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The cost of phasing out coal: Identifying and overcoming socio-political barriers

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Abstract

IPCC climate mitigation scenarios project rapid coal phase-out as an integral part of climate change mitigation. Despite the diffusion of cost competitive low-carbon alternatives to coal power, some argue that current decline is not in line with climate mitigation targets, and that rapid coal phase-out depicted in climate scenarios is not socio-politically feasible. This dissertation conceptualizes rapid coal power phase-out as one of three interconnected policy problems, as it affects the survival of coal power companies and related jobs, and the development of regions which heavily rely on coal power generation. In addition to coal phase-out policies, governments implement just transition strategies to address these policy problems: domestically, these policies financially compensate coal companies, regions and workers, and on international level, recent Just Energy Transition Partnerships support emerging economies with large coal fleets. However, while some argue that such policies are essential to enable rapid coal phase-out, others question the effectiveness and fairness of financial compensation for coal incumbents.

This dissertation contributes to the debates around feasibility and fairness of coal phase-out through two major avenues. First, it identifies that coal phase-out affects three interconnected systems: the technological system of coal power generation to be phased out, the industrial system comprised of coal companies that needs to adapt to coal phase-out, and regions heavily reliant on the coal industry that need to reorient. This dissertation develops a framework that allows researchers to diagnose the key socio-political mechanisms depending on the phase of decline each system is in and proposes policy sequencing of different strategies over time to decouple the decline of industry and regions from the decline of the technology. Second, inspired by the recent application of Daniel Kahnemann's "inside" and "outside view" to climate science, this dissertation studies existing coal phase-out commitments and just transition strategies as reference cases to better understand the socio-political feasibility of coal phase-out in climate mitigation scenarios. It finds that while coal phase-out commitments have diffused to countries with larger shares of coal in their electricity mix, accelerated policy-driven coal phase-out commitments tend to be accompanied by just transition strategies. Implementing similar just transition strategies in the two countries with the largest coal fleets globally, China and India, in line with 1.5°C -2°C IPCC scenarios might require most, if not all, of the $100 billion annual climate finance pledged by Global North countries.

This dissertation contributes to better understanding key socio-political mechanisms affecting coal phase-out and proposes a quantitative approach to measure what it takes to overcome them, thus enabling a more informed debate on the effectiveness and fairness of compensation schemes as well as an opportunity to incorporate socio-political feasibility into climate mitigation models. Future research on the cost and management of just transition strategies is required as these strategies are at very early stages of implementation, and more reference cases added as new strategies emerge. Additionally, similar strategies and financial compensation accompanying past decline episodes may shed further light on the cost of accelerated coal phase-out.

Appended Publications

This dissertation is based on the following papers:

Paper I Nacke, L., Cherp, A., Jewell, J. (2022). Phases of fossil fuel decline: Diagnostic framework for policy sequencing and feasible decline pathways. *Oxford Open Energy*.

J.J. and A.C. conceptualized the article. L.N. conducted the literature review and case studies. L.N. and J.J. wrote the original article. All authors revised the article. J.J. supervised the work.

Paper II Vinichenko, V., Vetier, M., Jewell, J., Nacke, L., Cherp, A. (2023). Phasing out coal for 2 °C target requires worldwide replication of most ambitious national plans despite security and fairness concerns. *Environmental Research Letters*.

J.J. and A.C. conceptualized the article. M.V. and L.N. collected data on coal phase-out pledges. V.V. led data analysis and visualization. L.N. conducted data analysis on effects of the Russo-Ukrainian war on coal phase-out pledges. V.V. wrote the original article, all authors revised the article.

Paper III Nacke, L., Vinichenko, V., Cherp, A., Jakhmola, A., Jewell, J. Socio-political cost of accelerating coal phase-out, 18 April 2023, PREPRINT (Version 1) available at Research Square [https://doi.org/10.21203/rs.3.rs-2733550/v1].

JJ & AC conceived the study. JJ, AC and LN developed the Methodology. LN led investigate and data curation. LN, VV, and AJ conducted formal analysis. LN and JJ wrote the original draft with contributions from AC. All authors contributed to visualisation. JJ provided supervision and LN project administration. JJ acquired funding.

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1. Introduction

The most urgent power source to be phased out for climate change mitigation is coal power: in 1.5°C-consistent IPCC scenarios, unabated[1] coal power generation declines by 88% (median estimate) between 2020 and 2030, and much faster than other fossil fuels (Muttitt et al., 2023). This is a massive challenge globally, as coal is the largest single source of power generation, supplying roughly one third of electricity worldwide (IEA, 2023a). Technically, this challenge seems surmountable: low-carbon alternatives to coal power generation are available and the cost of renewable technologies continues to decline in many markets and are now cheaper than coal power (IEA, 2023b).

However, socio-politically there are challenges to implementing rapid coal phase-out. First, national governments that plan coal phase-out often face resistance from negatively impacted groups such as workers (Abraham, 2017), companies (Geels, 2014; Markard, 2018) and regions with a highly concentrated coal industry (Henry et al., 2020; Johnstone & Hielscher, 2017). Second, countries and regions where coal resources and power plants are concentrated are likely to bear a higher share of the burden of global coal phase-out (Muttitt et al., 2023; Vinichenko et al., 2021). Countries with emerging economies and large coal fleets, such as India and Indonesia, have raised concerns about the cost of coal phase-out at international climate negotiations (Rathi & Chaurdhary, 2021; The Straits Times, 2021). Finally, larger geopolitical shifts particularly related to the Russo-Ukrainian war signal a third challenge: since the beginning of the war, energy security has gained importance compared to climate change mitigation, especially in European countries with a dependency on Russian oil and gas (Tollefson, 2022). These challenges lead to a dilemma of how to implement rapid coal phase-out which is also socially and politically acceptable (Newell et al., 2022; Patterson et al., 2018).

One political strategy to enhance the social and political acceptability of coal phase-out are 'just transition' policies (Jakob et al., 2020; Kramer, 2022; Voss & Rafaty, 2022; Wong et al., 2022). Such policies aim to address negative effects of coal phase-out, such as job losses and bankruptcy of companies in coal-dependent regions, often through financial transfers. At national level, they often include compensation for coal workers, companies and regions among other actors negatively affected by coal phase-out. At the international level, such policies support coal phase-out in countries with emerging economies and a high share of coal in the electricity system, such as Indonesia, South Africa, and Vietnam (European Commission, 2022a, 2022b; Foreign & Commonwealth and Development Office, 2022). Similar programs are under discussion with India and Senegal (Kramer, 2022; Mathiesen & Barigazzi, 2022). However, there is disagreement about the effectiveness of these policies, as well as about what kind of support, and to whom, they should include. Some argue that just transition policies are crucial to achieve coal phase-out, both for countries within the EU and for major coal consumers such as China (Timmermans, 2022; Voss & Rafaty, 2022). Others criticize such policies for burdening taxpayers to further support incumbents, and potentially

[1] Unabated coal power generation means coal use without Carbon Capture and Storage.

even prolonging the duration of coal phase-out (Oei, 2020). This presents a dilemma as governments face additional costs for coal phase-out in spite of the fact that it is one of the most accessible climate mitigation measures in terms of availability of cheap alternatives.

This dissertation speaks to the policy challenge of phasing out coal without triggering social and political backlash or imposing excessive policy costs. To do this, it bridges the empirical literature on the dynamics of coal phase-out with the modeling literature on cost-effective climate mitigation pathways. The empirical literature is grounded in a rich understanding from small and large-n studies on why and how coal declines in countries and sub-national regions (Brauers et al., 2020; Cui et al., 2021; Diluiso et al., 2021; Edenhofer et al., 2018; Jewell et al., 2019; Ohlendorf et al., 2022; Stognief et al., 2019; Trencher et al., 2020; Vinichenko et al., 2021). The modelling literature shows how fast coal phase-out occurs for climate change mitigation targets under different technological and economic assumptions (Riahi et al., 2015; Rogelj, Popp, et al., 2018; Rogelj, Shindell, et al., 2018). Connecting these two literatures requires addressing three research questions:

- What are the main mechanisms associated with the persistence or decline of coal at the regional, national and global level?
- How do these mechanisms depend on the economic and political context?
- What do they imply for feasible policy options?

Paper I addresses all three questions through a literature review on coal phase-out and fossil fuel decline. Based on this review, it proposes a framework to diagnose the main mechanisms depending on the phase of coal decline, and to address these mechanisms through a policy sequence. Paper II addresses the first two questions through empirical analysis of national coal phase-out commitments and characteristics of the countries that made these commitments. Paper III addresses the third question through empirical analysis of just transition strategies that aim to overcome socio-political barriers to coal phase-out.

This dissertation first outlines the background and approach to diagnosing and learning from socio-political mechanisms affecting coal decline. Second, it summarizes the three papers which address this overarching question[2]. Section 3 describes their methods, and Section 4 highlights their main results. Finally, this dissertation discusses its contributions and the broader questions it raises in the scientific and political context.

[2] Note that this dissertation presents selected results in the context of its research focus. Paper II in particular provides more extensive analysis and results than presented here. Please refer to each paper for its broader methods, results, and contributions.

2. Background and approach

2.1 Mechanisms of coal phase-out

Rapid coal phase-out projected in climate mitigation scenarios has been criticized as not adequately considering mechanisms of socio-political feasibility (Bi et al., 2023; Muttitt et al., 2023; Spencer et al., 2018). This dissertation proposes a systems approach to diagnosing techno-economic and socio-political mechanisms that affect feasible decline pathways. Inspired by Elinor Ostrom and colleagues(McGinnis & Ostrom, 2014; Ostrom, 2007), such an approach divides overarching systems into several co-evolving subsystems, and studies mechanisms and variables related to each of the subsystems. This enables scholars to understand the combination of mechanisms that lead to either stalled or sustained decline of coal power. Systems are also embedded in broader political and economic settings that influence how the sub-systems interact with each other (McGinnis & Ostrom, 2014; Ostrom, 2007, 2011). Ostrom and her colleagues applied this approach to the study of socio-ecological systems, such as the use of a lake for fishing(Ostrom, 2007). Cherp *et al.*(2018) and Foxon (2011) have previously applied similar approaches to the study of energy transitions.

For the case of coal phase-out, identification of sub-systems is guided by three interconnected policy problems:

- the policy problem of phasing out coal power generation for climate change mitigation affects the technological system.
- the policy problem of the survival or death of companies in the coal sector affects the industrial system.
- the policy problem of the recovery of coal-intensive regions affects the regional system.
- the political action system (Easton, 1957) encompasses the policy approaches in response to each of these policy problems.

Figure 1 shows the relationship between the three coal-related systems and the PAS, as well as two specific strategies within the PAS addressed in this dissertation.

Different academic disciplines provide insights into the mechanisms and variables for each of these systems. Mechanisms related to the decline of coal technologies have been discussed by socio-technical transitions scholars, mechanisms related to the evolution of the coal industry by business and management scholars, and mechanisms related to the recovery of coal-intensive regions by regional geographers and economists as well as just transitions scholars.

The socio-technical literature highlights that the diffusion and cost decline of low-carbon alternatives can accelerate the phase-out of coal power generation (Anderson & Tushman, 1990; Fouquet & Pearson, 2012; Griliches, 1957). Despite these economic drivers, actors within the incumbent regime such as coal power companies can pursue strategies to sustain the declining technology. Such strategies can include political lobbying, retrofitting existing assets or building new assets that better comply with environmental standards and regulations (Geels, 2014; Loorbach et al., 2017; Ohlendorf et al., 2022; Unruh, 2002;

Utterback, 1994). Incumbents are more likely to resist if their assets are younger and more valuable: as coal power plants age over time, or coal mines become depleted, their economic value decreases, and a phase-out of the asset means a lower loss to the owner (Spencer et al., 2018; Turnheim & Geels, 2012). However, when plants become retrofitted or newly built through new investments, a phase-out leads to higher sunk costs and potential resistance (Trencher et al., 2020). One dominant explanation for slow coal decline that combines many of these mechanisms is 'lock-in' – recent literature on lock-in emphasizes that technologies have become strongly embedded in society as infrastructure, user practices and institutions are built around technologies (Loorbach et al., 2017; Seto et al., 2016; Trencher et al., 2020; Unruh, 2000). In relation to coal phase-out, this becomes clear as electricity grids are built to accommodate coal power plants, or as workers are strongly unionized and have access to decision-making.

