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Phasing out coal for 2 °C target requires worldwide replication of most ambitious national plans despite security and fairness concerns

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Abstract

Ending the use of unabated coal power is a key climate change mitigation measure. However, we do not know how fast it is feasible to phase-out coal on the global scale. Historical experience of individual countries indicates feasible coal phase-out rates, but can these be upscaled to the global level and accelerated by deliberate action? To answer this question, we analyse 72 national coal power phase-out pledges and show that these pledges have diffused to more challenging socio-economic contexts and now cover 17% of the global coal power fleet, but their impact on emissions (up to 4.8 Gt CO_2 avoided by 2050) remains small compared to what is needed for achieving Paris climate targets. We also show that the ambition of pledges is similar across countries and broadly in line with historical precedents of coal power decline. While some pledges strengthen over time, up to 10% have been weakened by the energy crisis caused by the Russo-Ukrainian war. We construct scenarios of coal power decline based on empirically-grounded assumptions about future diffusion and ambition of coal phase-out policies. We show that under these assumptions unabated coal power generation in 2022–2050 would be between the median generation in 2 °C-consistent IPCC AR6 pathways and the third quartile in 2.5 °C-consistent pathways. More ambitious coal phase-out scenarios require much stronger effort in Asia than in OECD countries, which raises fairness and equity concerns. The majority of the 1.5 °C- and 2 °C-consistent IPCC pathways envision even more unequal distribution of effort and faster coal power decline in India and China than has ever been historically observed in individual countries or pledged by climate leaders.

1. Introduction

The goal of 'consigning coal to history' from COP26 [1] seems within reach considering the shrinking pipeline of new coal power plants (figure S1) and increasing number of countries pledging to stop using coal [2]. However, some suggest that committed emissions from existing and planned coal power plants are already incompatible with Paris temperature targets [3–5] and major coal power consumers like China and the US have not committed yet to coal phase-out. Given these contradictory trends, what are feasible trajectories of future coal phase-out and what does it mean for the climate?

One way to address this question is to examine historical precedents for fossil fuel decline. Vinichenko *et al* [6] show that even the fastest decline in individual countries was generally slower than what is required at the continental scale for reaching 1.5 °C warming targets. Yet, it is plausible that future energy transitions can be accelerated by policies [7] motivated by climate concerns [8].

Following this logic, empirically-grounded assumptions about future policies can help construct feasible coal decline trajectories which are more ambitious than just a continuation of historic trends. But what can be the basis for such assumptions?

A natural starting point is to investigate governmental commitments to phase-out unabated coal under the Powering Past Coal Alliance (PPCA) [9] and the Global Coal to Clean Power (GCCP) Initiative [10]. Jewell *et al* [11] showed that in 2018 PPCA membership was limited to wealthy and well-governed countries with older power plants that used little coal and therefore did not significantly contribute to the emission reductions required for reaching the climate goals. Yet this analysis only provided a snapshot of coal phase-out pledges, without investigating whether they spread to more countries or get stronger over time [12].

The diffusion of climate policies [13] can be analysed using a feasibility space, which is a tool for assessing the feasibility of a climate action by its characteristics, context or implementation levels, grouped into feasibility zones or separated by feasibility frontiers [6, 11, 14, 15]. Here we construct a feasibility space of coal phase-out pledges where the extent of policy adoption is demarcated by a dynamic feasibility frontier, such as one constructed by Jewell *et al* [11]. Bi *et al* [16] argue that two main mechanisms can affect the international diffusion of coal phase-out policies: (a) national dynamics from increasing capacities for coal phase-out in individual countries (which can be visualised as countries moving through the feasibility space and towards or across the feasibility frontier) and (b) global dynamics such as declining costs of alternative technologies and increasing international pressure making it feasible for more countries to adopt phase-out pledges (which can be visualised as the feasibility frontier itself shifting). Bi *et al* [16] investigate the former and show that it is unlikely to trigger coal phase-out policies in major coal users such as China and India before mid-century. Here we explore the second mechanism, finding it more effective in the diffusion of phase-out pledges.

In parallel to diffusion, the ambition of coal phase-out policies may increase over time due to expanding domestic political support coalitions in a process known as ‘ratcheting up’ [17, 18], and in a similar process one can even expect late-adopters to have more ambitious phase-out policies than frontrunners, since they may be able to deploy coal alternatives faster [19, 20]. On the other hand, neither rapid policy diffusion nor increasing ambition can be taken for granted. Energy security crises, such as the recent disruption of Russian gas supplies to Europe may delay or reverse coal phase-out policies. Adverse distributional effects of coal decline can trigger countervailing domestic resistance [21–23] and slow the international diffusion of anti-coal policies particularly if their burden is perceived as unfair [24, 25]. Finally, late-adopters may lack capacity to quickly match, least over-perform, the commitments of climate leaders [11, 26, 27]. In sum, theoretical arguments alone cannot provide a basis for realistic assumptions about the future diffusion and ambition of climate policies.

By examining new coal phase-out pledges, we show that they are expanding to more challenging contexts and now cover 17% of the global installed coal-fired capacity, almost four times more than in 2018. However, the economic and institutional capacities still limit the diffusion of pledges and their effect on emissions remains a fraction of what is required for 1.5 °C or 2 °C targets. With respect to ambition, we estimate that most pledges imply a pace of coal power decline comparable with the pace observed historically in large countries, that the ambitions do not generally increase over time, and that about 10% of the installed capacity under coal phase-out commitments are at risk of being delayed by energy security concerns caused by the Russo-Ukrainian war. Based on these observations, we identify a set of scenarios for future coal decline ranging from limited diffusion and constant ambition to rapid worldwide diffusion and increasing yet empirically-grounded ambition of coal phase-out policies. We estimate that under these feasible scenarios, the cumulative unabated coal power generation in 2022–2025 ranges from levels consistent with 2 °C warming to levels implying warming above 2.5 °C. We show that in higher ambition scenarios the burden of premature coal power retirement disproportionately falls on developing and emerging economies with less capacity to implement phase-out policies, which presents additional policy challenges.

2. Method

In this paper we empirically analyse the diffusion and ambition of coal phase-out policies to develop feasible scenarios of policy-driven decline of coal power (figure 1). We calculate the capacity of coal-fired power plants in national and subnational jurisdictions that have adopted coal phase-out pledges either within the PPCA, the GCCP, or outside of these international initiatives. We compare the national contexts of countries adopting coal phase-out pledges to the nine countries with the largest coal power fleets but no phase-out pledges who together account for 83% of global coal-fired power generation (figure 2). We also estimate how much the pledges reduce emissions relative to a reference retirement case where all coal power plants operate at the average load factor until the end of the average national historical lifetime [28]—table 1 and note S1.

