,62] envision energy demand reduction as a major emission reduction strategy. Although we show that moderate decline of fossil fuels has more frequently occurred under slower demand growth, demand reduction was not the major cause of fossil fuel decline in most historical episodes except those linked to the collapse of the USSR (Figure 4). Although electricity demand reduction caused by the COVID-19 pandemic has contributed to a decline in the use of coal,[58,63] this decline is unlikely to be of the speed and scale needed to meet climate targets.[64] In summary, while technological advances have been necessary for fossil fuel decline, no single technology seems to be poised to deliver the decline required for reaching climate targets, and thus deploying technology mixes will be essential. Another technology that may be relevant to the future rate of fossil fuel decline is CCS. Gas decline rates could be significantly dampened if CCS is deployed fast enough; however, the availability of CCS has almost no effect on the urgency of coal power phase-out in scenarios (Figure S9).

The second lesson is that historical precedents of rapid fossil fuel decline almost always involved not only technological advances but also strong state policies. The rapid phase-out of oil in the 1970s–1980s was driven by concerns over energy security, and the introduction of nuclear power and other strategies of this period required considerable state intervention.[21,65] More recently, policies to reduce the use of fossil fuels have been motivated by concerns over climate change. So far, the pledges to phase out unabated coal made by the members of the Powering Past Coal Alliance[23] in response to the Paris Agreement (2015) do not envision phasing out coal faster than historically observed rates (Figure 2) and have been limited to wealthy countries that produce and use less coal and have aging power plant fleets.[23] The recent commitment of China to net zero emission by 2060 is another example of a new climate policy, although it remains to be seen whether it will imply phasing out coal faster than historically observed rates. More broadly, state policies stimulated the recent expansion of renewables,[66,67] and carbon prices[68] have encouraged the switch from coal to natural gas. These policies succeeded where they have managed to address multiple complexities, including the need to destabilize fossil fuel sectors to trigger their decline and at the same time address concerns of affected stakeholders and the distributional consequences of phase-out. Weakening coal regimes can take a long time, as in the case of the UK, which started such efforts in the 1980s[25] and achieved the fastest historically observed decline of −30% some 30 years later (from 2007 to 2017). This shows that decline can undergo non-linear accelerations after years of gradual destabilization; however, it may be difficult to replicate over the short term, particularly in major coal-consuming countries with younger plants and vigorous domestic coal production.[23] By 2007, the average age of coal plants in the UK was 35 years, compared with 12 years in China today.[49] It is not a coincidence that China, South Korea, and other Asian countries with large and younger coal fleets aim for net zero emissions for 2060, about four decades from now. Transitions away from coal in such cases inevitably trigger resistance from various social actors associated with the coal sector and invoke the issue of distribution of costs and benefits of fossil fuel decline.[69,70] This explains the need for policies that are able to navigate these interests by going beyond the weakening and destabilization of fossil fuel sectors and addressing the challenge of "just transitions," as exemplified by the recent German strategy of coal exit developed in cooperation with stakeholders in affected regions and industries, including companies, workers, and communities.[71]

The final lesson from historical precedents is that political motivation alone is not enough to implement sufficiently strong, nuanced, and long-term policies leading to fossil fuel decline. What is required in addition is strong state capacity. Most historical episodes took place in technologically advanced countries with strong governance capacities signaled by their economic wealth, strength of democracy, political stability, and high social capital. The importance of economic and institutional capacities has been documented in the case of introducing nuclear power,[72] broader response to the oil crises,[21] coal phase-out pledges,[23] and expansion of renewable energy.[66] In a globalized world, technological and political capacity is located not only in individual countries but also in international networks facilitating the flows of finances, technology, ideas, and political influences. The centrality of international cooperation has been documented with respect to many mechanisms involved in fossil fuel decline ranging from an earlier switch to nuclear power[73,74] to the recent coal phase-out pledges[75] and the adoption of renewables.[18,76,77]

These three lessons mean that the scale and speed of fossil fuel decline envisioned in the majority of the IPCC 1.5°C-compatible scenarios would require adopting low-carbon technologies at least as fast as nuclear power was adopted in the second half of the last century; political motivations at least as strong as in the past responses to oil crises; economic and institutional capacities comparable with those of Western countries; and worldwide economic, technological, and policy cooperation. Since all of these requirements are very challenging, scenarios where fossil fuel decline rates are more explicitly aligned with national capacities and targets should be considered as more realistic.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

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Materials availability

Not applicable to this study.