While investments in coal technology and specialization in skills required for coal mining and power generation create strong links between the technology and coal companies (Klepper & Simons, 1996; Peltoniemi, 2011), these systems can uncouple, a process which is influenced by several mechanisms. For example, companies can invest in alternative technologies such as renewables, so that the same company can persist as a technology declines. At the most basic level, companies can switch from coal to an alternative fuel (such as biomass or gas) (Hicks & McGovern, 2009). Whether companies are able to re-invest depends on whether they have the knowledge and resources to adopt new technologies (Harrigan, 1980; Peltoniemi, 2011). It may be easier to reorient if existing business models, competencies and skills can be transferred to the new technology (Agarwal & Tripsas, 2008; Anderson & Tushman, 1990). If many companies reorient to new technologies and divest from coal power generation, this advances technological decline. However, companies may also pursue a strategy of resistance rather than adaptation to technological change, where they may either ignore this change for as long as possible, or lobby for policies in support of the incumbent technology (Harrigan, 1980; Markard, 2018; Ohlendorf et al., 2022; Utterback, 1994). In cases where coal workers are unionized, unions may pursue their own strategies of resistance or adaptation (Abraham, 2017; Galgóczi, 2020; Goods, 2013). Depending on which strategies companies choose, and how successful these are, the overall industry structure may change: companies within the industry may merge, go bankrupt or move abroad (Deily, 1991; Klepper & Simons, 1996; Peltoniemi, 2011).

Bankruptcy or flight of coal companies especially affects regions where these companies were previously concentrated. It is for example likely that coal companies cluster (Breinlich et al., 2014) in regions with available coal resources (Yoon, 2017). The quick retreat of coal companies from such regions can lead to exacerbated unemployment effects, a loss of tax revenue, and ultimately cause stagnated economic development and outmigration (Breinlich et al., 2014; Johnstone & Hielscher, 2017; Simmie & Martin, 2010; Stognief et al., 2019), which some authors have described as a regional lock-in (Martin & Sunley, 2006). The degree to which regions are able to recover from the loss of the coal industry may also depend on geographical or political characteristics, such as the availability of land for new technologies or companies, the availability of natural resources, financial incentives for entrepreneurship, among others (Breinlich et al., 2014; Glaeser et al., 2012; Yoon, 2017). Regional governments can pursue different strategies in response to coal power decline, ranging from resistance through lobbying the national government for prolonged support, to renewal, through promoting the arrival of new businesses and the hiring of new personnel (Breinlich et al., 2014; Kline & Moretti, 2013; Oei et al., 2019). The degree to which regional governments can implement their preferred strategies depends on their autonomy from national governments, as well as their connectedness to the coal industry (Breinlich et al., 2014; Glaeser et al., 2012; Rector, 2018; Stognief et al., 2019).

There are some overlaps between the three systems discussed above. Similar actors are connected to each of the three systems: for example, power companies in the coal industry use coal power generation technology and are situated in coal regions. Nevertheless, conceptualizing these systems separately is important because it enables the development of strategies to bridge the dilemma between the speed of coal phase-out on the one side, and social acceptability and justice concerns on the other side (Newell et al., 2022). Such strategies are contained in the political action system (PAS), which includes actions that result in laws and regulations affecting coal power generation - in other words, political decisionmaking (Easton, 1957). The PAS is in turn affected by actors within the regional, industrial and technological systems. For example, public awareness of climate change or environmental pollution can result in pressures to phase out coal faster(Green, 2018), whereas energy security concerns (for example due to the recent energy crisis in Europe, or due to rising energy demand in emerging economies) can lead to support for fossil fuel technologies (Ohlendorf et al., 2022; Tollefson, 2022).

Finally, all of these systems are enclosed in broader economic and socio-political settings (Ostrom, 2007). These types of settings include for example the size of the national economy (Jewell et al., 2019), the type of democracy and to what extent stakeholders have access to decision-making (Rentier et al., 2019), and whether the energy market is liberalized or not (Turnheim & Geels, 2012). The difference between these settings and the PAS is that, while specific policies can change relatively quickly, the processes by which political decisions are made, the relative wealth and rate of economic growth, and the way in which energy markets are structured (for example privatized vs publicly owned companies) tends to change over a much longer period of time, and thus does not co-evolve to the same extent as the other systems.

Conclusion

Several mechanisms affect technological, industrial and regional systems, which in turn affect the PAS and its outputs: policies for coal phase-out. This section has given an overview of different that address the question “What are the main mechanisms associated with the persistence or decline of coal at the regional, national and global level?”. The following section reviews an approach to learn about socio-political feasibility of coal phase-out from empirical case studies.

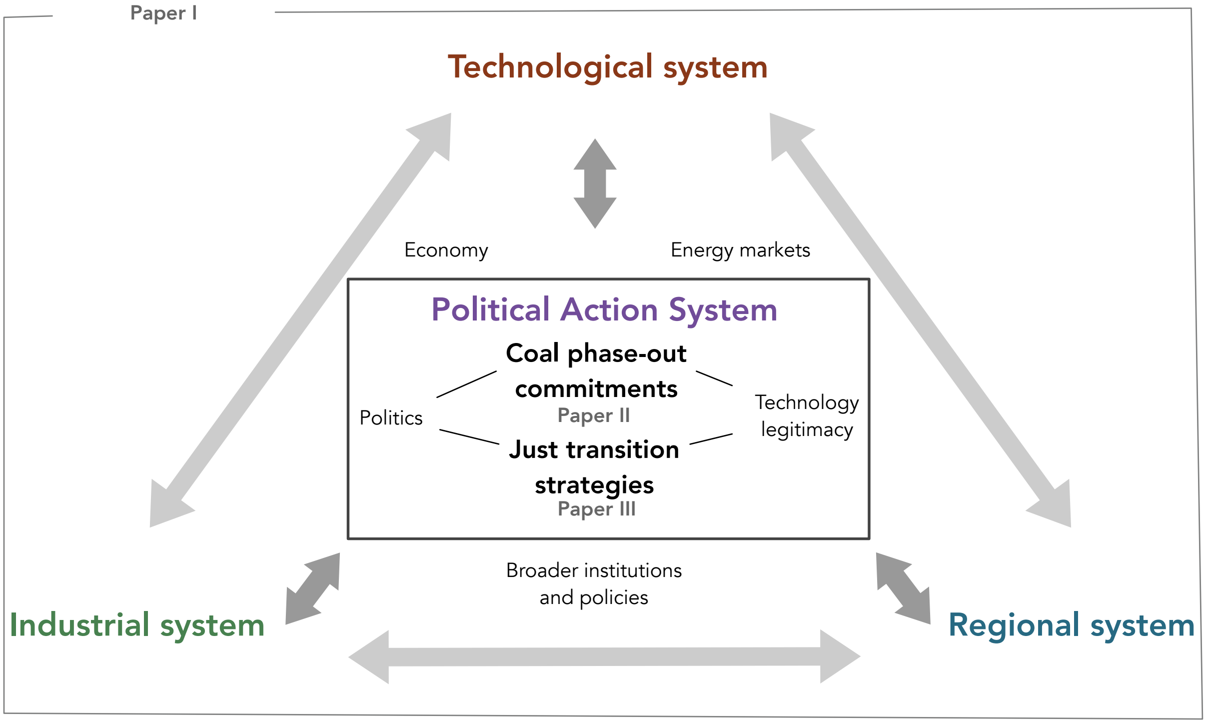

Figure 1. Systems of coal decline, political strategies for coal decline and papers in this dissertation studying these systems. *Adapted from Paper I. This figure shows the three systems implicated by coal decline (technological, regional and industrial), as well as the political action system in relation to each of these systems. The broader context (Economy, energy markets and broader institutions and policies) is captured around the political action system.*

2.2 Approach to studying political action systems with multiple mechanisms – The inside-outside view

PASs are affected by multiple mechanisms, such as strategies of actors that resist coal phase-out (Geels, 2014; Stognief et al., 2019), state interests such as energy security (Fothergill, 2017; Ohlendorf et al., 2022), and state capacities such as the wealth of a country (Jewell et al., 2019). These mechanisms provide constraints or enablers for PASs to introduce climate mitigation policies such as coal phase-out. In other words, they affect the feasibility of climate mitigation policies. Jewell and Cherp (Jewell & Cherp, 2023) define feasibility of climate options as “do-able under realistic assumptions” that are backed by strong evidence. This definition of feasibility is different from “plausibility” of pathways in climate scenarios, which “provid[e] a useful context to understand technical and economic concerns [but needs] to be strictly differentiated from feasibility … in the real world” (Riahi et al., 2015).

Climate scenarios follow what Kahneman and Lovallo (Kahneman & Lovallo, 1993) termed “the inside view”: they see climate change as a unique problem and focus on the unique possibilities and challenges related to this problem, assuming that skilled and committed policymakers can overcome them (Jewell & Cherp, 2023). Scenarios provide many insights into possible solutions for climate change mitigation based on current knowledge of causal mechanisms and internally consistent assumptions (Jewell & Cherp, 2023). However, not all relevant mechanisms may be known, observable or quantifiable in a way consistent with climate scenarios, leading to an emphasis on techno-economic mechanisms over socio-political mechanisms which “might render … model solutions unattainable” (Riahi et al., 2015).

In contrast to the inside view, “the outside view” focuses not on the details of the unique problem at hand, but rather studies several relevant cases that are similar to the problem (Jewell & Cherp, 2023; Kahneman & Lovallo, 1993). An example of this approach are studies that compare historical analogues to future climate scenarios (Napp et al., 2017; Pielke et al., 2008; Semieniuk et al., 2021; Smil, 2010; Jan Christoph Steckel et al., 2013; Vinichenko et al., 2021) to develop benchmarks for what may be feasible based on historical experience. One criticism of these approaches is that the future can develop differently than the past, for example due to motivation for climate action (Fouquet & Pearson, 2012; Kern & Rogge, 2016), or cost decline of renewables (Creutzig et al., 2017).

Jewell and Cherp (2023) introduce feasibility spaces as an approach that bridges the inside and the outside view to address these tensions. They introduce five steps to building feasibility spaces:

1. **Defining the target case.** Relevant target cases can be climate mitigation options from climate scenarios, such as the IPCC AR6 scenario database, or national climate targets. This dissertation focuses on the decline of coal power generation in 1.5°C- and 2°C-consistent IPCC AR6 scenarios.
2. **Identify reference cases.** Relevant reference cases tend to be similar in outcome, or in context, to the target case. However, the degree to which references cases are similar to the target case needs to be balanced with the number of relevant cases, as to enable the availability of data for meaningful (statistical) analysis. This dissertation uses past coal decline trajectories, coal phase-out commitments, and just transition policies as reference cases for coal decline in climate scenarios (see Section 2.3).
3. **Measure and compare reference case outcomes.** To compare reference cases to each other, and to target cases, outcomes may need to be normalized to account for different system characteristics such as system size. In this dissertation, for example, the rate of coal decline is normalized to electricity system size, and compensation cost is normalized to avoided emissions of coal phase-out.
4. **Construct a feasibility space.** A feasibility space is a virtual space which depicts the distribution of outcomes (such as the rate of change in coal power generation) across reference cases in relation to relevant characteristics, which have been identified as causally linked to the outcome through analysis of the reference cases (such as change in total electricity demand over the same period as coal decline). This dissertation includes several feasibility spaces, such as coal phase-out commitments mapped to national and coal sector-related characteristics (Paper II and III), and compensation cost mapped to national GDP (Paper III).
5. **Map target case(s) on the feasibility space.** Finally, target cases can be mapped to feasibility spaces. This can enable a relative feasibility assessment: if target cases have similar characteristics to reference cases, this provides evidence for the assumption that the respective climate action may be “do-able”. If they are less similar to reference cases, this does not mean the action is impossible, but that unprecedented effort or other major developments may be required to achieve these outcomes. This dissertation compares the characteristics of countries with coal phase-out

commitments to major coal consumers without coal phase-out commitments (Papers II and III).

Conclusion

Not all socio-political mechanisms are represented in climate scenarios(Jewell & Cherp, 2023). To better understand the feasibility of policy options projected in climate scenarios, this dissertation constructs feasibility spaces to compare to climate scenarios, as proposed by Jewell and Cherp (2023). The target case of this dissertation is coal decline in major coal consuming countries. Specifically, Paper III studies the target case of coal phase-out in IPCC AR6 1.5°C- and 2°C-consistent scenarios for the two countries with the largest coal fleets globally: India and China. The following section describes the reference cases: existing coal phase-out and just transition policies compensating affected actors.