We analyse the international diffusion of pledges by comparing their current extent to an earlier snapshot [11], using a similar statistical analysis and the ‘feasibility space’ [15] constructed by Jewell *et al*

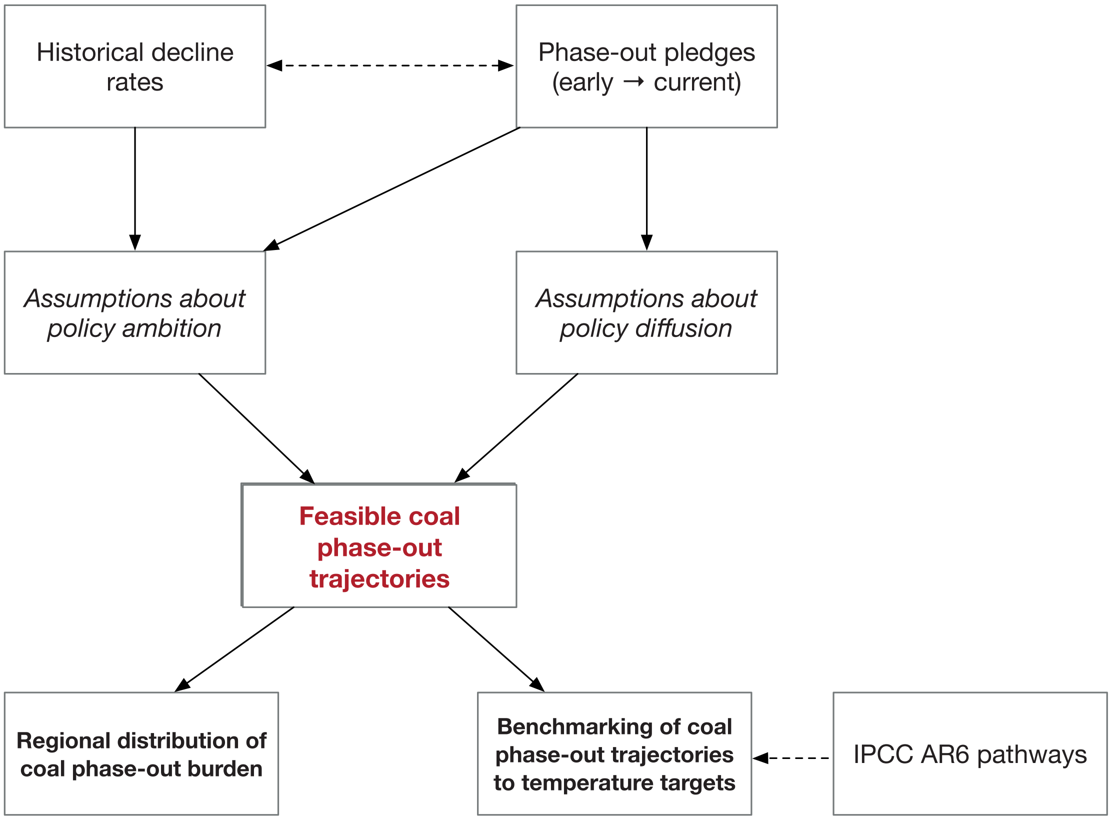

Figure 1. Organisation of research in this article. Plain text—inputs, *italic*—assumptions used in building coal phase-out trajectories, bold—results. Dashed lines—use of contextual information for analysis and benchmarking.

[11] for all countries that had at least 1% of electricity from coal power in 2016 before countries started to make coal phase-out pledges ($n = 68$)—note S1. To assess 'pledges at risk' due to the energy crisis in 2022, we identify national political statements about possible delay or reversal of coal phase-out plans and calculate the coal power capacity in affected countries. We estimate the ambition of phase-out pledges by the implied 'coal power decline rate', calculated as the share of coal in power generation in the year of adopting the pledge divided by the number of years between the pledge and the phase-out date—note S1. Measured in this way, the ambition can be directly compared with historical rates of fossil fuel decline [6] as well as across countries and with rates in future scenarios.

We use the results of these analyses to construct scenarios based on empirically-grounded assumptions about the diffusion and ambition of coal phase-out policies. Each scenario involves the diffusion of coal phase-out policies to some or all global regions and subsequent coal decline at a constant rate relative to the total electricity supply, consistent with rates implied in phase-out pledges and observed historically. By varying the extent of diffusion and the ambition of coal phase-out policies, we arrive at a suit of 12 policy scenarios further supplemented by a reference scenario, where all coal power plants operate to the average national lifetime and no new coal power plants are constructed, except for those already in construction as of early 2022. We further explore the sensitivity of our policy scenarios to the speed of policy diffusion by varying the year in which pledges are adopted.

To relate our scenarios to temperature outcomes, we calculate cumulative unabated power generation from coal in 2022–2050 and benchmark it to the generation in the IPCC AR6 pathways [29, 30]—note S1. To compare coal phase-out 'effort' across regions, we estimate emission reductions in the policy scenarios by subtracting their emissions from those in the reference retirement scenario and use the reductions per unit of gross domestic product (GDP). Finally, we calculate maximum coal decline rates in the IPCC pathways and compare them to the pledged and historical rates. More details on methods are provided in note S1.

3. Results

3.1. More countries adopt coal phase-out pledges, but their diffusion is constrained by national capacities and their effect remains limited

Our prior study [11] estimated that the PPCA pledges made by 30 nations in 2017 and 2018 covered about 4.4% of the global coal power plant fleet and would result in 1.6 Gt of avoided CO_2 emissions by 2050. Since then, 18 new countries have joined

Table 1. Coverage and effect of national and subnational coal phase-out pledges. To illustrate the coverage and effect of coal pledges, countries are divided into three groups: (A) those joining the PPCA in 2017–2018, (B) those joining the PPCA in 2019–2022 plus four non-PPCA members (Bulgaria, Czechia, Panama, and Romania) that in 2021 pledged to phase-out coal before 2040; and (C) non-PPCA members signing the GCCP plus Myanmar that adopted its pledge independently. Estimates for coverage and effect for (A) are from [11]. For (B) and (C), ranges reflect uncertainty in the pledged phase-out date addressed through central, pessimistic, and optimistic interpretations for each country's pledge (note S1 and table S1). For sensitivity of avoided emissions to load factor, efficiency, plant lifetimes and coal-to-gas substitution see note S1, figure S2. For the number of countries with coal and coverage of global installed capacity, the effect of 'pledges at risk' due to the Russo-Ukrainian war (table S5) is shown in the column 'all countries with pledges'.

	(A) Original PPCA members 2017–2018	(B) PPCA and similar pledges in 2019–2022	(C) Non-PPCA members signing GCCP	All countries with pledges
Number of countries	30	22	20	72
…with coal (*pledges at risk due to the war*)	15	18	12	45 (*11*)
…with set phase-out dates	14	18	11	43
Pledged phase-out years median (range)	2025 (2020–2030)	2030 (2022–2050)	'Major economies by the 2030s, globally by the 2040s' (Art 2) [10]	—
Coverage of global installed coal-fired capacity (*pledges at risk due to the war*)	4.4%	5.4%	5.8%	16.8% (*1.7%*)
Proportion of global coal capacity prematurely retired, central estimates (pessimistic-optimistic)	2.0%	2.8% (2.7%–3.0%)	2.7% (0.1%–5.4%)	7.5% (4.8%–10.4%)
Gt CO_2 avoided emissions by 2050, central estimate (pessimistic-optimistic)	1.6	2.3 (2.0–3.0)	0.9 (0.1–5.5)	4.8 (3.7–10.1)

the PPCA [2] and 19 additional countries signed the less demanding GCCP [10]. In addition, five countries have committed to coal phase-out and two more countries committed to not building new coal power plants without subscribing to either PPCA or GCCP (tables 1 and S1). These new pledges, including those made at subnational levels (table S2), quadruple the coverage of the global coal power fleet to 17% (18% including no new coal power plants commitments) and triple the avoided emissions to 4.8 $GtCO_2$ (table 1, note S1). Moreover, the pipeline for coal power plants construction is about half what it was in 2017 and less than a quarter what it was ten years ago (figure S1). Nevertheless, the emission reductions induced by pledges are still more than an order of magnitude less than the committed emissions embedded in coal power plants (260 $GtCO_2$ [3]) and the emission reductions required in 1.5 °C- and 2 °C-consistent mitigation pathways compared to the reference retirement scenario: 130 $GtCO_2$ (median; inter-quartile range 100–148 $GtCO_2$) and 94 $GtCO_2$ (73–116 $GtCO_2$) respectively (tables S3 and S4, note S1).