Data and code availability

For the identification of historical decline episodes, we used data from IEA World Energy Balances,[1] and for the identification of decline rates in scenarios we used data available from the IPCC 1.5°C Scenario Explorer and Data[2] as described in experimental procedures. The code used in the analysis (for calculating historical fossil fuel decline rates and those in scenarios, building a feasibility space for fossil fuel decline, and a feasibility heatmap) and the datasets generated during the study (a list of significant decline episodes, fossil fuel decline rates in climate scenarios, and a feasibility heatmap for scenarios) are available as: Vinichenko V., Cherp A., Jewell J. (2021). Code and data for "Historical precedents and feasibility of rapid coal and gas decline required for the 1.5°C target" (a One Earth article), version 1.0: https://zenodo.org/record/5532577. Fossil fuel decline feasibility heatmap for 1.5°C-compatible scenarios is also available as a supplemental data file Data S1.

Defining sample for historical analysis

For the historical analysis, we define our national sample as all countries with total electricity supply over 10 TWh/year. This covers 105 countries with the largest electricity systems accounting for over 97% of electricity production today (Table S1). We excluded very small countries for two reasons. First, in very small countries, relatively small-scale physical changes in the electricity system, like installing or retiring a single generation unit, would lead to a large decline rate at the national level. Second, in these countries, electricity systems are often not systems in the strictest sense but rather part of electricity systems of larger neighboring countries. For example, Luxembourg, a small country in Europe, imports three-fourths of its total electricity supply.[1]

We identify 37 national cases where decline is over 5% per decade in systems over 100 TWh/year, which we consider most relevant for climate change mitigation and analyze in more detail, as described below. Additionally, we calculate historical decline for the five regions, matching the regions from the IPCC 1.5°C Scenario Explorer and Data[2] as closely as possible (Table S2), and identify an additional five cases of rapid decline in global regions where decline exceeds 5%. We also identify one global case of significant decline. These 37 national cases, five regional cases, and one global case where decline is faster than 5% per decade in systems over 100 TWh/year are the focus of our substitution analysis (Figure 3) and the basis for our feasibility space for decline (see "Constructing a feasibility space for fossil fuel decline" below).

Identifying scenarios compatible with 1.5°C target

For the analysis of future scenarios to meet the 1.5°C target, we use all 1.5°C-compatible pathways from the IPCC 1.5°C Scenario Explorer and Data[5,2] (Version 2.0). In our analysis, we distinguish between low- or no-overshoot and high-overshoot pathways as defined in the database. For each pathway, we conduct our analysis for each of the five regions that are reported: Asia, Latin America (LAM), the Middle East and Africa (MAF), OECD, and the Reforming Economies (REF) – corresponding to the former Soviet Republics – Table S2.

Calculating decline rates

To calculate decline rates, we use electricity output of a given technology, because this is directly linked to carbon dioxide emissions and therefore is the most relevant for climate analysis.