2.3 Reference cases: Strategies for coal phase-out

This section focuses on two outputs of the PAS that address the policy problems related to coal decline and phase-out which this dissertation uses as main reference cases to better understand the feasibility of coal decline depicted in climate scenarios: coal phase-out commitments and just transition policies.

2.3.1 Coal phase-out commitments

Historically, coal power generation (and the use of other fossil fuels) has significantly declined in several countries (Muttitt et al., 2023; Vinichenko et al., 2021). The fastest episode of coal decline relative to electricity system size has occurred in the UK from 2007-2017 at about 30% over ten years, even though coal has been declining at different rates since the 1980s (Vinichenko et al., 2021). During the decline episode from 2007-2017, coal decline was accompanied by a demand decline of about 15% (Vinichenko et al., 2021). The UK was also among the first countries to politically commit to coal phase-out – in 2017, the UK and Canada founded the Powering Past Coal Alliance (PPCA), which had been joined by 30 countries until 2018(Jewell et al., 2019). Blondeel *et al.* (2020) find that countries with no domestic coal power generation at all are most likely to join the PPCA, and that a large domestic coal mining industry also decreases the likelihood of joining the PPCA. Jewell *et al.* (2019) developed a feasibility space based on all PPCA members that have coal power generation in their electricity mix at the time of joining the PPCA, and found that countries with higher governance capacity and a lower share of coal in electricity generation were most likely to commit to phasing out coal.

Despite historical coal decline and existing coal phase-out commitments, current coal trajectories are not in line with political climate targets such as the Paris agreement(Cui et al., 2019; Edenhofer et al., 2018). Some argue that the diffusion of climate mitigation policies may be able to provide this acceleration (Kern & Rogge, 2016). Mechanisms that support such diffusion may be increasing climate concerns (Kern & Rogge, 2016), as well as anti-fossil fuel norms and international pressure that rises as more countries adopt coal phase-out pledges (Bi et al., 2023; Green, 2018). Bi *et al.*(2023) find that increasing international pressure, as well as cost decline of competing technologies, can shift feasibility frontiers over time to make it possible that coal phase-out commitments are made in less favorable contexts. Additionally, governments' capacities can shift over time, so that governments become more capable of implementing climate action.

However, there are also barriers to international diffusion of coal phase-out. First, the burden of phasing out coal may be perceived as unfair in countries where young coal power plants supply increasing energy demand for emerging economies (Jakob et al., 2020). In a review of eight major coal countries (including China, Indonesia and Vietnam), Ohlendorf *et al.* (2022) find that economic growth is the "single most important objective" and drives coal deployment. Steckel and Jakob (2022) also argue that in some contexts, capacities to implement coal phase-out may be lacking. Additionally, the strength of the coal industry may hinder coal commitments to be made (Ohlendorf et al., 2022).

Notwithstanding these barriers, since 2019, many new coal commitments have been made. In 2021 for example, twenty-three new countries committed to phasing out coal by either joining the PPCA or signing the Global Coal to Clean Power (GCCP) Statement at COP26 (Neagu & Taylor, 2021; PPCA, 2021; UNFCCC, 2021). The diffusion of coal phase-out commitments over time provides a unique reference case to test whether the feasibility frontier for coal phase-out has shifted over time. Additionally, since its beginning in 2022, the Russo-Ukrainian war significantly changed the international energy policy landscape (Tollefson, 2022). What role did the war, and related energy security concerns, play for the implementation and diffusion of coal phase-out commitments?

2.3.2 Just transition policies

In addition to coal phase-out policies, several countries have developed strategies that address the second and third policy problem: the reorientation of companies in the coal sector, and the recovery of coal regions. These policies are often termed 'just transition' policies that accompany coal phase-out laws, and often include financial support to negatively affected actors. The concept of 'just transition' originated from labour unions in the US and Canada, to support laid-off workers as domestic polluting industries were closed (Galgóczi, 2020; Rector, 2018; Stevis & Felli, 2020). Over time, 'just transitions' have become associated with climate change mitigation, as labour unions promoted the concept at international climate negotiations, with a focus on the employment effects of climate change mitigation measures such as coal phase-out (Stevis & Felli, 2015, 2020). Beyond employment effects, energy and climate justice scholars have studied just transition policies, considering whether they enable an overall more fair and equitable society (McCauley & Heffron, 2018; Newell & Mulvaney, 2013; Stevis & Felli, 2020). Justice scholars examine for example whether the process by which a strategy was decided upon was inclusive, or whether it addresses existing societal inequalities (Newell & Mulvaney, 2013; Stevis & Felli, 2020). Just transition policies have also been proposed as one way to address global equity concerns of coal phase-out (Jakob et al., 2020; Stevis & Felli, 2020), for example through international financial transfers. However, just transitions may also raise equity and fairness concerns. One such concern is whether the compensation of fossil fuel incumbents is fair, especially considering this compensation is financed by tax revenues (Oei, 2020).

This dissertation focuses on just transition policies that are explicitly linked to coal phase-out commitments. In the short term, these policies may reduce resistance by powerful incumbents and thus help accelerate coal phase-out (Patterson et al., 2018; Jan C. Steckel & Jakob, 2022; Timmermans, 2022). In the long term, they can address broader fairness concerns by supporting the recovery of coal regions and coal companies as well as the re-employment of coal workers (Harrahill & Douglas, 2019; Johnstone & Hielscher, 2017; Jan C. Steckel & Jakob, 2022).

Germany is one of the most prominent examples of such a compensation scheme, having allocated more than EUR40 billion in compensation to coal regions, as well as compensating coal companies and coal workers (2020; ZEIT Online, 2020). The basis for the coal phase-out and compensation plan was a compromise reached by the Commission for Growth, Structural change and Employment (dt. Kommission Wachstum, Strukturwandel und Beschäftigung), installed by the government and including representatives of coal industry, workers, regions, as well as climate science and environmental organisations (Brauers et al., 2022; Reitzenstein & Popp, 2019). Several other countries such as Canada and Chile have installed similar Commissions (Brauers et al., 2022).

In addition to transfers on national level, international transfers to support coal phase-out include for example the EU's Just Transition Fund (European Commission, 2023), which provides financial support to the EU regions most vulnerable to negative effects of climate change mitigation. More recently, Just Energy Transition Partnerships (JETPs) have been established as a new mechanism to support climate change mitigation in emerging economies (Kramer, 2022). These JETPs entail provisions for financial support to emerging economies to implement a plan for decarbonisation of the electricity system, including the decline of coal power generation. So far, JETPs have been agreed with South Africa, Indonesia and Vietnam as recipient countries, and further partnerships are in discussion with India and Senegal (European Commission, 2022a, 2022b; Foreign & Commonwealth and Development Office, 2022; Kramer, 2022; Sarr & Fall, 2022). JETPs have the potential of being especially influential in the international diffusion of coal phase-out commitments by kicking off coal phase-out in contexts where capacities may be relatively lower and the strength of the coal sector relatively larger.

However, since JETPs and other just transition policies are in very early stages of implementation, it is not yet clear to what extent they will help accelerate coal phase-out. While some highlight the importance of just transition schemes to ensure social acceptability of climate mitigation measures (Jakob et al., 2020; Patterson et al., 2018; Voss & Rafaty, 2022), others warn that consensus-driven negotiations may fall short of international climate targets (Newell et al., 2022), and may bear the risk of prolonged coal power generation pushed for by pro-coal interests (Reitzenstein & Popp, 2019). While there have been studies focusing on individual just transition policies, or comparing them in selected countries (Brauers et al., 2022; Reitzenstein & Popp, 2019; Voss & Rafaty, 2022), there has been no systematic assessment of all compensation schemes. How expensive are such schemes, what are they financed from and who receives this finance? How do they relate to the speed of coal phase-out? Such an assessment can contribute to debates around the cost, climate effectiveness and justification of compensation schemes (Kramer, 2022).

Conclusion

National coal phase-out commitments, and the compensation schemes accompanying them, serve as an empirical window into socio-political mechanisms affecting coal phase-out. While there have been studies of coal phase-out commitments in the past, recent political developments such as the Russo-Ukrainian war and the diffusion of coal phase-out commitments to new countries raise questions about whether feasibility frontiers have changed over time. Additionally, there is uncertainty regarding the relationship between compensation schemes and the speed versus justice dilemma of coal phase-out. The following section outlines the methods by which this dissertation addresses these uncertainties.

3. Methods: Studying socio-political barriers of coal phase-out and strategies to overcome them

3.1 Mechanisms and phases of decline (Paper I)

Paper I builds on Ostrom and colleagues' (McGinnis & Ostrom, 2014; Ostrom, 2007) approach to identify the relevant systems implicated by fossil fuel decline, and retrieve the mechanisms affecting the evolution of each of these systems from the relevant literature. Mechanisms are then mapped to the respective system: sociotechnical transitions literature describes the mechanisms affecting the technological system of coal power generation, business and management literature describes the mechanisms affecting the industrial system comprised of coal companies, and regional geography and economics literature describes the mechanisms affecting regional systems rich in coal resources and assets. The results of the literature review inform a framework that shows the evolution of each of the three systems as it undergoes different phases of decline and outlines the conditions under which these systems are likely to co-evolve or decouple. Finally, Paper I proposes the approach of policy sequencing to support coal decline throughout the different phases. While Paper I mainly offers a conceptual contribution, it also contains three illustrative case studies that showcase the different phases of decline.

3.2 Calculating and comparing decline rates (Paper II)

Paper II compares historical coal decline rates and decline rates implied by national coal phase-out pledges. Coal decline rates are normalized to the total electricity supply (TES). This ensures a more meaningful comparison of reference cases to each other (see Section 2.2).

Historical national decline rates are retrieved from Vinichenko *et al.*(2021), who identify 37 cases of relevant national fossil fuel decline: decline of over 5% per decade in systems over 100 TWh/year. They focus on large systems because in relatively small systems, small absolute changes would lead to a large decline rate. Additionally, in countries with small TES, most electricity is often imported, meaning that they are not "systems in the strictest sense, but rater part of electricity systems of larger neighboring countries"(Vinichenko et al., 2021). Historical decline rates are calculated by dividing the difference between unabated coal power generation at the beginning and the end of each identified period by the average of TES over the same period.

To estimate coal decline rates implied by national phase-out pledges, the share of coal in TES is calculated for the year in which coal phase-out was pledged. Coal share is then divided by the duration of coal phase-out from the year the pledge was made until the year in which coal is to be phased out. This method assumes stable TES over time. If TES would increase in the future, normalized decline rates would become slower, and if TES would decrease in the future, normalized decline rates would become faster, which is intuitive as declining energy demand is likely to enable faster coal phase-out.

3.3 Diffusion of coal phase-out commitments and delay due to the Russo-Ukrainian war (Paper II)

Paper II follows the evolution of coal phase-out commitments both since 2017, and since the beginning of the Russo-Ukrainian war. First, global coal phase-out commitments (by 2022) are systematically captured. The review includes countries' participation in political initiatives such as the Powering Past Coal Alliance (PPCA) and the Global Coal to Clean Power (GCCP) agreement. It also includes international and EU-wide documents such as Nationally Determined Contributions (NDCs), National Energy and Climate Plans (NECPs) and National Recovery and Resilience Plans (NRRPs) (the latter two are submitted to the EU). To ensure that all national commitments are captured, a systematic google search is conducted to retrieve any additional coal phase-out commitments. Government documents and press releases containing the year in which coal phase-out is committed by are also retrieved. Countries with coal phase-out commitments are divided into three groups, to compare national characteristics across these groups: Group 1: countries which committed to coal phase-out before 2019; Group 2: countries which committed between 2019 and 2022; Group 3: GCCP signatories with no other coal phase-out commitments. These groups function as reference cases, and their national characteristics are compared to target cases: the nine largest coal consumers globally without coal phase-out commitments. This sheds light on the evolution of the feasibility space for coal phase-out over time, and on how similar countries with coal phase-out commitments are to major coal consumers.