In parallel with this expansion of pledges, the 2022 Russo-Ukrainian war has prompted at least 11 European countries to consider delaying or reversing phase-out of coal power plants to reduce their dependence on Russian gas imports (tables 1 and S5). These countries currently have some 35 GW or 10% of total coal power capacity under phase-out pledges, which is equivalent to 1.7% of the global installed capacity. While Germany and Poland, the two European countries with the largest coal fleets, have considered delaying coal phase-out, they recently re-committed to their pledges (table S5). The war also affects coal phase-out in Ukraine (a PPCA member) with its 25 GW of coal power capacity.

Coal phase-out pledges have become feasible in a wider range of countries. Countries that joined the PPCA in 2017 and 2018 were primarily located in Western Europe, generally used less coal, had older power plants and higher GDP per capita and state capacity as measured by the Functioning of Government index (FoG) [31] than those pledging phase-out in 2019–2022, which also included an increasing number of non-European countries (figures 2 and S3).

The diffusion of coal phase-out pledges can be visualised with a feasibility space [15] that shows the movement of the dynamic feasibility frontier [15] (figure 3). Following Jewell *et al* [11], we define the dimensions of the feasibility space as (a) the coal share in electricity and (b) FoG, which measures the absence of undue influence on elected government, government transparency and checks against political corruption [31]. The former is an indicator of

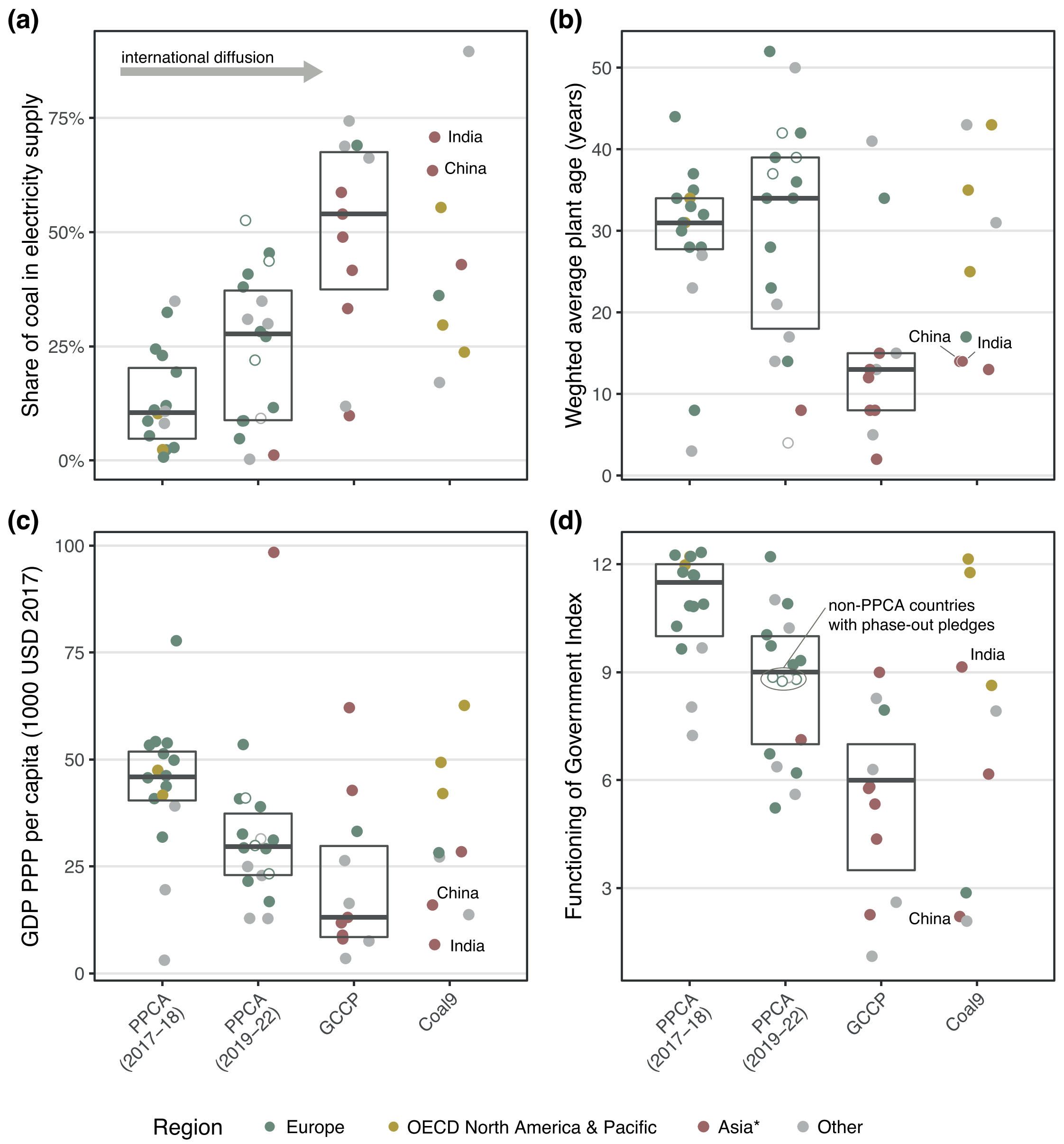

Figure 2. Characteristics of countries with different timing and type of coal phase-out pledges as well as without pledges. (a) Share of coal in the electricity supply. (b) Average age of coal power plant units, weighted by capacity. (c) GDP PPP per capita. (d) Functioning of Government index. See note S1 for data sources and definitions of variables. The figure shows 68 countries with electricity production from coal >1% of electricity supply in 2016 (the sample in [11]). PPCA (2017–18)—countries that joined the PPCA in 2017–2018; PPCA (2019–22)—the countries that joined the PPCA in 2019–2022 and four countries with pledges to phase-out before 2040 (Bulgaria, Czechia, Panama, and Romania—hollow dots); GCCP—signatories, which are not PPCA members, excluding Morocco that opted out of Article 2; Coal9—the world's largest nine users of coal power with no coal phase-out pledges (Australia, China, India, Japan, Malaysia, Russia, Turkey, the US, and South Africa) that collectively account for 83% of global coal-fired generation. Boxes represent interquartile ranges for the respective variables and country groups; thick lines within boxes represent medians; dots represent individual countries. Dot colour represents regions (table S6). *Asia combines China+, India+, and Rest of Asia. See figure S4 for coal production per capita.

the strength of the coal sector as well as the scale of the challenge in substituting coal with other sources and thus represents the overall cost of coal phase-out. We use the latter as an indicator of the capacity of a government to address the challenges of coal phase-out such as overcoming coal vested interests and supporting rapid expansion of alternative sources. These two variables are statistically significant in predicting coal phase-out pledges both as of 2018 [11] and 2022. The structure and dynamics of the feasibility space are robust against alternative measures of the cost of phase-out and capacity to overcome these costs (figure S5 and table S7).