We calculate the decline rates as a change in electricity generation from a given source expressed as percentage of the average system size at the beginning and the end of the same period (Equation 1) (Figure S14):

$$D_i = \frac{S_{i1} - S_{i0}}{(T_0 + T)_1} * 2 \quad \text{(Equation 1)}$$

where:

- S_{i1} is electricity generation from a given source (i) at the end of the decline period
- S_{i0} is electricity generation from the same source (i) at the beginning of the period
- T_0 and T_1 are the total electricity supply (the size of the electricity system) at the beginning and the end of the period, respectively

The total electricity supply represents the total amount of electricity used within a given entity (country or region). It is calculated as total domestic electricity production minus electricity exports plus electricity imports (Equation 2).

$$T = P - E + I \quad \text{(Equation 2)}$$

where:

- P is total electricity production
- E is total electricity exports
- I is total electricity imports

Normalizing the decline to the overall electricity supply accounts for how significant a decline episode is in relation to the entire electricity system, rather than in relation to the individual energy source. For example, consider an electricity generation source that generates 50 GWh, or 5% of a country's electricity supply, and falls to 25 GWh over 10 years. If we were to measure the decline of this source in relation to itself, the decline rate would be 50%, which would not account for the fact that the source itself is relatively unimportant in the overall electricity system. Since we are interested in decline in the broader context, normalized decline is a more useful metric.

Since the total electricity supply changes over time, in our main analysis we use the average of the total electricity supply over the time period ($\frac{T_0 + T_1}{2}$) for normalization. We also conduct a sensitivity analysis where we normalize decline to the total electricity supply at the beginning (T_0) and the end (T_1) of the episode, which does not qualitatively change our findings (Figure S15).

When calculating historical decline rates, we correct for the fact that electricity production can fluctuate on an annual basis by smoothing the historical data from the IEA Energy Balances[1] using 3-year running averages. We then calculate 10-year decline rates for all countries in our sample and for the five regions that match the regions from the IPCC 1.5°C Scenario Explorer and Data.[2] For each country or region, we identify the non-overlapping decline episodes with the highest decline rates.

In our main analysis, we omit 97 decline episodes in which the declining source returns to the initial level within 10 years of the end of the episode. We also include a sensitivity analysis where, in addition to omitting these episodes with full rebound, we adjust the decline rates in the remaining episodes for the partial rebound that happens within 10 years of the end of the decline episode (Figures S4 and S16). We also conduct a sensitivity analysis using 20-year periods rather than 10-year periods (Figure S11).

We also estimate decline rates implied by pledges of members of the PPCA, an initiative launched in 2016 whose members have committed to phase out unabated coal power generation.[23,78] To do so, we identify the starting year that would provide the maximum decline rate ($Year_{max}$) and project the maximum possible decline rate based on the pledged phase-out date(s)[23] assuming that coal-fired generation declines from the amount in the starting year (S_{max}) to zero in the pledged phase-out year ($Year_{phase-out}$). As Figure S17 illustrates, this prevents underestimating decline rates, which could happen if we only assumed the decline between the most recent year for which generation data are available and the pledged phase-out date. Since total electricity supply in the future phase-out year is unavailable, in this calculation we use total electricity supply in the last year for which data are available (T_{last}) as the electricity system size. To make these data comparable with our other observations, we normalize them to a 10-year period (Equation 3).

$$D_{PPCA} = \frac{-S_{max}}{T_{last}} * \frac{10}{Year_{phase-out} - Year_{max}} \quad \text{(Equation 3)}$$

For climate mitigation scenarios, we calculate decline rates for each decade between 2020 and 2050 for electricity generation from each fuel in each region and globally using the IPCC 1.5°C Scenario Explorer and Data[5,2] (Version 2.0). We do that for all 1.5°C-compatible scenarios where electricity generation data are available (85 global, 79 for MAF and REF, 69 for Asia and OECD, and 68 for LAM). We conduct the two sensitivity analyses on the decline rates in future scenarios that could affect our results: using total electricity supply at the beginning and end of the period rather than the average (Figure S15) and using 20-year rather than 10-year time periods (Figures S11 and S12).

Calculating demand change and defining fuel substitution

We consider the concurrent change in electricity demand and substitution of the declining fuels as important contextual factors of fossil fuel decline in addition to the electricity system size (Figures 3, S6, and S7). We define electricity demand as the total amount of electricity consumed within the given entity (losses included), so it is numerically equivalent to total electricity supply (total electricity production adjusted for net imports; see above). To calculate demand change (C_{Dem}), we use a method similar to the one we use for calculating fossil fuel decline rates and normalize changes in total electricity demand to the average total electricity supply (Equation 4):

$$C_{Dem} = \frac{T_1 - T_0}{(T_0 + T)_1} * 2 \quad \text{(Equation 4)}$$

where T_0 and T_1 is the total electricity supply (or demand) at the beginning and the end of the period respectively.