To capture the risk of coal phase-out delay due to the Russo-Ukrainian war, we conduct systematic Google searches in April, June, July and December 2022, using the search string "[country name] + coal phase out" and reviewed news articles and other reports published since the start of the war on 24 February 2022. This analysis focuses on European countries. These countries are closest to the Russian border and several countries have large dependencies on Russian oil and gas, thus their energy plans are most likely to be affected by the unstable geopolitical relationship and embargoes on oil, gas and coal.

One limitation regarding the analysis and comparison of coal phase-out commitments across countries is the extent to which commitments are reliable. For example, it is unclear whether commitments under the GCCP should be considered similarly reliable as other national coal phase-out commitments enshrined in national laws. Indonesia for example, which has signed the GCCP and receives funding under its JETP, has 12 GW coal power under construction, and roughly 10 GW more are likely to be built (Montrone et al., 2023).

3.4 Amount and distribution of coal phase-out compensation (Paper III)

Building on the data collection of coal phase-out commitments for Paper II, Paper III includes a systematic google search of compensation schemes related to coal phase-out pledges for paper III. The search strings "[country name] + coal phase-out + just transition" and "[country name] + coal phase-out + compensation" are used to retrieve government documentation such as laws, just transition plans and national budgets; as well as press releases and, where necessary, third party reports. From these documents, beneficiaries and origins of compensation as well as the amount of compensation paid by each country are identified.

Similarly to the study of coal phase-out commitments, a limitation is that compensation schemes are formalised to varying degrees in different countries. While in some countries compensation has already been enshrined in national laws (e.g. Netherlands, Germany and Canada), in other countries, laws are still under deliberation at the time of writing (e.g. Poland). Just Energy Transition Partnerships (JETPs) are only at early stages of implementation, and while current agreements express potential for continuation of funding over a longer period of time, it is unclear how large such compensation will be. These limitations are addressed by including compensation not confirmed in national legislation as an 'upper estimate' of an uncertainty range. However, the database of compensation schemes needs to be continuously updated to reflect changes in compensation commitments.

3.5 Relationship between compensation and coal phase-out acceleration (Paper III)

To relate the amount of compensation to the acceleration of political coal phase-out commitments, avoided emissions of coal phase-out are calculated for each country with a coal phase-out commitment using the method developed by Jewell *et al.*(Jewell et al., 2019). Essentially, the variable of avoided emissions captures how much earlier power plants are retired than their natural retirement age, estimated as the historical average of power plants' age at retirement within a country. All countries with coal phase-out commitments are mapped against avoided emissions, to find out whether countries with higher avoided emissions tend to compensate affected actors.

A multiple variables regression analysis serves as an additional test of the mechanisms affecting coal phase-out compensation, using the amount of compensation as the dependent variable and testing several independent variables reflecting the coal sector and government capacities. These include for example avoided emissions of coal phase-outs, amount of coal mined, national GDP and a measure of the quality of democratic governance.

One limitation is that there is a relatively small sample of 20 countries that compensate affected actors of coal phase-out. One agenda for future research is to add additional compensation cases as they arise. This can increase the robustness of the statistical analysis, and can test whether the same mechanisms remain relevant over time, or whether other mechanisms emerge.

3.6 Cost of just transition for China and India (Paper III)

The empirical analysis of countries with coal phase-out compensation functions as reference case to estimate the cost of a potential compensation scheme for our target cases: 1.5°C- and 2°C- consistent coal phase-out of the countries with the largest coal power plant fleets globally, China and India. First, coal phase-out scenarios for China+ and India+ regions are built in line with 1.5°C- and 2°C-consistent IPCC pathways. IPCC AR6 C1 and C2 pathways are selected as 1.5°C-consistent pathways, and C3 and C4 as 2°C-consistent pathways. China+ and India+ regions are used due to the resolution of IPCC scenarios, and because each country accounts for at least 97% of coal power generation in its respective region.

Avoided emissions of coal phase-out in China+ and India+ regions are estimated by comparing IPCC-consistent emissions to emissions if coal plants in both regions retire according to their natural retirement age. Avoided emissions are applied to the best performing regression models (Section 3.5) to understand how large compensation for 1.5°C- and 2°C-consistent coal phase-out might be for China and India respectively. This results in an approximation of compensation cost for China and India based on the regression results of analysing empirical coal compensation schemes. However, as previously discussed, this regression includes a relatively small number of cases. Statistically significant mechanisms may change as more cases are added to the regression analysis, or as mechanisms change over time.

4. Results

4.1 Mechanisms affecting socio-political feasibility of coal phase-out (Papers I and II)

The following section summarizes the results from three papers in the context of this dissertation. For the full results and detailed discussion, please refer to each paper.

4.1.1 Main mechanisms depend on the phase of decline (Paper I)

Coal phase-out affects three systems: the technological system of coal power generation, the industrial system of coal companies, and the regional system of actors and assets within certain geographical boundaries. Finally, coal phase-out is affected by outputs, i.e. policies, from the political action system (PAS), such as environmental standards or coal power generation bans. Actors within the three systems may influence the PAS to encourage policies that either sustain or phase-out coal power generation. Each of these systems undergoes several phases of decline. As the coal power technology declines, it seems natural that the three systems co-evolve with each other, which means that the development of one system affects and is mirrored in the other systems so that they undergo similar phases(Norgaard, 1994; Ostrom, 2007). However, systems may also decouple and develop independently from each other(Norgaard, 1994). Paper I outlines potential pathways for coal decline where systems either co-evolve or decouple, and propose a policy sequence (Leipprand et al., 2020; Meckling et al., 2017; Pahle et al., 2018) to enable rapid and socially acceptable coal phase-out.

In the first phase, all systems are tightly coupled: coal power generation is locked in (Turnheim & Geels, 2012), the industrial system is mature (Peltoniemi, 2011) and regional characteristics are stable (Simmie & Martin, 2010). In this phase, policies that destabilize the status quo can kick-off coal decline. In the second phase, coal power generation is destabilized and declines (Loorbach et al., 2017; Turnheim & Geels, 2012), accompanied by the closure or flight of companies in the industrial system (Lieberman, 1990; Peltoniemi, 2011) and a downturn in the regional system as the number of jobs in and tax returns from the coal industry declines (Simmie & Martin, 2010). Here, a mix of policies can sustain coal decline on the one hand, and manage resistance to decline on the other hand. In the last phase where coal is phased out (Loorbach et al., 2017), systems may continue to co-evolve: coal companies may continue to flee to other countries or go bankrupt (Lieberman, 1990), and regions may enter a survival mode (Simmie & Martin, 2010), for example materializing in a high unemployment rate and persistent outmigration. However, systems can also decouple: for example, companies can upgrade and invest in alternative technologies or services (Martin & Sunley, 2006). Similarly, coal regions can renew and attract new industries that are not coal-related (Simmie & Martin, 2010). Different policies can support such decoupling, such as just transition policies for regions, or R&D support for companies.

Of course, decoupling can also occur before the last phase of decline, for example in the illustrative case of South Africa. At the time of analysis, the technological system is in the first phase: coal power generation is locked in and provides about 80% of electricity in 2022 through a mature industry dominated by the state-owned utility Eskom (Baker et al., 2014; Burton et al., 2018; Department of Mineral Resources and Energy, 2019). However, at regional level, there are discussions of just transition and a decoupling from the technological system (Life After Coal, 2021; Strambo et al., 2019). Additionally, in the PAS, there are looming changes: one plan has been to divide Eskom into separate companies responsible for different tasks such as power generation or distribution (Department of Mineral Resources and Energy, 2019). Most recently, a Just Energy Transition Partnership (JETP) has been agreed with South Africa, which entails financial support for coal phase-out (European Commission, 2022b). One goal of the JETP is to support the unbundling of Eskom, and thus destabilize the current lock-in, as well as support regions affected by changes to South Africa's electricity system.

An example of coal power generation in the second phase is the US. Examples of relevant indicators are that coal is not competitive in relation to gas and other power technologies (Hauenstein & Holz, 2021; Mendelevitch et al., 2019), demand is stagnating (Coglianese et al., 2020; Mendelevitch et al., 2019), the coal power fleet is aging (Hauenstein & Holz, 2021), the number of companies in the coal sector (Cha, 2020; EIA, 2020; Mendelevitch et al., 2019) and the tax base in coal regions such as Appalachia or the Powder River Basin (PRB) is declining (Carley et al., 2018; Cha, 2020). While there have been some policies attempting to address resistance against coal decline and regional decay, such as support for regional innovation and economic development (Roemer & Haggerty, 2021), resistance to coal decline remained strong and was utilized for example by Donald Trump in his presidential campaign (Cha, 2020).

Finally, an example of the third phase of coal phase-out is coal mining in the Netherlands, which has been phased out in the 1970s (a policy for coal power phase-out is currently underway). The decline of coal power was kicked off by the discovery of the Groningen gas field, and was largely supported by the industrial system - especially workers' unions were in favor of reorienting towards more profitable chemicals and other industries (Gales & Hölsgens, 2017; Kaijser, 1996). Policies to support the reorientation of companies and the retraining of workers were put into place (Gales & Hölsgens, 2017). One former coal company that entered the chemicals sector managed to thrive, while other companies closed (Gales & Hölsgens, 2017; Jeannet & Schreuder, 2015; Normann, 2019). Regional development was hampered by the oil crisis which ensued shortly after the coal phase-out and hindered the growth of new industries (Kaijser, 1996).

These empirical cases illustrate the co-evolution, but also the decoupling of systems implicated by coal phase-out. They also show that different types of policies are employed across contexts and throughout phases of decline to support coal phase-out regional economic development. The recent example of South Africa's JETP provides an example of combining incentives for destabilization of the technology with support to industry and regions, while the technological system is still locked in, and may be an interesting case for further observation and analysis.

4.1.2 Countries pledge coal phase-out rates up to the speed of fastest historical decline (Paper II)

Comparing the implied rates of pledged coal decline across countries shows that most countries pledge phase-out of up to 30% coal decline per year. Only three countries pledge coal decline faster than this: Panama, Greece, and Czechia, which all have total electricity supply below 100 TWh/year. Generally, faster decline is pledged by countries with smaller shares of coal in their electricity system. The fastest ten-year period of historical coal decline has been 30% of decline in the United Kingdom between 2007-2017. However, this decline period was accompanied by electricity demand decline, and has not been sustained over a longer time period: overall coal decline in the UK has occurred over decades and been interspersed with periods of stagnation (Vinichenko et al., 2021).

4.1.3 Energy security concerns since Russo-Ukrainian war have a limited effect on coal phase-out diffusion (Paper II)

Since 2018, twenty-three new countries have committed to phasing out coal by either joining the PPCA or making separate national pledges, and nineteen additional countries have signed the Global Coal to Clean Power (GCCP) statement. For Paper II, all countries with coal phase-out commitments are divided into three groups:

- **Group 1**: committed to coal phase-out between 2017 and 2018
- **Group 2**: committed between 2019 and 2022
- **Group 3**: signed the GCCP, which is a less demanding commitment as it pledges to phase out coal "in the 2030s (or as soon as possible thereafter) for major economies and in the 2040s (or as soon as possible thereafter globally" (UNFCCC, 2021)

Countries in Group 1 tend to have the lowest share of coal in electricity supply, highest GDP per capita (adjusted for Purchasing Power Parity), and most transparent governance.

Countries in Group 3 have the highest share of coal in electricity supply, lower GDP per capita, and less transparent governance. Countries in Group 3 also have a much younger power plant fleet on average, while the average age of coal power plants in Group 1 and 2 is similar (even though the variance is larger for Group 2). Overall, this indicates that the feasibility frontier for coal phase-out has shifted over time to less favorable contexts. China and India, the two countries with the largest coal fleets globally, seem to be most similar to Group 3 as they have a relatively high share of young coal plants in their electricity supply, and GDP per capita is relatively low.

Despite the diffusion of coal phase-out commitments to other contexts, the beginning of the Russo-Ukrainian war in 2022 and related embargoes, electricity price increases and the overal volatile political situation, led to increased energy security concerns for many European countries, as Russia is a major oil and gas supplier to Europe(Tollefson, 2022). How did this affect coal phase-out commitments of European countries?