The likelihood of PPCA membership in both 2018 and 2022 is affected by the costs of phase-out and the state capacities. However, the 2022 frontier notably expands, encompassing 16 new countries in addition to the 15 which fall within the 2018 frontier. While the expanding feasibility frontier shows how coal phase-out becomes feasible in more challenging contexts, the movement of individual countries within the feasibility space shows how their national contexts may

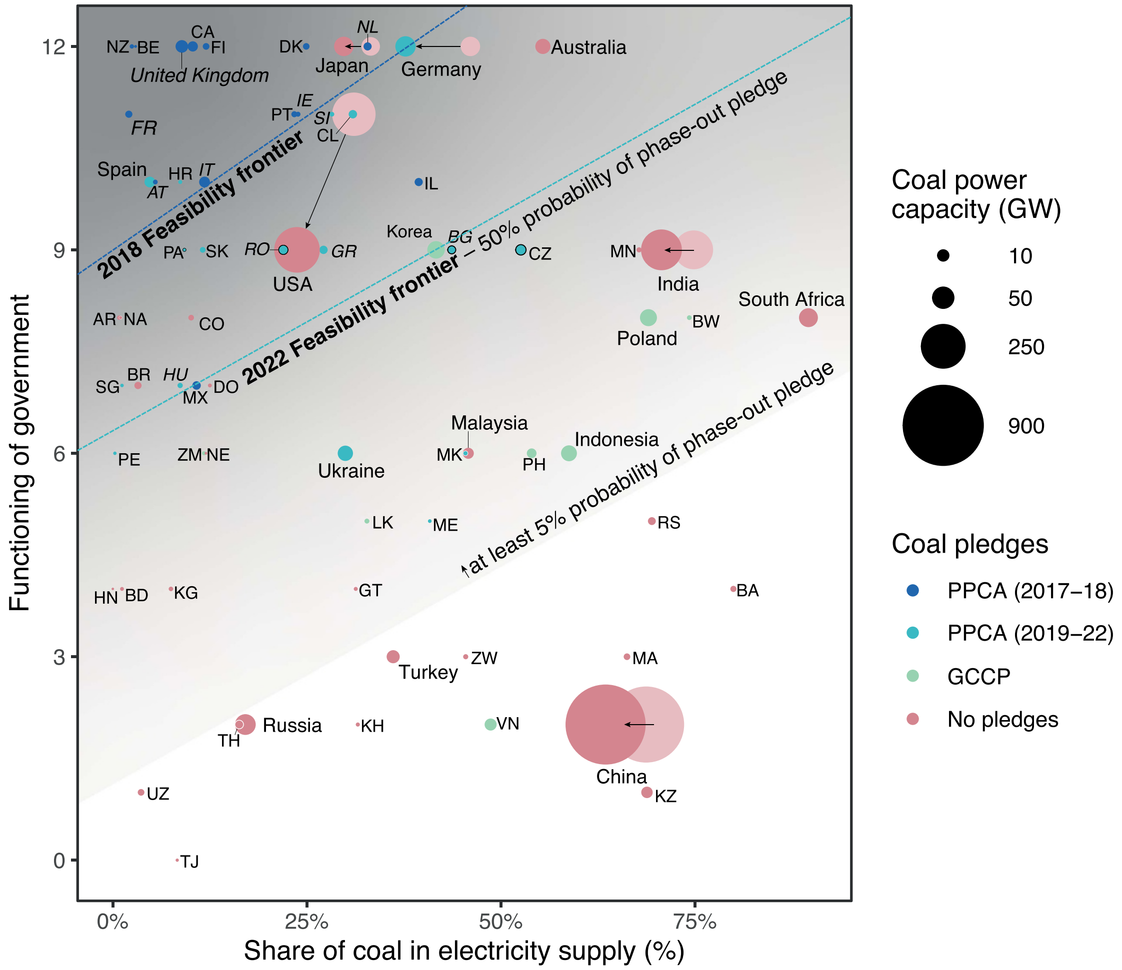

Figure 3. The evolution of the feasibility space for coal phase-out pledges. The two feasibility frontiers correspond to 50% probability of being a PPCA member based on the logistic regression analysis of PPCA membership in 2018 from [11] and in 2022 (our calculations) respectively, using percentage of coal in electricity supply and the Functioning of Government index as independent variables. The shading represents the predicted probability of a country with given characteristics being a PPCA member based on the analysis of the 2022 membership. The figure shows 68 countries with electricity production from coal >1% of electricity supply in 2016 (the sample in [11]). The dot size represents the total installed capacity of coal-fired plants in the beginning of the year of the coal phase-out pledge. Dot colour represents the type and the timing of pledges (or the absence of a pledge). Dots with black outline represent four countries that pledged to phase-out before 2040 (Bulgaria, Czechia, Panama, and Romania) in 2021 outside of the international initiatives and are treated similarly to PPCA (2019–22) countries in our analysis. For the five countries with the largest coal fleets, the shift between 2016 and 2019 is also shown. Italics represent pledges at risk from the Russo-Ukrainian war (table S5). See table S8 for country codes.

become more or less favourable to coal phase-out. So far, these latter changes have not been a decisive factor in changing the likelihood of coal phase-out pledges (figure 3). We did not find any systematic dependence between national coal phase-out pledges and the relative cost of coal power and renewables in countries (figure S6) or national plans for carbon capture and storage (note S2).

3.2. The pledged rates of coal decline are in line with historical precedents with limited evidence of ratcheting up

Countries with larger shares of coal power tend to pledge later phase-out dates. The *implied phase-out rate* or the relationship between the share of coal in electricity and the number of years before the pledged phase-out date, is remarkably stable for both earlier and later pledges. (figure 4(a), table S1). The implied phase-out rates are somewhat lower for countries with higher coal shares, which is in line with the historical experience of the UK and Germany where initially large shares of coal have been targeted for phase-out. In both countries, periods of coal power decline were interspersed by periods of stagnation, which slowed down the overall decline rate (figure 4(a)).

The implied coal decline rates can be compared across countries and to the fastest historical rates of coal power decline [6] (figure 4(b)). Like in historical cases, faster decline is only pledged in smaller countries because it is more difficult to implement rapid phase-out in large heterogeneous systems. All decadal coal decline rates pledged in electricity systems larger than 100 TWh/year (approximately the size of the Netherlands) are slower than the 30% rate