To characterize a decline episode in terms of fuel substitution, we calculate the change in each electricity generation source C_i, also normalizing it to the total electricity system size (Equation 5):

$$C_i = \frac{S_{i1} - S_{i0}}{(T_0 + T_1)} * 2 \quad \text{(Equation 5)}$$

We identify the largest and the second largest growing electricity sources. Then we classify our historical episodes by their primary type of substitution: fuel switching, where the largest growing electricity source is another fossil fuel; nuclear substitution, where the largest growing electricity source is nuclear power; substitution with renewables, where the largest growing electricity source is non-hydro renewables; and demand decline, when the total electricity system shrinks more than the increase in any individual source (Tables S3 and S4). We also report the secondary type of substitution, which is the second largest growing electricity source (or demand decline). If both the first and second largest growing electricity sources are fossil fuels, the episode is classified only as fuel switching; if the second largest substituting electricity generation source accounts for less than 10% of the total growth in growing energy sources, the episode is considered a case of single-source substitution, and no secondary substitution is reported.

Examining the relationship between decline rate and system size

We examine the relationship between the decline rate and system size by estimating how the maximum observed decline rate varies with the size of the energy system (Figure 2). We identify the historical maximum rates, which can be considered a feasibility frontier if only system size is considered, by generating a spline approximation with the ggplot package in Rstudio using selected boundary points in Figure 2. In our main analysis, we include regional entities that are aggregations of national systems. We conduct a sensitivity analysis of the decline-rate-size relationship where we exclude regional episodes and only include national decline episodes (Figure S3).

We also test the possibility that the observation of faster decline rates of smaller entities is simply a statistical artifact and the result of more observations of smaller systems. To do so, we divide our sample of historically observed decline episodes into two subsamples using different system size thresholds (100, 200, and 300 TWh/year) and test the hypothesis that the rate distributions within the subsamples of larger and smaller systems have the same characteristics using two statistical tests.

First, we use the non-parametric Anderson-Darling test[79] to check the probability that the two observed samples come from the same underlying distribution. The p value produced by this test is the probability of getting the observed difference between the two empirical samples provided that they come from the same distribution (Table S5; Note S1). Second, we test the probability that the observations in our subsamples of larger systems have the same probability of exceeding a given decline rate threshold (−20%, −25%, or −30%) as the proportion of observations in the smaller systems subsamples exceeding the same threshold. We use binomial distribution[80] to estimate the probability of getting the empirically observed or smaller number of cases exceeding the threshold within the larger systems subsample under this assumption. This produces a p value that, if small enough, can be used to reject the null hypothesis that episodes in both subsamples have the same probability of exceeding the rate threshold. We repeat each test for different decline rate thresholds (Table S5; Note S1).

Constructing a feasibility space for fossil fuel decline

We construct a feasibility space for fossil fuel decline based on all significant historical decline episodes (10-year decline rates faster than 5% and average annual total electricity supply >100 TWh/year: 37 national, five regional, and one global episode). The coordinates defining the space are 10-year fossil fuel decline rate and change in total electricity demand over the same period (both normalized to the average system size). In order to characterize the strength of historical precedents for different combinations of decline and demand change, we developed a density map based on the number of observations in each zone and the size of the systems in that zone.

First, we divide the space into discrete bins (5% on the fossil fuel decline axis and 15% on the demand change axis) and calculate the weighted count of historical episodes (Figure S8A). The episodes are weighted by log-transformed system size (e.g., the weight for 100 TWh/year is 1, for 1,000 TWh/year it is 2, for 10,000 TWh/year it is 3) to give more significance to larger entities comparable with regions used in scenarios. We assign the episode GB07-17C with decline rate 30.1% to the range 25%–30%, and the episode ID07-17O with demand change 60.1% to the range 45%–60%.