Since the start of the Russo-Ukrainian war, five countries reiterated their original coal phase-out commitments, indicating that there are no plants to delay coal phase-out. Notably, this group of countries includes Poland and Germany, the European countries with the largest coal fleets. However, five countries show changes to coal phase-out pledges or coal legislation, and six countries are potentially at risk of delaying or reversing coal phase-out. While some countries make explicit statements about prolonging the use of coal (e.g. Greece, Hungary) or proposing to re-start already closed power plants (e.g. Austria, France), others are increasing the short term use of coal (e.g. Italy, Netherlands).

Overall, this assessment suggests that while there is some risk of delay of coal phase-out and increasing use of coal in the short term, there is no complete turnaround on the goal of coal phase-out. Most statements seem to treat coal power as a short term, rather than a long-term solution, such as Bulgaria which aims to maintain coal power until two planned nuclear reactors are built (see Paper II, Table S5).

Table 1 Risk of delay or reversal of coal phase-out in European countries*. Based on Table S5, Paper II. This table shows European countries with coal phase-out commitments, and whether coal phase-out commitments in these countries are at risk due to the Russo-Ukrainian war. This table does not include Ukraine, which committed to phasing out coal in 2021 before the start of the war. Ukraine is excluded due to the clear disruption of the ordinary implementation of plans and targets.*

Risk of delay or reversal of coal phase-out	Countries (bold: 5 countries with largest coal fleets)	Installed GW coal
Yes	Bulgaria, France, Greece, Hungary, Ireland	11
Potentially	Austria, **Italy**, Netherlands, Romania, Slovenia, **UK**	22
No risk	Croatia, **Czechia**, Denmark, **Germany**, **Poland**	84
No evidence	Finland, Montenegro, North Macedonia, Slovakia, Spain	6
Total	-	122

4.2 Compensation to overcome socio-political feasibility challenges

4.2.1 Coal phase-out compensation to coal regions, workers and companies is roughly comparable to EU carbon price (Paper III)

To overcome national barriers to coal phase-out, several governments have introduced just transition policies that compensate affected actors and support adjustment to coal phase-out. Compensation schemes in most countries compensate domestic coal regions (see Table 2). The Netherlands, which phased out domestic coal mining in the 1970s, also supports a Colombian coal mining region(Covenant in respect of improvements in the coal supply chain, 2020). Ten compensation plans mention specific support to coal companies, and eight plans mention specific support to coal workers. Six plans explicitly mention support for renewables technologies, but do not specify which actor will receive this support. It may thus either be used by (former) coal companies, their subsidiaries, or new entrants.

Table 2 Groups of actors that benefit from compensation schemes. *This table summarizes the groups of actors that benefit from compensation schemes, based on the beneficiaries and purposes outlined in compensation strategies. Based on Supplementary Table 1, Paper III.*

Coal regions		Coal companies	Coal workers
Germany	Bulgaria	Germany	Germany
Indonesia	Slovakia	Indonesia	South Korea
Vietnam	Portugal	Vietnam	Poland
Poland	Hungary	Poland	Spain
South Korea	Slovenia	South Africa	Canada
Spain	Netherlands (abroad)	Slovakia	Slovakia
Greece	Croatia	Finland	France
Czechia	France	Netherlands	Chile
Canada	North Macedonia	Chile	North Macedonia
Italy	South Africa	Ukraine	Ukraine

While there are 24 countries that plan compensation, it is only possible to quantify costs of 21 plans. For Chile and North Macedonia, data on the cost of compensation is not available, and Ukraine is excluded from analysis due to the Russo-Ukrainian war. In total, the 21 remaining countries pay $186 billion to compensate for coal phase-out (best estimate - 118-253 full range). About half of this compensation is paid as international transfers, including EU transfers to member states and JETPs to South Africa, Indonesia and Vietnam. The other half of payments are domestic transfers by national governments. Uncertainty in quantifying compensation arises for example from cases where amount of compensation could not be confirmed in official government documentation, or cases where compensation is dependent on future developments (such as the indicated extension of Just Energy Transition Partnerships that is dependent on political action in the recipient countries).

Compensation varies by country, from $0.1-65 billion (best estimate - 0.1-79 full range). What is this variation based on? One hypothesis is that the amount of compensation depends on the extent to which a coal phase-out pledge accelerates natural retirement of the coal fleet. This can be operationalized by calculating avoided emissions of coal phase-out, which captures the size and average age of the national coal fleet (see section 3.5, Jewell *et al.*(2019), Papers II and III for details). Phasing out larger and younger coal fleets is likely to be more expensive since this increases the amount of stranded assets. Normalised to avoided emissions of the coal phase-out, coal phase-out compensation is largely consistent with the carbon price under the EU Emissions Trading Scheme over the past five years. One clear outlier is Hungary: total compensation tends towards the lower range ($0.3 bn), but normalised to avoided emissions is roughly $3000/tCO2. This is because avoided emissions in Hungary are very low (0.1 Mt CO2), as the country only phases out one very old coal power plant as well as a small coal mining industry (Botár, 2022).

4.2.2 Politically driven, accelerated coal phase-outs are accompanied by compensation schemes (Paper III)

To further investigate the relationship between accelerated coal phase-out and compensation, all countries with coal phase-out commitments and compensation are mapped onto a feasibility space, by the amount of avoided emissions and the amount of installed coal capacity. The concept of avoided emissions captures an additional aspect to the rate of coal decline, namely the age of the retired power plant fleet (see Section 3.5). This is relevant from a climate mitigation perspective because older power plants are more likely to be phased out for techno-economic reasons, while it requires political effort to phase out younger plants that lead to large stranded assets and whose phase-out is more likely to be resisted by power plant owners. The feasibility space shows that countries with higher avoided emissions tend to compensate affected actors (see Figure 1, Paper III). Here, this is captured in Table 3, which shows that even though twenty countries phase out coal without compensation affected actors, these countries phase out roughly one fifth of coal capacity, and roughly one ninth of avoided emissions of countries with compensation schemes. Additionally, most countries that pay compensation also have a domestic coal mining industry, while more than half of countries without compensation do not mine coal.

Table 3. Countries with coal phase-out commitments, installed coal, avoided emissions and pledged compensation. *Number of countries with and without compensation schemes, avoided emissions and pledged compensation are based on own analysis for Papers II and III. Data on installed capacity and number of coal plants is retrieved from the World Electric Power Plants Database(S&P Global, 2021). For detailed information on each country, see Supplementary Table 2, Paper III.*

	Nr of countries (without any coal mining)	GWe & (Number) of operating coal plants	Avoided emissions (Mt CO2)	Pledged compensation ($billion)
Phase-out pledges & compensation schemes	23 (3)	258 (1536)	5790 (4660-7650)	186 (118-253)
Phase-out pledges, no compensation schemes	20 (11)	51 (320)	657	-

Countries with avoided emissions above 500 Mt CO2 and above 20 GWe installed coal capacity, most of which also have a domestic coal mining industry, pay compensation above $10 billion. While wealthier countries with large coal fleets pay compensation (almost) exclusively from national funds, such as South Korea and Germany, emerging economies such as Indonesia and Vietnam receive international transfers. Countries with lower avoided emissions and smaller fleets pay up to $1 billion of phase-out compensation. Almost all of the latter group of countries are EU member states, and about two-thirds (65% central estimate) of compensation is paid by international transfers such as the EU Just Transition Fund. A multiple variables regression analysis confirms that for the sample of countries with both coal phase-out commitments and associated compensation, the variable of avoided emissions of coal phase-out is significantly correlated to compensation. The best-performing models also control for the level of democracy (measured by the indicator polyarchy) or GDP, and the amount domestic of coal mining (see Table 4).

Table 4. Variables and coefficients of best-performing regression models. *This table shows the variables and coefficients of our two best performing regression models, ranked by Aikaike Information Criterion (AIC) and Adjusted* R^2*. Polyarchy is an aggregate indicator that captures governments' responsiveness to citizens for example through fairness of elections and freedom of association and expression(Coppedge et al., 2022). For more details on the regression analysis and an overview over all models, see Supplementary Note 3, Paper III.*

Variable	Model A	Model B
Avoided emissions (Mt CO2)	36.9*** (4.5)	33.9*** (6.5)
Coal and lignite mining (Mt)	49** (13.7)	57.4* (15.5)
Polyarchy	-21,949* (8,984)	
GDP ($ million)		0.001 (0.002)
AIC	313	319
Adj.R2	0.87	0.83

4.2.3 Compensation to achieve 1.5C°/2C° climate mitigation pathways for China and India might strain domestic and international budgets (Paper III)

Paper II finds that rates of coal decline envisioned by 1.5°C- and 2°C-consistent IPCC AR6 scenarios for China and India are faster than rates of pledged coal phase-out commitments in large countries, such as Germany, and faster than any historically observed decline episodes. For EU and OECD countries, IPCC AR6 scenarios envision coal decline pathways in line with empirically observed phase-out commitments. This indicates equity concerns of climate mitigation effort globally, as a major burden falls on major coal consumers with growing economies and energy demand. In 1.5°C- and 2°C-consistent scenarios, avoided emissions of coal phase-out for China and India are 13-18 times as high as avoided emissions of all current coal phase-out pledges globally.

Based on empirically observed compensation, how expensive would compensation be for these major consumers if they phased out coal in line with 1.5°C and 2°C pathways? Based on the best performing regression models (Section 4.2.2), 1.5°C-consistent compensation for China and India would be 17 times as large as compensation of all currently pledged compensation schemes. Compared to national GDP, India bears an especially large burden with 1.5°C-consistent compensation above 2% of national GDP.

What national and international financial flows may provide potential avenues for funding of such compensation? One possibility for domestic funding might be to redirect coal subsidies, which in China are larger than tax revenues(Clark & Zhang, 2022) but still much smaller than required compensation. One possibility for international funding are JETPs, of which one is under discussion with India (Kramer, 2022). At COP26, the Indian Prime Minister requested $1 trillion in international climate finance (Rathi & Chaurdhary, 2021) - per year of coal phase-out, this would be roughly double 2°C-consistent compensation cost in India, and similar to 1.5°C-consistent cost. If it is funded by international flows, modelled compensation for China and India would require most, or all of, climate finance by Global North countries who pledged to transfer $100 billion per year to poorer countries to support climate change mitigation there (IEA, 2021).

5. Discussion and Conclusions

5.1 Returning to the research questions

Global and rapid coal phase-out is a key climate mitigation measure, highlighted by many climate models. Despite the availability of cheaper alternatives, existing political action for coal decline does not align with climate mitigation targets (Cui et al., 2019; Edenhofer et al., 2018). This dissertation addresses three overarching research questions:

The first question asks, "What are the main mechanisms associated with the persistence or decline of coal at the regional, national and global level?" To answer this question, coal phase-out is conceptualized as one of three interconnected policy problems, including the survival of companies in the coal sector and the recovery of regions where coal assets are concentrated. Paper I draws on coal phase-out literature and finds that the mechanisms affecting coal phase-out change throughout the phases of decline. Once coal power generation has been destabilized, resistance against company closure and regional downturn are the key risks for sustained coal decline.

The second questions asks, "How do these mechanisms depend on the economic and political context?" Paper I draws on McGinnis and Ostrom's (2014; also Ostrom, 2007) approach to conceptualize the technological, industrial, regional and political action system (PAS) as co-evolving subsystems, which are affected by developments in the broader socio-political and economic settings (see Figure 1). Paper II analyses political coal phase-out pledges as reference cases and finds that, while coal phase-out commitments diffuse to more challenging contexts, the strength of the coal sector and national capacity to overcome costs of coal phase-out still affect the likelihood of national coal phase-out pledges. Paper II also studies the effect of a recent development in the broader geopolitical setting, namely the Russo-Ukrainian war, on European coal phase-out commitments. While there is evidence of coal phase-out delay in several countries, the majority of capacity under European coal phase-out pledges remains committed under the original timeframe. Three of Europe's largest coal consumers have reiterated their phase-out commitments since the start of the war (Table 1).

The third question asks, "What do [these mechanisms] imply for feasible policy options?" Paper I proposes sequencing of policy options to address the main mechanisms at each phase of coal decline. Paper III studies the interaction of two policy options for coal phase-out: political coal phase-out pledges and just transition policies that compensate affected actors. It quantifies the cost of existing compensation schemes, and finds that policy-driven, accelerated coal phase-out is accompanied by compensation schemes, especially in countries with domestic coal mining (Table 3). The amount of compensation is proportional to the extent of premature retirement of coal power plants (measured by avoided emissions), and similar to the price of carbon under the EU Emissions Trading Scheme. Paper III applies these reference cases to China and India, the two countries with the largest coal fleets globally, and finds that similar compensation in line with 1.5°C- and 2°C- consistent IPCC pathways would be 17 times as large as compensation of all currently pledged compensation schemes, and comparable to total climate finance pledged by Global North countries at COP (IEA, 2021).