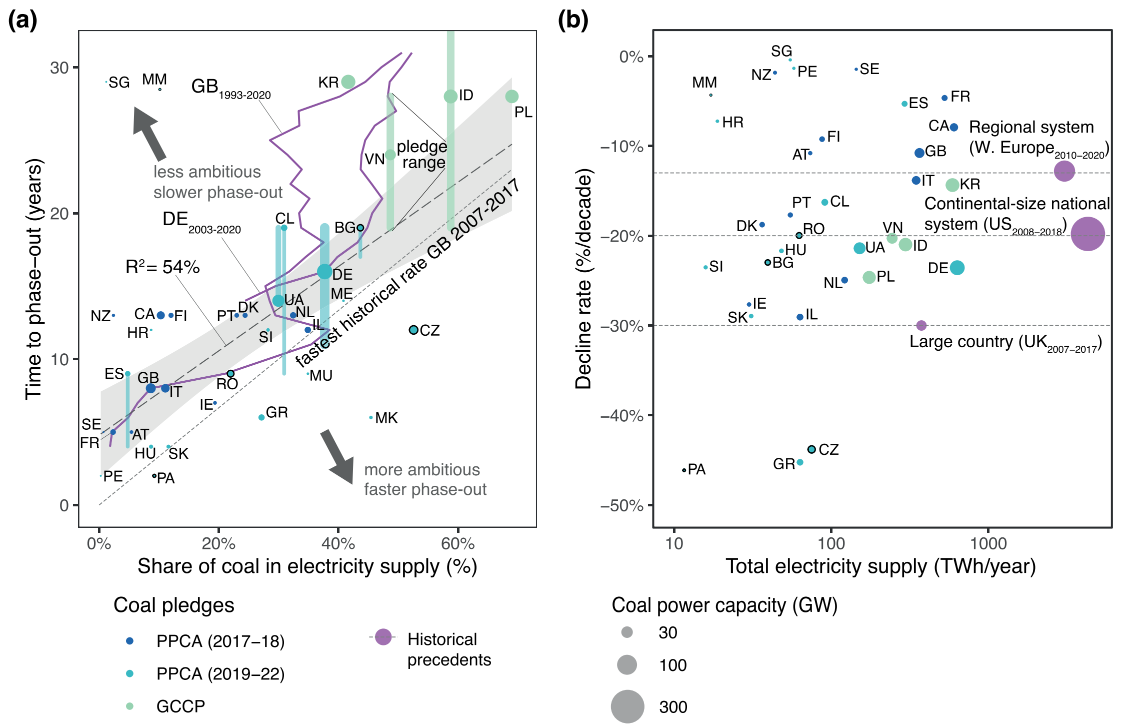

Figure 4. The pledged phase-out time as a function of share of coal in electricity and total electricity supply and coal decline rates implied in the phase-out pledges. Both panels include all countries with electricity production from coal >1% and coal phase-out pledges, except for countries with total electricity supply <10 TWh/year in panel (b). Dots with black outline represent five countries that took pledges in 2021 outside of the international initiatives (Bulgaria, Czechia, Panama, and Romania have the same colour as PPCA (2019–22) countries, Myanmar—as GCCP signatories). Dot size represents total installed capacity of coal-fired plants in the beginning of the year when they pledge coal phase-out. (a) The time between the pledge and the announced phase-out date as a function of the share of coal in electricity supply. Vertical lines represent ranges of pledged dates for selected countries (table S1, note S1). The dashed line shows the trend based on linear regression with a confidence interval, the dotted line—the fastest historically observed rate of coal power phase-out in a large country (UK) from Vinichenko *et al* [6]. Purple lines represent historical evolution of coal power in the UK and Germany (the assumed phase-out dates are 2024 and 2035 respectively). See table S8 for country codes. (b) Coal decline rates implied in the national pledges (as % of the total electricity supply per decade) as a function of total electricity supply in the year of taking the pledge. For countries with a range of phase-out dates the central estimate is used. Purple circles and dashed lines represent historical benchmarks of coal decline (see text).

observed in the fastest historical episode in a large country, the UK in 2007–2017. Germany's implied decline rate is faster than the decline rate observed in the US in 2008–2018 (20%) (the fastest decline in the largest energy system under a single national jurisdiction). Finally, many existing pledges imply decline rates faster than 13% per decade observed in Western Europe in 2010–2020, the fastest decline in a regional constellation of countries. Overall, adjusted for country size, the decline rates implied in existing pledges do not signal an acceleration of coal phase-out beyond what was observed historically.

Pledges can be strengthened or weakened over time. In what can be seen as evidence of 'ratcheting up', five PPCA members have brought their phase-out date up by one or two years, Israel—by five years, Germany—by five to eight years, and Portugal—by nine years. On the other hand, France delayed its planned phase-out date by a year and Senegal built its first coal power plant after joining the PCCA (table S1). Further delays may be expected due to energy security concerns triggered by the Russo-Ukrainian war (table S5). Thus, the 'ratcheting up' so far has been unstable and vulnerable to external shocks.

3.3. Under empirically-grounded assumptions about diffusion and ambition of coal phase-out policies global coal power emissions range from compatible with 2 °C warming to above 2.5 °C warming

First, we construct a reference retirement scenario where the only new power plants to be constructed are those currently under construction [28] and existing power plants are retired at their average national retirement age—note S1. In the remaining policy scenarios, we project the identified regularities in the diffusion and ambition of phase-out policies between three world regions: *Europe, OECD North America & Pacific*, and Asia plus rest of the world (*Asia + ROW*). The *Europe* region is identical to the 'Europe' region in the IPCC AR6 scenarios (with ten regions or R10), *OECD North America & Pacific* region is a combination of 'North America' and 'OECD Asia and Pacific' R10 regions, and *Asia + ROW* region is an aggregate of the remaining seven R10 regions (table S6). Europe and OECD are comprised of high-income countries with older coal power plants and slowly growing electricity demand, where most historical episodes of coal power decline have been observed [6], and where

Table 2. Coal phase-out scenarios and emissions from unabated coal. In the reference scenario (called 'Ref.'), no new power plants are constructed, except for those already in construction as of early 2022, and the existing power plants are retired at the average historical retirement age. The remaining policy scenarios are defined by a combination of the extent of diffusion and the level of ambitions (decline rates) of coal phase-out policies in different regions. *OECD + Europe* includes Europe, North America, and OECD Asia and Pacific; *Asia + ROW* includes the remaining seven regions out of ten IPCC regions (R10, table S6, note S1). *Europe* implements coal-phase-out policies from 2022, and all other regions start implementing phase-out policies from 2027. Coal decline rates are percentages of total electricity supply per decade. Numbers in the cells show cumulative global emissions from unabated coal generation (2022–2050) in Gt CO_2 and how these relate to respective emissions in IPCC AR6 pathways.

		Limited diffusion from Europe to OECD N.Am. & Pacific by 2027	Global diffusion from Europe to all regions by 2027		
			Decline rate for *Asia + ROW*		
		Ref. for *Asia + ROW*	13%	20%	30%
Decline rate for *OECD + Europe*	13%	192 (between IPCC 2.5 °C and 3 °C medians)	167 (slightly above IPCC 2.5 °C median)	138 (between IPCC 2 °C and 2.5 °C medians)	114 (slightly above IPCC 2 °C median)
	20%	187 (between IPCC 2.5 °C and 3 °C medians)	161 (slightly above IPCC 2.5 °C median)	132 (between IPCC 2 °C and 2.5 °C medians)	108 (slightly above IPCC 2 °C median)
	30%	182 (between IPCC 2.5 °C and 3 °C medians)	157 (slightly above IPCC 2.5 °C median)	128 (between IPCC 2 °C and 2.5 °C medians)	104 (slightly above IPCC 2 °C median)

Reference scenario (Ref. *OECD + Europe*/Ref. *Asia + ROW*)—208 (slightly below IPCC 3 °C median).

most phase-out pledges are located (table S1). Due to these commonalities, for part of our analysis we merge them into a single *OECD + Europe* region. In contrast the *Asia + ROW* region, where Asian countries account for over 90% of coal-fired generation, generally has much younger coal power plants, rising electricity demand, lower incomes, virtually no historical decline episodes, and fewer phase-out pledges.

The coal decline scenarios are structured along two dimensions: diffusion and ambition of phase-out policies (table 2). In all policy scenarios, coal phase-out policies are present in *Europe*, where most countries already pledged phase-out (table S1). In the '*limited diffusion*' scenarios, policies diffuse only to the *OECD North America & Pacific* while *Asia + ROW* follows the reference case retirement. In the '*global diffusion*' scenarios, phase-out policies also diffuse to the *Asia + ROW* region. In the main set of scenarios coal phase-out pledges outside *Europe* are adopted in 2027, which is consistent with the observed movement of the feasibility frontier (figure 3). We also vary the start of diffusion to the *Asia + ROW* region from 2022 to 2040 (figure 5(b)).

For each assumption about diffusion, we assume three levels of **ambition** of the pledges: phasing out coal power at a constant rate of 13%, 20% or 30% relative to the region's total electricity supply per decade. These rates capture the range of the decline rates implied in the existing pledges as well as observed in the fastest historical cases for various sizes of electricity systems (figure 4(b)). An important consideration is that the regions we consider, especially *Asia + ROW* are larger than all historical entities, even the US and Western Europe. Various combinations of the diffusion and ambition assumptions give rise to 12 scenarios (table 2, figure 5).

Figure 5(a) compares cumulative unabated coal generation in 2022–2050 in our scenarios with the generation in the IPCC AR6 pathways grouped by the temperature outcome. Coal-based generation in the reference retirement scenario is just under the median value of 3 °C-consistent pathways. Coal power generation in the *limited diffusion* scenarios is comparable to the third quartile of 2.5 °C-consistent pathways, but significantly higher than in most 2 °C- and all 1.5 °C-consistent pathways. Coal power generation in the *global diffusion* scenarios is determined by the ambition of policies in *Asia + ROW*. The 13% decline rate results in coal generation just above the median of 2.5 °C-consistent pathways, while the 30% decline rate generally matches the median of 2 °C-consistent pathways. Figure 5(b) explores the effect on cumulative coal-fired generations of earlier or later adoption of pledges in *Asia + ROW*. Faster decline can compensate for slower diffusion: for example, the median cumulative generation across 2.5 °C-consistent pathways can be achieved by 13% decline starting around 2025, 20% decline starting around 2031, or 30% decline starting around 2034.