Due to the limited number of observations, the weighted density map produced this way is discontinuous and has some gaps. Therefore, second, we produce a smoother augmented map for the purpose of estimating the feasibility of future scenarios. In doing so, we assume that slower decline rates under the same demand change are easier to achieve and hence more feasible; the same decline rate is more feasible at a slower demand growth (or faster demand decline), since there is less need for substituting outgoing sources. Therefore, an empirical datapoint within a given bin provides evidence of feasibility not only for that bin but for all bins to the top and/or the left of it in Figure S8A (with the exception of zone D containing crisis-driven episodes; see below). For example, a historical episode with decline rate −12% and demand change +17% also provides evidence of feasibility for decline rate −6% and demand change 0%, even if there is no historical datapoint at the latter pair of coordinates. Therefore, we calculate an augmented score for each bin by summing weighted counts across all bins to the right and/or the bottom of it (i.e., with faster decline rates and/or fasted decline growth), the count for the bin itself included (Figure S8B).

Third, we identify three feasibility zones based on the augmented scores from most to least feasible (Figures 4 and S8C) where:

- A: score >10
- B: 10 > score >0
- C: score = 0 (i.e., no historical precedents)

The area with demand decline faster than −15% over 10 years contains only historical episodes associated with crises; we designate this area as zone D (Figure S8C). While there are historical precedents of such decline, all of them were triggered by the collapse of the Soviet Union, a unique event not envisioned in climate change mitigation scenarios.

Finally, we use this feasibility space to map decline of coal and natural gas for each of the five regions in climate change mitigation scenarios (Figure 5 and Table 1). In the main text, we focus on coal and natural gas and the time periods where decline rates are the highest.

Building a heatmap for scenarios

We also use the feasibility space to produce a heatmap for each scenario. To do so, we project each fuel/region combination for three periods (2020–2030, 2030–2040, and 2040–2050) in each scenario onto the feasibility space and report the feasibility zone where the decline rate for each fuel/region/time period combination falls (Data S1). We also include a summary heatmap with a summary feasibility score for each scenario based on the lowest feasibility score in any fuel/region/time period (Data S1; Table S8), since a feasibility concern in any fuel/region/time period will decrease the feasibility of the whole scenario. In producing summary scores, we treat zone D (crisis-driven decline) as less feasible than zones A and B, but more feasible than zone C (no precedents).

Calculating age of power plant fleets

To characterize regional and national power plant fleets, we calculate weighted average age of power plants (Equation 6):

$$Age = \frac{\sum_i (Year_0 - Year_i) * MW_i}{\sum_i MW_i} \quad \text{(Equation 6)}$$

where:

- $Year_0$ is the year for which the average age is calculated
- $Year_i$ is the year when the plant i started operation
- MW_i is its installed capacity

The summation is over all plants operating in $Year_0$.

We use World Electric Power Plant database[49] and Global Coal Power Tracker[50] as sources of plant age data.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.09.012.

ACKNOWLEDGMENTS

This work was supported by the Research Council of Norway under the Analyzing Past and Future Energy Industry Contractions: Towards a Better Understanding of the Flip-Side of Energy Transitions project under grant agreement no. 267528/E10 (project Contractions). A.C. received support from the European Union's Horizon 2020 research and innovation program under grant agreement no. 821471 (project ENGAGE). We are grateful to Jan Minx for comments on our research.

AUTHOR CONTRIBUTIONS

Conceptualization, J.J., V.V., and A.C.; methodology, V.V., J.J., and A.C.; formal analysis, and visualization, V.V.; data curation, V.V., J.J., and A.C.; writing – original draft, V.V. and J.J.; writing – review & editing, J.J., A.C., and V.V.; supervision and funding acquisition, J.J.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: December 10, 2020
Revised: December 16, 2020
Accepted: September 28, 2021
Published: October 22, 2021

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