5.2 Contributions

This dissertation contributes to the broader research agenda on the socio-political feasibility of coal phase-out and climate mitigation more generally in several ways.

Methodologically, this dissertation develops an approach to estimate the cost of overcoming socio-political barriers to coal phase-out by quantifying the cost of coal phase-out compensation. This is different from types of costs captured in other studies, such as investment cost to switch from one fuel to another (International Energy Agency, 2022), or changes to energy system cost (Energiewende & enervis, 2021). While these studies may capture what it takes to make coal phase-out techno-economically feasible, estimated compensation cost quantifies the cost of making coal phase-out socio-politically feasible. Empirical cases of compensation cost and coal phase-out pledges are used as reference cases to estimate compensation scenarios for our target cases: coal phase-out under 1.5°C- and 2°C-consistent IPCC pathways for China and India.

Conceptually, quantifying cost of overcoming socio-political barriers bridges insights from empirical literature on coal phase-out and techno-economic approaches often applied in the modelling literature with a focus on the cost of mitigation. In addition to coal phase-out, this approach could potentially be applied to other policy arenas where policymakers face resistance, such as the growth of renewables technologies. Paper I also develops a conceptual framework to diagnose decline mechanisms not only depending on the political and geographical context, but also on the phase of decline, and to develop policy sequences to decouple the decline of industry and regions from the decline of the technology. This contributes to the debate on appropriate policy options for coal decline by sequencing two seemingly contradictory strategies: destabilizing incumbents or compensating affected actors, such as coal companies and regions (Kivimaa & Kern, 2016; Steckel & Jakob, 2022; Turnheim & Geels, 2012).

Empirically, Paper II finds that over time, political commitments for coal phase-out are spreading to more difficult contexts, largely despite challenges in the broader political and economic settings. This contributes to debates around the diffusion of climate policy over time (Bi et al., 2023; Green, 2018; Ohlendorf et al., 2022). Paper III also builds a novel database of compensation schemes, as well as their costs, beneficiaries and origins of compensation flows, and links these to the acceleration of coal phase-out through political commitments. This contributes to debates around the role and cost of just transition policies to overcome the “speed versus justice” dilemma of coal phase-out (Newell et al., 2022).

5.3 Broader questions and future work

The approaches and findings presented here give rise to several broader questions and uncertainties which may inform future research agendas.

First, there are questions around the diffusion and strength of compensation policies. Policy approaches can spill over across countries as they learn from each other’s experiences, and countries such as Indonesia and India have already asked for international finance for climate change mitigation and coal phase-out (Rathi & Chaurdhary, 2021; The Straits Times, 2021). South Africa is the first country receiving global transfers under its Just Energy Transition Partnership (European Commission, 2022b) without having a concrete coal phase-out pledge. A similar partnership is now under discussion with India. Paper III provides a first estimate of how large compensation may be in countries like India and China for climate-consistent coal phase-out, but as compensation policies extend to new contexts, additional analysis is necessary to discover if the feasibility frontier changes over time, similarly to what Paper II finds for coal phase-out commitments.

Second, there are questions around how compensation schemes will be implemented and managed. For example, it is unclear what accountability measures will be used to ensure funds are used for the intended purposes. Since compensation policies are also very recent, it is unclear what their effectiveness will be in the long-term - how will coal phase-out experiences differ in regions that receive compensation compared to regions that did not receive compensation? Will compensation ultimately support the decoupling of regional and industrial from technological systems? These questions are particularly relevant in light of the finding that countries with lower institutional capacity have higher compensation.

An additional uncertainty relates to the question how coal decline and phase-out unfolds in countries without compensation. While Paper III suggests that policy-driven, accelerated coal phase-out in countries with larger coal fleets is typically accompanied by compensation, there are countries that phase out coal without compensation schemes, or where coal power and/or coal mining have declined in the past without deliberate compensation schemes. Two such examples are coal decline in the US by 20% between 2008 and 2018, and in the UK by 30% between 2007 and 2017 (Vinichenko et al., 2021). In both cases, the discovery of affordable gas resources has driven coal phase-out – a mechanism which may not be desirable to replicate for climate change mitigation. While the US has not yet politically committed to coal phase-out, and the UK’s 2017 coal phase-out pledge has not been directly accompanied by a single just transition policy, there have been funds and policies in both countries supporting coal regions, workers and/or companies. These include for example the Coalfields Regeneration Trust and Regional Growth Fund in the UK that both precede the coal phase-out commitment (Wong et al., 2022), as well as the ‘Partnerships for Opportunity and Workforce and Economic Revitalization (POWER) Initiative’ in the US (Roemer & Haggerty, 2021). These exploratory insights indicate that techno-economically driven coal decline for climate change mitigation may also require compensation. Future research may systematically investigate whether historical coal decline episodes without political commitments were accompanied by compensation, and how these costs relate to the cost of policy-driven coal phase-out.

The approaches developed here can also be applied to further research beyond coal phase-out. The diagnostic framework for decline can be applied to other declining carbon intensive technologies, such as energy-intensive industries like steel making. The approach to quantifying compensation can be applied to other climate mitigation measures that face resistance. These include not only the phase-out of fossil fuels, but also the expansion of renewables such as wind power which faces resistance for example in Germany and Sweden. Finally, the compensation cost can be integrated into models which develop climate mitigation and energy transition pathways.

6. References

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Paper I

Phases of fossil fuel decline: Diagnostic framework for policy sequencing and feasible transition pathways in resource dependent regions

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Review

Phases of fossil fuel decline: Diagnostic framework for policy sequencing and feasible transition pathways in resource dependent regions

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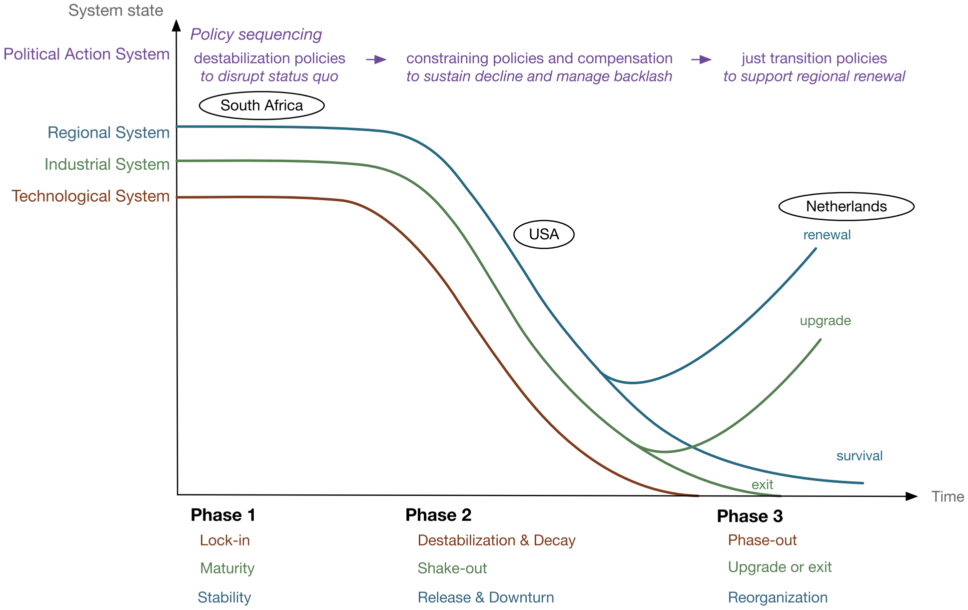
Abstract

Phasing out fossil fuels requires destabilizing incumbent regimes while protecting vulnerable groups negatively affected by fossil fuel decline. We argue that sequencing destabilization and just transition policies addresses three policy problems: phasing out fossil fuels, transforming affected industries, and ensuring socio-economic recovery in fossil resource-dependent regions. We identify the key mechanisms shaping the evolution of the three systems associated with these policy problems: (i) transformations of technological systems addressed by the socio-technical transitions literature, (ii) responses of firms and industries addressed by the management and business literature and (iii) regional strategies for socio-economic recovery addressed by the regional geography and economics literatures. We then draw on Elinor Ostrom's approach to synthesize these different bodies of knowledge into a diagnostic tool that enables scholars to identify the phase of decline for each system, within which the nature and importance of different risks to sustained fossil fuel decline varies. The main risk in the first phase is lock-in or persistence of status quo. In the second phase, the main risk is backlash from affected companies and workers. In the third phase, the main risk is regional despondence. We illustrate our diagnostic tool with three empirical cases of phases of coal decline: South Africa (Phase 1), the USA (Phase 2) and the Netherlands (Phase 3). Our review contributes to developing effective policy sequencing for phasing out fossil fuels.

Graphical Abstract



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Lay Summary

Phasing out coal and other fossil fuels is essential for avoiding dangerous levels of climate change. However, coal phase-out leads to both job losses for coal miners and lost tax revenues for coal intensive regions. How can policymakers deal with these challenges without stalling coal decline? Here, we show that policies should be selected based on the phase of the decline. We map three such phases and explain how to identify them. In the first phase, the biggest risk is the preservation of the status quo so policies should focus on breaking coal lock-in. In the second phase, when the use of coal is declining, firms are struggling or fleeing, and the region suffers from economic downturn and a falling tax base, the biggest risk is backlash from companies, workers and communities so policies should focus on mitigating impacts on affected actors. Finally, in the third phase, when coal is phased out and firms have exited or upgraded, the biggest risk is regional despondence so policies should focus on socio-economic recovery. We illustrate our diagnostic tool and policies at each phase with case studies of South Africa (Phase 1), the USA (Phase 2), and the Netherlands (Phase 3).

INTRODUCTION

Mitigating climate change requires rapid and radical decline of fossil fuel use [1]. In November 2021, the leadership of COP26 announced that 'coal [is] consigned to history' [2]. Twenty-three new countries joined the existing 42 countries [3, 4] in committing to phase out coal power [2, 5]. Additionally, two new declarations were announced at COP26: The Statement on International Public Support for the Clean Energy Transition, under which signatories pledge to end public support for unabated fossil fuel use in energy [6] and the Just Transition Declaration, supported by the International Labor Organization under which signatories pledge support for affected workers and industries [7].

These initiatives highlight the dilemma that policymakers face in formulating feasible fossil fuel phase-out plans. Any phase-out strategy must overcome carbon lock-in [8, 9] and resistance [10] by destabilizing existing regimes [11, 12] through creative destruction policies that withdraw financial and other support [13]. However, such policies risk triggering backlash from affected companies [14], workers [15] and communities [16, 17]. As a result, many emphasize the importance of just transition policies [17–21] including through financially compensating firms, workers and regions negatively affected by phase-outs [16, 17, 22]. A natural question arising from this dilemma is what the right policy mix is between creative destruction and just transition policies to achieve fossil fuel phase-out [23].

In this paper, we use insights from literature and illustrative case studies of coal power decline to argue that there is no universal policy mix but rather that policies should be sequenced overtime, similar to policy sequencing for clean energy introduction [24, 25]. Policy sequencing for decline can deal with three interconnected policy problems: phasing out fossil fuels, managing the transformation of affected industries, and ensuring socio-economic recovery in the regions dependent on fossil fuel resources. As the importance of these policy problems varies over the phases of decline, giving rise to different risks to sustained fossil fuel decline, different policies are needed to respond to these risks. Inspired by the scholarship of Elinor Ostrom and the Bloomington School [26–28], who believed that the first step of developing policy advice was diagnosing the state of a system, we develop a diagnostic framework for fossil fuel decline [29]. We propose a method to identify the current phase of transformation of fossil fuel technologies, related industries and resource dependent regions, to inform policies that are both effective and feasible at a given time.

In the first phase, the technology is locked-in, the industry is mature, the region is stable and the main risk is maintaining the status quo. In the second phase, the technology begins to diminish, the industry to waiver, the region to struggle and the main risk is backlash from affected actors. In the third phase, the technology is no longer used, the industry has either left or reinvented itself and the main risk is regional despondence.