The coal phase-out scenarios illustrated in figure 5 show that future coal emissions will be primarily affected by policies in Asia rather than in Europe and

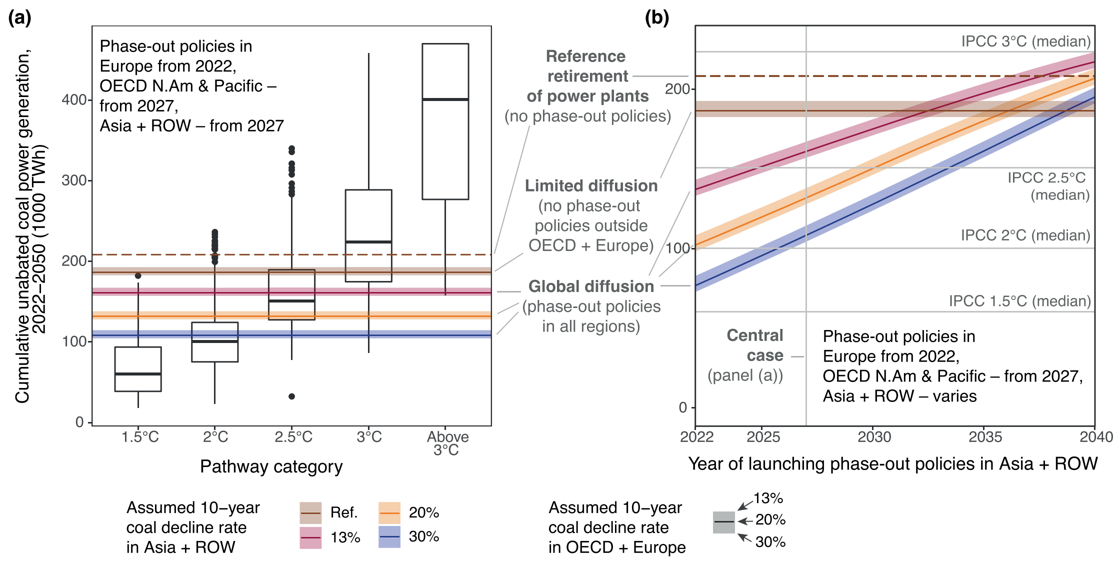

Figure 5. Global cumulative power generation from unabated coal in counterfactual coal decline scenarios compared to IPCC AR6 pathways (2022–2050) and the effect of the speed of policy diffusion. Colours represent different decline rates in *Asia + ROW*. Ranges of the same colour represent different decline rates in *OECD + Europe* (combination of *Europe* and *OECD North America and Pacific*), given a constant rate in *Asia + ROW*. The decline rates are % of the average total electricity supply per decade. (a) Global cumulative power generation from unabated coal in coal decline scenarios compared to IPCC AR6 pathways. Dashed line—reference decline trajectory where power plants retire at the respective average national lifetime. Boxes and whiskers—cumulative unabated generation from coal (2022–2050) in IPCC AR6 pathways by temperature category. Thick horizontal line—median, box—inter-quartile range; whiskers and dots—full range. (b) Effect of the speed of policy diffusion. The speed of policy diffusion is represented by the year in which the decline starts in *Asia + ROW* (the beginning of decline in *Europe* and *OECD North America and Pacific* is the same as in panel (a)). Horizontal lines represent medians of the respective temperature categories of IPCC pathways.

OECD. This means that emerging economies in Asia with their large and young power plants would need to bear a larger share of global coal phase-out effort necessary for achieving global climate targets. In the scenario where phase-out policies rapidly diffuse and coal declines by 30% per decade around the world, the avoided emissions per unit of GDP will be 3.4 times higher in Asia than in OECD and Europe. This disparity is reduced in half in case coal power declines at 13% in all regions, but equal distribution of effort is only possible when the rate of coal decline in OECD is 30% and in Asia—13% (table S9), which is roughly compatible with 2.5 °C warming.

4. Discussion

Though national decisions to phase-out coal result from complex political processes [9, 27, 32], we show that there are strong regularities in both the presence and ambition of coal phase-out pledges. The pledges are initially adopted in wealthy countries with small coal power fleets and then diffuse to countries with lower incomes and larger coal use. This diffusion seems to be faster than what can be predicted from the change of national characteristics so that the moving feasibility frontier illustrated in figure 3 may reach China and India much earlier than ca 2045 as estimated in the central case in [16]. However this expansion momentum should not be taken for granted [24]. Coal phase-out commitments may also be vulnerable to delays or reversals due to energy security shocks.

We find that the ambition of coal phase-out pledges is surprisingly consistent across countries including between ‘climate leaders’ adopting pledges earlier and ‘followers’ adopting pledges later. This means that the benefits of policy and technology learning accessible to the followers may be cancelled out by their less favourable socio-political circumstances [33]. Remarkably, the ambition of coal phase-out pledges remains within the feasibility zones of historically observed coal power decline in [6].

The empirically observed regularities in the diffusion and ambition of coal phase-out pledges can support assumptions about feasible policy-driven decline of coal power in the future. Under the most optimistic assumptions involving rapid worldwide diffusion and maximum ambition of coal phase-out policies, coal emissions would be consistent with about one-half of the 2 °C pathways, but still higher than in most 1.5 °C pathways. Under more realistic assumptions, coal emissions would be higher than in most 2.5 °C compatible pathways, but still lower than in 3 °C pathways. Even these assumptions are ambitious; for example, they only account for new coal power plants already under construction, even though some countries still have plans for additional coal power [26]. Thus, while previous work has highlighted the