To develop a diagnostic framework, we identify relevant variables reflecting different causal mechanisms reported by three bodies of literature as driving or blocking fossil fuel decline in various systems: socio-technical transitions literature (the technological system), business and management literature (the industrial system) and regional geography and economics literature (the regional system). This phase- and mechanisms-based approach to diagnosing cases of decline enables scholars to identify contexts where there are similar challenges. This enables cross-case learning, which becomes increasingly important as decline strategies, particularly for coal, have burgeoned [30–32]. To develop our contribution, we focus on coal decline where there is both practical experience and a growing body of literature [30–34].

In the 'Methodology' section, we describe Ostrom's diagnostic approach for analyzing co-evolving systems and map the systems involved in fossil fuel decline. In the section 'Co-evolving systems, mechanisms and phases of decline', we review existing literature to identify the key mechanisms that shape decline in these systems as well as the phases of decline. The section 'Diagnosing the phases of decline' develops a diagnostic approach for identifying the phase of decline of each system, describes how to operationalize and benchmark key mechanisms through hierarchically ordered diagnostic variables and speaks to which policies are needed and feasible at each phase. We then provide illustrative applications of our framework to three cases. Finally, we conclude with the policy and research implications.

METHODOLOGY: THE INTELLECTUAL ROOTS OF A DIAGNOSTIC FRAMEWORK

Ostrom *et al.* [27] believed that the first step in formulating scientifically sound policy advice was to develop diagnostic methods to understand why some resource systems are sustained and others fail. In other words, they believed 'the long-term goal for scholars of sustainability science is to recognize which combination of variables tends to lead to relatively sustainable and productive use of particular resource systems ... and which combination tends to lead to resource collapses and high costs for humanity' (p. 15183). Similarly, the goal of our contribution is to enable scholars to understand under what conditions the use of fossil fuels steadily decreases and when such decline triggers societal backlash and stalled transitions. There were several principles of Ostrom's approach that we follow here.

Co-evolving systems

The first principle is to conceptualize the evolution in complex socio-ecological systems as co-evolution of different subsystems. Ostrom aimed for a 'serious study of complex, multi-variable, non-linear, cross-scale and changing systems' [29] (p. 15181). She believed that scientific progress was achieved when scholars recognized that such complex systems were 'partially decomposable in their structure' and could be represented as 'relatively separable subsystems that are independent of each other in the accomplishment of many functions and development but eventually affect each other's performance' [29] (p. 15182). A similar approach was used for the study of energy transitions [35, 36]. We follow this tradition and analyze fossil fuel decline and how it is expressed in technological, industrial, regional and political action systems (PASs), embedded in broader economic and socio-political settings.

While the boundaries of declining systems can be drawn in different ways, we structure them along three policy problems that the literature addresses: the decline and phase-out of fossil fuel technologies such as coal combustion for electricity generation; the transformation of firms in the industry using these technologies; and the recovery of regions dependent on fossil resources, assets and firms (what we refer to as 'resource dependent regions').

The first policy problem, reflected in the socio-technical transitions literature, focuses on the underlying causes of change and persistence in technological systems [10, 37–39].

The second policy problem, reflected in the business and management literature, focuses on transformation and strategies of firms comprising the industrial system in the face of technological change [40–42].

Finally, the third policy problem, reflected in regional geography and economics as well as in the just transition literature, focuses on regional characteristics and strategies that determine the resilience and recovery of regional systems in the face of technological and/or industrial disruption [43, 44].

We recognize that these policy problems and the systems they address are connected and overlap. Technological systems are strongly linked to the industries that use those technologies. Similarly, regions are often highly dependent on industries that support regions' social and economic development.

These links between the three systems explain their co-evolution, a concept that emerged initially in biology [45] but has been also used for analyzing how social, technological and ecological systems influence each other over time [35, 45, 46]. Co-evolving systems can be aligned, mutually reinforcing and thus locked-in [12, 35] but they can also decouple or unlock [45]. This is why 'It is...essential to study both the relatively independent development of each stream of history and their interdependencies, their loss of integration, and their reintegration' [47] (p. 127). The potential for systems to decouple is especially relevant for studying the decline of fossil fuels because if co-evolution is the expectation, identifying points at which they can decouple is key to identifying feasible paths for decline.

The three systems frame three policy problems that are addressed within the fourth system: the PAS [36, 48]. The PAS includes the policies that address each of these problems, such as deliberate destabilization policies that remove support from fossil fuel industries [13]. It also includes inputs from society, such as demands to reduce emissions, ensure energy security, maintain employment, protect vulnerable social groups, etc (see 'Political action systems and policy sequencing'). As the use of fossil fuels declines, the relative importance of these inputs changes. Due to such feedback mechanisms, the PAS co-evolves with the other three systems [49].

Finally, there are also broader socio-political and economic settings which provide the context for the evolution of the four systems, but which themselves do not co-evolve with these systems [50]. For regional fossil fuel decline, the relevant contextual setting may exist at the national (e.g. whether the political system is democratic) or at the global level (e.g. global coal trade) (see 'Economic and political settings').

Variables, mechanisms and pathways

A second key element of Ostrom's approach is identifying what she calls variables. Variable is a broad term denoting or characterizing an element in social or biophysical reality [26, 29]. For example, 'technology', 'industry', 'regions' and 'political actions' can be called top-level variables in Ostrom's terminology. Each of these contains components or characteristics that may be called second-level variables. These typically reflect disciplinary knowledge about a particular system or top-level variable, presented in the form of theories or concepts.

For our analysis, it is especially important to identify second-level variables that reflect the underlying mechanisms of change or continuity within each subsystem. For example, within the technological system, advances in competing technologies have been shown to influence the decline of fossil fuels [33]. This second-level variable can be further unpacked to third-level variables such as the cost of competing technologies, their technological maturity, their current market share and how close a region is to the technological core. Thus, the framework is conceptually and empirically flexible enabling scholars to walk up and down the variable hierarchy depending on the specific policy or scientific question at hand [26]. This approach has been applied to a vast array of socio-ecological problems; closest to our problem is its application to energy transitions [36].

Methodology

To build a diagnostic framework that can map fossil fuel decline pathways, we followed several steps in an iterative manner.

First, we reviewed literature that addresses three key issues relating to fossil fuel decline: the lock-in of carbon-intensive technologies, the feasibility of phasing these technologies out and the call for just transitions as carbon-intensive technologies are phased out. We retrieved these articles from Web of Science by searching for relevant terms, retrieving the most highly cited and most recent articles, and subsequently snowballing for other references. We then identified mechanisms and variables from this literature, which have been shown to impact the evolution of carbon-intensive technologies. We mapped the mechanisms in their relation to three key systems that are implicated by fossil fuel decline: technological, industrial and regional systems. Most of the literature we previously identified belonged to socio-technical transitions literature and informed our understanding of technological systems. We then retrieved additional papers from business and management literature (informing our understanding of industrial systems) and from regional geography and economics as well as just transition literature (informing our understanding of regional systems). We also held two expert consultation workshops in September 2020 and January 2021 with leading researchers and associated stakeholders in the fields of just transitions and decline in carbon-intensive regions [51], where we gathered feedback on our initial understanding of each system and retrieved additional recommendations for articles to include in our review. Table 1 shows how many articles we read from each set of literatures and the mechanisms we identified. In addition to the mechanisms, we also identify second- and third-tier variables that can be used to characterize the strength of these mechanisms (Table 2). We propose how these variables can be used to diagnose the phases and pathways of decline overtime.

For the PAS and the broader settings, we focus on identifying the key policies and broader mechanisms affecting technologies, industries and regions in decline. We also identify the inputs and feedbacks that affect these policies and the second- and third-level variables that characterize the broader settings. Mapping feasible decline pathways requires understanding mechanisms at various phases of decline and different policies that are required and feasible at these different phases. Ultimately, our diagnostic framework aims to inform policy sequencing for feasible pathways of decline, which we define as a sequence of developments leading to phase-out of fossil fuels without serious negative consequences for affected vulnerable groups. This definition builds on the use of the term pathway in different literature. In the socio-technical literature, pathways map discontinuity or continuity based on the combination of artifacts and actors [70, 134]; in contrast, the climate scenario literature primarily identifies 'techno-economically feasible pathways' to climate change mitigation based on different socio-economic and technological assumptions [135, 136]; and political science defines feasible pathways as actions and interactions of different actors towards a given outcome [137].

CO-EVOLVING SYSTEMS, MECHANISMS AND PHASES OF DECLINE

In this section, we present the results of our literature review that explores mechanisms and the evolution of technological industrial and regional systems. For each system, we first define the system's boundaries, elements and connections. Then we identify key mechanisms that explain the behavior and evolution of each system over time and finally we identify second- and third-level variables through which these mechanisms can be characterized. We then describe the PAS, as well as the broader economic and socio-political setting within which the four other systems are embedded.

Technological systems

A classic definition of a technological system is 'a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology' [52] (p. 94). Though technological systems perform material functions (such as energy provision), they are best defined in terms of practices and flows of knowledge [52]. This means coal-based economies are brought about by a certain set of social practices that animates the infrastructure and actor networks. The boundaries around technological systems can be drawn around different geographies [53], from global such as global coal trade [54], to national such as domestic coal production [55, 56], to regional such as regions that produce and mine coal [15, 57].

Technological systems include both artifacts such as power plants, grid infrastructure and mining equipment [56, 58–60] and agents such as utilities, mining companies and electricity consumers [9, 52]. Some scholars [9]

Table 1. Policy problems related to fossil fuel phase-out, epistemic communities and key mechanisms

Policy problem	Epistemic communities	Number of articles reviewed	Key mechanisms of decline
Fossil fuel decline and phase-out	Socio-technical transitions scholars	37 articles (9 overlap with other policy problems)	Technology competition, substitution and diffusion [61, 63] Lock-in [9, 66] Strategies of incumbent regimes [67, 90] Weakening of incumbent regimes [55, 56]
Economic hardship for and transformation of affected firms and industries	Business and management scholars	34 articles (9 overlap with other policy problems)	Firms adapt to technological change [40, 81] Firms, unions, workers resist change [15, 22] Firms restructure, exit or divest from declining sectors [40, 80]
Despondence of and socio-economic recovery in fossil fuel dependent regions	Regional geographers and economists and just transition scholars	21 articles (10 overlap with other policy problems)	Agglomeration economies and rigidity traps [89, 91] Regional economic development and employment [97, 98] Regional population: communities and demographics [43, 57] Regional responses [31, 100]

include policymakers as actors within the technology system as they shape rules and institutional constraints for technology use whereas others separate them into the PAS [36].

Mechanisms of technological decline

Key mechanisms of the decline of technological systems are identified in different scholarly traditions, particularly socio-technical transitions, technology lifecycle and evolutionary economics literatures.

Technology competition, substitution and diffusion

A key reason for change within technological systems is competition with newly emerging technologies [37, 38, 61, 62]. For example, growing utilization of natural gas, nuclear or renewable energy technologies may lead to decreasing coal use [33]. The diffusion of alternative technologies is determined by their advantages (e.g. cost, cleanliness, convenience) over incumbent ones [38, 46, 61, 62]. New technologies diffuse from the core where they are originally introduced to the periphery where they are adopted later [63, 64]. The advance of competing technologies is not linear: as they continue to diffuse, learning and economies of scale can lead to price-performance improvements that may increase their competitiveness and thus drive the decline of incumbent technologies.

Lock-in and path-dependence

A dominant explanation for the slow decline of fossil fuels is their lock-in [8, 9, 39]. Originating in the field of evolutionary economics, early studies on lock-in explained the persistence of inferior technologies despite the availability of better alternatives due to increasing returns from early technology adoption that inhibits technological change later on [65, 66]. This theory was later expanded to institutions [9], user practices [8] and discourses [55] by the socio-technical literature to explain the persistence of fossil fuels in the face of cleaner technologies.

Strategies of incumbent regimes

Lock-in is an overarching concept that encompasses several, more granular mechanisms, such as strategies of incumbent regimes including regime resistance [10], self-reproduction [37] and incremental adjustment [39, 67]. Regime resistance is one of the most obvious regime strategies and includes efforts to preserve the status quo including protecting subsidies for fossil fuels and undermining competing technologies—e.g. in the UK, coal was re-established as an affordable and secure energy source in public discourses [10]. Self-reproduction of the regime means strategies that renew the existing regime for instance through building new (fossil fuel) infrastructure or training new generations of workers and engineers [37]. Finally, incremental adjustment means small adaptations to external pressures [39, 67], such as installing air control equipment on coal power plants in response to air pollution (as was done in the 1970s) or advocating for clean coal and carbon capture and storage (CCS) to preserve the existing coal fleet. Often, strategies interact. For example, if an incumbent regime has pursued a strategy of self-reproduction and recently invested in a host of new assets, it will be more resistant [55].