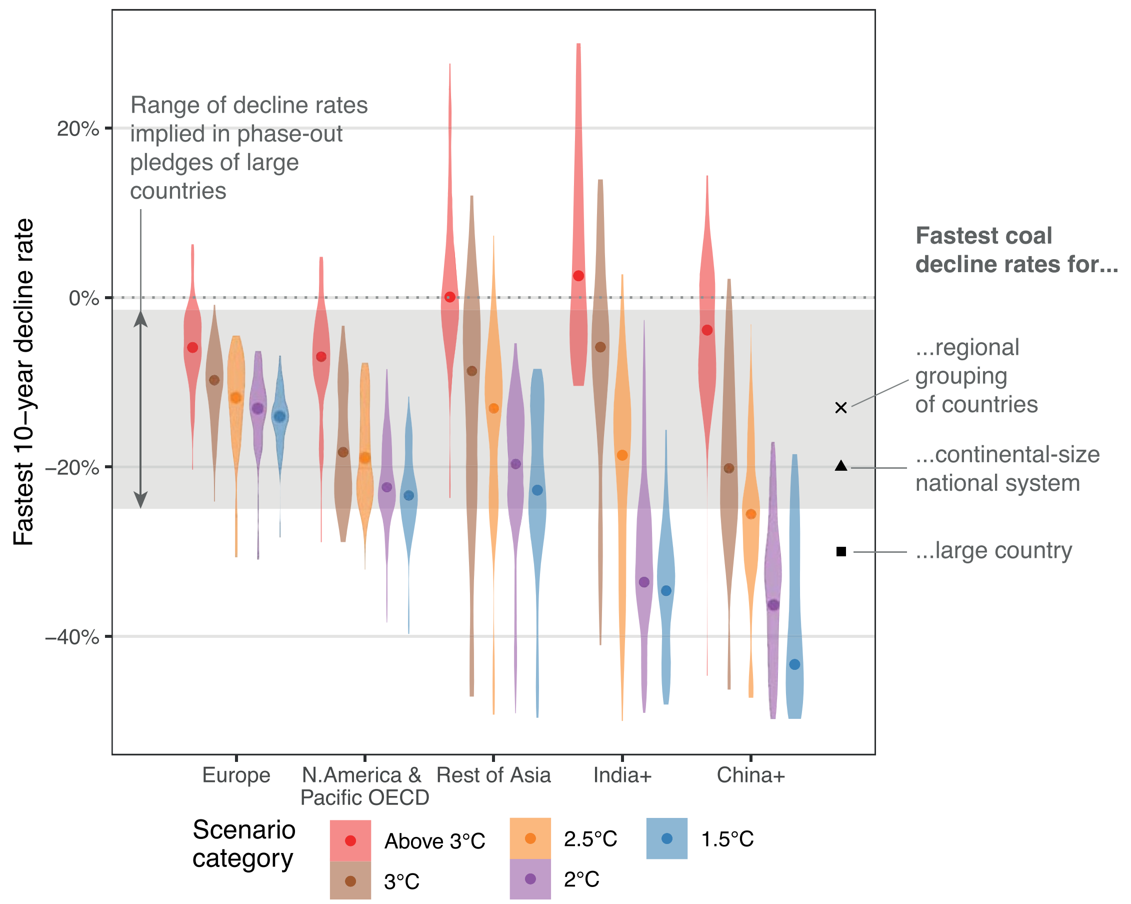

Figure 6. Fastest regional coal decline rates in IPCC AR6 pathways consistent with different temperature targets as compared to historical benchmarks. Fastest ten-year decline rates expressed as percentage of total electricity supply (note S1) are calculated for major coal-using regions in each pathway and grouped by scenario category (temperature target). Violins represent the density of rates; dots—median rates for the respective category/region combination; colours—scenario category. Faster rates are closer to the bottom of the figure. Grey band—range of decline rates implied in coal phase-out pledges of larger countries (total electricity supply >100 TWh/year), figure 4(b). Black symbols—historical benchmarks of coal decline also expressed as 10-year rates relative to the total electricity supply.

unrealistic nature of coal deployment in very high emission scenarios [34], our analysis establishes the lower end of a plausible [35] decline corridor.

Figure 6 shows that in the 1.5 °C and 2 °C-consistent IPCC pathways, decadal coal power decline rates in India+ and China+ regions are faster than in the existing national pledges of countries like Germany and the fastest historical episodes. Moreover, these pathways envision higher decline rates in India and China than in Europe and OECD which means the inequality of effort is even higher than in our scenarios. These differences stem from different approaches of envisioning the future of coal. The IPCC scenarios are primarily generated by cost-optimisation or simulation models depicting the behaviour of entire energy systems, economies, and climate and making exploratory rather than reality-bound assumptions about climate policies. In contrast, our scenarios only consider coal power but are based on empirically-derived assumptions about policies.

Our analysis stresses the challenges of coal phase-out that is compatible with strict climate targets. Part of the challenge is in instituting ambitious coal phase-out policies in all regions of the world, particularly in Asia [26]. To be in line with the 1.5 °C or 2 °C target, these policies should stipulate coal power decline faster than in the existing pledges of climate front-runners and faster than what was ever historically achieved even in an individual country. This also requires much stronger effort from India and China than from OECD countries. Such unequal effort sharing not only creates ethical problems but may also trigger resistance from countries where most effort is expected and thus jeopardize the feasibility of successful transition [36]. Furthermore, expecting higher effort from emerging economies may be unrealistic because these countries have less favourable conditions for coal phase-out policies (see figures 2 and 3 [37]). On the other hand, achieving an equal allocation of coal phase-out efforts while adhering to Paris targets is virtually impossible since European countries and other OECD members simply do not have enough potential for coal emission reduction.

Unequal burden allocation can be in part compensated through monetary transfers to alleviate justice and fairness concerns [38]. A coalition led by the US and Japan has pledged $20 billion to support Indonesia's coal phase-out [39] and the US, UK, EU, France, and Germany have pledged $8.5 for a just transition in South Africa [40]. More work is needed to understand the effectiveness of such initiatives since even these high sums may not be enough to sufficiently accelerate coal phase-out [41, 42]. Another approach is to reduce the required pace of the power sector's emission reductions through faster decarbonisation in other sectors [16, 43] or lessen the necessary rate of coal phase-out by retrofitting coal plants with carbon capture and storage [44, 45].

5. Conclusion

Developing feasible climate mitigation strategies is a key scientific and policy challenge. It requires understanding what climate solutions can be implemented in different contexts under realistic assumptions. Our analysis illustrates how this can be done with respect to coal power phase-out. We examine two major processes affecting coal phase-out policies: international diffusion and 'ratcheting up' of ambition which we use to develop empirically-grounded assumptions about a range of policies that can be expected in different regions in the future. This allows us to construct feasible coal phase-out scenarios.

We find that coal phase-out commitments are steadily diffusing to more difficult socio-political contexts and that if the most ambitious national pledges can be replicated worldwide, it would be possible to stay on track for 2 °C. Making this a reality faces two challenges. First, emerging economies, particularly in Asia, would need to bear a larger burden of coal phase-out which raises fairness concerns. Second, countries with coal phase-out commitments would need to stick to their plans even when facing energy security crises like the one caused by Europe's dependence on Russian gas.

Though our findings and scenarios are limited to coal, they can provide input to more complex models and scenarios as encouraged by [46] together with other feasibility assessments targeting different climate solutions such as [6, 33, 47–49]. There is an extensive research agenda on further developing this method [14] and extending it to a wider range of climate solutions.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare no conflict of interest.

Ethical statement

This research does not involve human participants or animal experimentation.

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References

[1] Climate Home News 2021 UK calls on countries to "consign coal to history" at COP26 (available at: www.climatechangenews.com/2021/05/14/uk-calls-countries-consign-coal-history-cop26/) (Accessed 28 April 2022)
[2] PPCA 2017 Powering past coal alliance: declaration (available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/740899/powering-past-coal-declaration.pdf) (Accessed 4 January 2022)
[3] Tong D, Zhang Q, Zheng Y, Caldeira K, Shearer C, Hong C, Qin Y and Davis S J 2019 Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target *Nature* **572** 373–7
[4] Cui R Y *et al* 2019 Quantifying operational lifetimes for coal power plants under the Paris goals *Nat. Commun.* **10** 4759
[5] Edenhofer O, Steckel J C, Jakob M and Bertram C 2018 Reports of coal's terminal decline may be exaggerated *Environ. Res. Lett.* **13** 024019
[6] Vinichenko V, Cherp A and Jewell J 2021 Historical precedents and feasibility of rapid coal and gas decline required for the 1.5 °C target *One Earth* **4** 1477–90
[7] Fouquet R and Pearson P J G 2012 Past and prospective energy transitions: insights from history *Energy Policy* **50** 1–7
[8] Kern F and Rogge K S 2016 The pace of governed energy transitions: agency, international dynamics and the global Paris agreement accelerating decarbonisation processes? *Energy Res. Soc. Sci.* **22** 13–17

[9] Blondeel M, de Graaf T V and Haesebrouck T 2020 Moving beyond coal: exploring and explaining the powering past coal alliance *Energy Res. Soc. Sci.* **59** 101304
[10] UNFCCC 2021 Global coal to clean power transition statement (available at: https://ukcop26.org/global-coal-to-clean-power-transition-statement/) (Accessed 15 November 2021)
[11] Jewell J, Vinichenko V, Nacke L and Cherp A 2019 Prospects for powering past coal *Nat. Clim. Change* **9** 592–7
[12] Green F 2018 The logic of fossil fuel bans *Nat. Clim. Change* **8** 449–51
[13] Tosun J and Croissant A 2016 Policy diffusion: a regime-sensitive conceptual framework *Glob. Policy* **7** 540
[14] Jewell J and Cherp A 2022 Feasibility spaces for climate action: a bridge between the inside and outside view *Scenarios Forum 2022 (Laxenburg, 20-22 June 2022)*
[15] Jewell J and Cherp A 2020 On the political feasibility of climate change mitigation pathways: is it too late to keep warming below 1.5 °C? *Wiley Interdiscip. Rev. Clim. Change* **11** e621
[16] Bi S, Bauer N and Jewell J 2022 Dynamic evaluation of policy feasibility, feedbacks and the ambitions of COALitions *Research Square* https://doi.org/10.21203/rs.3.rs-827021/v2 (Accessed 2 December 2022)
[17] Pahle M, Burtraw D, Flachsland C, Kelsey N, Biber E, Meckling J, Edenhofer O and Zysman J 2018 Sequencing to ratchet up climate policy stringency *Nat. Clim. Change* **8** 861–7
[18] Meckling J, Sterner T and Wagner G 2017 Policy sequencing toward decarbonization *Nat. Energy* **2** 918–22
[19] Gosens J, Hedenus F and Sandén B A 2017 Faster market growth of wind and PV in late adopters due to global experience build-up *Energy* **131** 267–78
[20] Grubler A, Wilson C and Nemet G 2016 Apples, oranges, and consistent comparisons of the temporal dynamics of energy transitions *Energy Res. Soc. Sci.* **22** 18–25
[21] Patterson J J, Thaler T, Hoffmann M, Hughes S, Oels A, Chu E, Mert A, Huitema D, Burch S and Jordan A 2018 Political feasibility of 1.5 °C societal transformations: the role of social justice *Curr. Opin. Environ. Sustain.* **31** 1–9
[22] Cha J M 2020 A just transition for whom? Politics, contestation, and social identity in the disruption of coal in the powder River Basin *Energy Res. Soc. Sci.* **69** 101657
[23] Bergquist M, Nilsson A, Harring N and Jagers S C 2022 Meta-analyses of fifteen determinants of public opinion about climate change taxes and laws *Nat. Clim. Change* **12** 235–40
[24] Jakob M *et al* 2020 The future of coal in a carbon-constrained climate *Nat. Clim. Change* **10** 704–7
[25] Galgóczi B 2020 Just transition on the ground: challenges and opportunities for social dialogue *Eur. J. Ind. Relat.* **26** 367–82
[26] Steckel J C and Jakob M 2022 To end coal, adapt to regional realities *Nature* **607** 29–31
[27] Ohlendorf N, Jakob M and Steckel J C 2022 The political economy of coal phase-out: exploring the actors, objectives, and contextual factors shaping policies in eight major coal countries *Energy Res. Soc. Sci.* **90** 102590
[28] S&P Global 2021 World electric power plants database (WEPP)
[29] Riahi K *et al* 2022 Mitigation pathways compatible with long-term goals *Climate Change: 2022 Mitigation of Climate Change. Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed P R Shukla *et al* ch 3 (https://doi.org/10.1017/9781009157926.005)
[30] Byers E *et al* 2022 AR6 scenarios database *Zenodo* (https://doi.org/10.5281/zenodo.5886912)
[31] Freedom House 2022 Freedom in the world 2022 methodology *Freedom in the World 2022 Methodology* (available at: https://freedomhouse.org/reports/freedom-world/freedom-world-research-methodology) (Accessed 28 April 2022)
[32] Brutschin E, Schenuit F, van Ruijven B and Riahi K 2022 Exploring enablers for an ambitious coal phaseout *Politics Gov.* **10** 200–12
[33] Cherp A, Vinichenko V, Tosun J, Gordon J A and Jewell J 2021 National growth dynamics of wind and solar power compared to the growth required for global climate targets *Nat. Energy* **6** 742–54
[34] Ritchie J and Dowlatabadi H 2017 Why do climate change scenarios return to coal? *Energy* **140** 1276–91
[35] Pielke R, Burgess M G and Ritchie J 2022 Plausible 2005–2050 emissions scenarios project between 2 °C and 3 °C of warming by 2100 *Environ. Res. Lett.* **17** 024027
[36] Leimbach M and Giannousakis A 2019 Burden sharing of climate change mitigation: global and regional challenges under shared socio-economic pathways *Clim. Change* **155** 273–91
[37] Spencer T, Colombier M, Sartor O, Garg A, Tiwari V, Burton J, Caetano T, Green F, Teng F and Wiseman J 2018 The 1.5 °C target and coal sector transition: at the limits of societal feasibility *Clim. Policy* **18** 335–51
[38] Höhne N, den Elzen M and Escalante D 2014 Regional GHG reduction targets based on effort sharing: a comparison of studies *Clim. Policy* **14** 122–47
[39] Taylor M 2022 Analysis: can Indonesia ditch coal and improve lives with new green deal? Reuters *Reuters* (available at: www.reuters.com/business/cop/can-indonesia-ditch-coal-improve-lives-with-new-green-deal-2022-11-18/) (Accessed 13 December 2022)
[40] European Commission 2022 South Africa just energy transition investment plan (available at: https://ec.europa.eu/commission/presscorner/detail/en/STATEMENT_22_6664) (Accessed 12 December 2022)
[41] Listiyorini E and Dahrul F 2022 Indonesia's $600 billion plan to shut coal plants struggles for support—bloomberg *Bloomberg* (available at: www.bloomberg.com/news/articles/2022-09-15/indonesia-s-600-billion-plan-to-curb-coal-struggles-for-support#xj4y7vzkg) (Accessed 13 December 2022)
[42] Ray L 2021 South Africa needs significantly more money to help phase out coal *Carbon Tracker* (available at: https://carbontracker.org/south-africa-needs-significantly-more-money-to-help-phase-out-coal/) (Accessed 12 December 2022)
[43] Muttitt G, Price J, Pye S and Welsby D 2022 Ignoring socio-political realities in 1.5 °C pathways overplays coal power phaseout compared to other climate mitigation options *Research Square* https://doi.org/10.21203/rs.3.rs-1419087/v1 (Accessed 11 October 2022)
[44] United States Department of State, United States Executive Office of the President 2021 The long-term strategy of the United States: pathways to net-zero greenhouse gas emissions by 2050 (available at: www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf) (Accessed 13 December 2022)
[45] Global CCS Institute 2022 Global Status of CCS 2022 (Washington, DC: Global CCS Institute) (available at: https://status22.globalccsinstitute.com/wp-content/uploads/2022/12/Global-Status-of-CCS-2022_Download_1222.pdf) (Accessed 7 December 2022)
[46] Trutnevyte E, Hirt L F, Bauer N, Cherp A, Hawkes A, Edelenbosch O Y, Pedde S and van Vuuren D P 2019 Societal transformations in models for energy and climate policy: the ambitious next step *One Earth* **1** 423–33
[47] Semieniuk G, Taylor L, Rezai A and Foley D K 2021 Plausible energy demand patterns in a growing global economy with climate policy *Nat. Clim. Change* 1–6
[48] Bager S L and Persson U M 2021 Reis TNP dos. Eighty-six EU policy options for reducing imported deforestation *One Earth* **4** 289–306
[49] Odenweller A, Ueckerdt F, Nemet G F, Jensterle M and Luderer G 2022 Probabilistic feasibility space of scaling up green hydrogen supply *Nat. Energy* **7** 854–65