Weakening of incumbent regimes

The strength of incumbent regimes is associated with the value of technological artifacts, such as power plants, also called assets. Assets' value diminishes as they age. As the value of assets decreases over time, and a larger share of investment is recovered, lower sunk costs for companies may reduce resistance against decommissioning these assets. Jewell *et al.* [56] for

Table 2. Definitions and diagnostic variables of the three co-evolving systems and their phases of decline, the PAS and wider economic and socio-political setting

System (top level variable)	System definition	Phases of decline	Diagnostic variables
Technological	'A technological system [is] a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology.' [52]	1. Lock-in 2. Destabilization and decay 3. Phase-out [11, 39]	**Advances in competing technologies** Cost of competing technologies, rate of growth, market shares, whether the region is in core, rim or periphery of competing technology **Regime strength** Construction of new plants, age and value of assets, number of jobs, diversity of regime actors **Regime strategies** Self-reproduction, adjustment to change, resistance by fighting against change or transformation by incremental innovations
Industrial	Firms that provide a specific service or product [77]	1. Maturity 2. Shake-out 3. Upgrade or exit [40, 80, 96]	**Industry organization** Number of firms, networks between firms, national origin and ownership of firms, unionization of workers and power of unions **Firms' capacities** Size, resources, innovativeness (e.g. R&D), diversification **Industry dynamics** Restructuring through nationalization or privatization, mergers, splits, divestment
Regional	A subnational area drawn around certain economic activities that may have high overlap with administrative regions [92]	1. Stability 2. Release and downturn 3. Reorganization [91]	**Legacy** Geography (connectedness, infrastructure, natural resources, location) Economy (dependence on coal, diversity, wealth) Demographics (aging of population) Local institutions and political factors (degree of autonomy, capacities, mode of operation of local institutions) **Dynamics** Economic, employment and migration trends and expectations **Strategies** Responses by governments, communities, companies and other regional actors
Political Action System	System of actions related to making socially binding decisions [48] that affect fossil fuel use		**Policies, politics and technology legitimacy** Anti-fossil fuel norms, public opinion Substance and structure of political debate (e.g. polarization) Policies and regulations (subsidies, taxes, bans, support for competitors, just transition policies)
Economic and socio-political setting	Economic and political factors that affect the decline of technological, industrial and regional systems while not being integral parts of these systems		**National economy and energy markets** Wealth, growth and inequality Energy markets (liberalization, energy demand, import dependence, domestic resource depletion) **Broader policies and institutions** Strength and type of democracy Technology regulations and institutions

instance show that the age of national power plant fleets is one factor that explains membership in the PPCA. Other mechanisms of regime weakening may be the decline of profitability compared with alternative resources and technologies [37], or the decreasing relevance of core competences and skills of incumbent regimes [38, 58, 59]. This weakening can also result from developments in the broader setting (see 'Economic and political settings'), such as depletion of natural resources [11, 58, 67].

Diagnostic second- and third-level variables for technological system decline

The variables to diagnose decline of technological systems may be grouped into (i) advances in competing technologies, (ii) regime strength and (iii) regime strategies.

Advances in competing technologies can be measured as the cost of competing technologies [38, 61, 62], their rate of growth and market shares [68, 69]. It is also important to consider whether a region/country is in the core, rim or periphery of competing technologies for ease of uptake [64].

Regime strategies refer to self-reproduction, adjustment to change, resistance [10, 42] and transformation strategies [70] that are characterized by either fighting change or pursuing incremental innovations. Self-reproduction strategies are generally reflected through investment in existing assets such as building new coal plants, adjustment to change through retrofitting such as installing air control equipment or CCS and resistance through influencing discourses and lobbying for supportive policies.

Regime strength can be measured through the strength of regime activities such as construction of new power plants [71], age and value of assets [37, 56], number of jobs associated with the technology [71], diversity of regime actors [37, 72] and relevance of core competences and skills [38].

Technology lifecycle phases

Technological systems transform along pathways [70] through different phases from technological invention to the emergence of a dominant design, followed by a period of incremental change [73]. While the dynamics of the innovation and diffusion phases of technologies have been extensively studied, and the depiction of phases of take-off, growth and maturity as S-curve is decades old [64, 74, 75], the phases of technology decline are less developed. Jakob *et al.* [76] suggest sequencing phase-outs based on age profiles and Turnheim and Geels [11] outline different phases of regime destabilization highlighting the responses of regime actors. Similarly, Utterback [37] describes regime responses to technological change on the firm level. Loorbach *et al.* [39] describe different potential trajectories of socio-technical systems including a path of destabilization, chaos, breakdown and phase-out. Drawing on the main theories in the socio-technical transitions literature and the concept of an inverse s-curve, we delineate **lock-in**, **destabilization & decay**, and **phase-out** as the three decline phases of technological systems. Decay here includes the phases of chaos and breakdown [39] before phase-out occurs. We use the terms 'destabilization' and 'phase-out' to delineate specific temporal phases in the decline of a technological system although other authors may use these terms to describe the overall process of decline [11, 138].

Industrial systems

Industrial systems encompass firms that provide a specific service or product [77]. For example, the coal industrial system includes the firms that mine and transport coal as well as those running coal plants. While the overlap between industrial and technological systems often leads to their conceptualization as a single system [12, 78, 79], the two can also evolve independently with firms rising and falling as a technology persists or, alternatively, firms reorienting toward different technologies as the market evolves. In the case of coal, we can see this distinction clearly. The industrial system includes equipment manufacturers, utilities, mining companies and coal transport companies, whereas the technological system includes the practice of mining and burning coal to produce electricity. An electrical utility (a firm in the industrial system) may substitute coal in its power plants with natural gas or biomass or invest in offshore wind turbines, thus becoming part of a different technological system.

Mechanisms of industrial decline or survival

Key mechanisms describing the evolution of industrial systems are described primarily within the literature on the industry lifecycle (ILC) from business and management studies and in empirical studies on coal decline from a variety of disciplines.

Adapting to technological change

The ILC literature focuses on individual firms and aims to identify how their attributes enable them to thrive and survive throughout the lifecycle of the industry within which they are embedded [73, 77, 80]. The ILC literature finds that first movers, i.e. companies who adopt technologies early on, have higher survival rates throughout the ILC [40, 77]. They benefit from cumulative learning during industry emergence, from cost spreading of research and development (R&D) expenditure, and from economies of scale earlier than others [40]. However, early movers also experience disadvantages in situations of rapid technological change, as established incumbents can find it more difficult to adapt to an environment that renders their knowledge and competences obsolete [40, 81]. Additionally, different types of innovations may make it easier or harder for companies to adapt. Competence destroying innovations, i.e. those that render existing skills and competences obsolete, are more difficult to adapt to than competence enhancing innovations that build on existing skills [38, 82]. The case of fossil fuel phase-out, which requires rapid and radical technological change, could be a situation where existing skills and competences become obsolete, and first movers and incumbents are at a disadvantage. Whether firms can adapt to technological change may also depend on the availability of finances or resources for R&D spending [42, 57].

Resistance to technological change

As rapid technological change imposes the need on incumbents to revise business models, competences and skills, they may resist this change [14]. They may choose different strategies, such as ignoring technological change especially early on, or lobbying policymakers for support [14, 37, 42]. Additionally, firms may target innovation at the level of components to secure continuity at the level of overall systems and minimize costs and disruptions [67]. Within many fossil fuel industries, workers are unionized [15, 22, 83]. In some cases, unions' interests may align with those of companies to slow down technological change [9]. Unions often lobby against technological change and industry decline to protect their members' jobs [15, 22].

Re-structure, exit or divestments

The organization of industries, such as ownership (nationalization or privatization) may affect technological change. In turn, technological decline may trigger re-organization of industries including a declining number of firms due to exits, mergers, acquisitions or splits. Hicks and Govern [84] for instance argue that electricity market privatization in the UK has led to a shift from coal to gas power plants due to the declining profitability of coal compared to gas (see also [34]). As technologies decline, industries go through a process called 'shake-out' where firms decide to either fully exit an industry or to 'stake-out' and only modestly decrease their investment [80]. While the term 'shake-out' is used both in the growth phase of an industry to signal winnowing of firms [77] as they compete within a new market and in the decline as competition grows even tougher [80], here, we use the latter definition.

When firms fully exit an industry, they sell off assets and cease activities related to the declining technological system and may also declare bankruptcy, move abroad or diversify into a new industry related to another technological system [40, 85]. The decline in the number of firms may thus indicate the decline of the industrial system [72]. Rector [86] for instance illustrates how the Big Three automobile companies moved from Detroit to Mexico, where they faced fewer environmental regulations. When firms decide to pursue a 'stake-out' strategy, they aim to prolong their association with the declining technology. As incumbents may find it harder to adjust to technological decline, new entrants are likely to be successful during times of rapid technological change [40]. Finally, firms may merge as industries decline [77] or create separate daughter companies that adopt competing technologies [37].

Diagnostic second- and third-level variables for industrial system decline and survival

Diagnostic variables for industrial systems may be grouped into (i) industrial organization; (ii) industry dynamics, or changes in the industry set-up over time; and (iii) firms' capacity.

In describing **industrial organization**, the literature refers to the structure of the relevant industrial sector, such as the number of firms within the industry [82, 85, 87, 88] and the networks between them [89], the national origin and ownership of companies [90] and the degree of unionization and the power of unions [15, 22].

Industry dynamics may be characterized by restructuring (nationalization versus privatization), mergers, splits and level divestment [37, 42, 80, 84].

Firms' capacity under decline is often described by size (small firms may benefit during decline because they can survive in the face of lower demand) [80], R&D [42, 57] and diversification into alternative technologies [37].

Industry lifecycle phases

The full industrial lifecycle (ILC) starts from emergence through maturity to decline in the shape of an inverted U. Here, we focus on the right side of that inverted U-shaped curve and start with industry **maturity**, which under a declining industry is followed by firm **shake-out** [80]. As the industry declines further, firms either **upgrade** or **exit** (Fig. 2).

Regional systems

Regional systems encompass diverse actors and artifacts situated within geographical boundaries [86, 91] and associated with administrative borders [92]. Actors and artifacts within regions are mainly connected due to their geographic proximity. Certain regions are rich in coal resources and associated assets such as power plants and mining equipment [15], and carbon-intensive industries have agglomerated there [43, 89]. These assets form large technical systems and can undergo decline or reconfiguration [93, 94]. Beside firms and infrastructures, regional systems also contain local communities, including employees of the coal sector [16, 86].

Mechanisms of regional decline and renewal

Mechanisms relevant to regional decline of technological systems are documented in regional economics and geography literature as well as more recent literature on just transitions. These mechanisms include economic and social changes and response strategies that may become locked together in vicious or virtuous downward or upward spirals.

Agglomeration economies and rigidity traps

At the intersection of regional and industrial systems lies the concept of agglomeration and dispersion of industries. Agglomeration means that industries form geographically concentrated clusters [43, 89]. There can be geographic reasons for such clustering, such as natural resource availability which attracts certain types of industries [95]. The coal industry is a natural example of this with the industry being concentrated where there are cheap and available coal resources. Agglomeration can also happen in the absence of natural resources through lowering transaction costs if suppliers are clustered in the same region, through the clustering of labor with relevant skills and competences, and through increased opportunities to learn from other firms [89].

While regional agglomeration can create a strong economic base and job opportunities, there may also be disadvantages. Martin and Sunley [96] for instance describe a negative lock-in, where higher embeddedness induces inflexibility and hinders innovation. Such a negative lock-in may lead to rigidity traps, lowering resilience in response to shocks such as industrial decline or phase-out [57, 91]. In the case of the decline of a highly agglomerated regional industry, connected industries may also withdraw investments and reduce their activities [91]. Oei *et al.* [31] for instance illustrate the cases of the Ruhr and Saarland regions throughout the decline of hard coal mining in Germany, which negatively affected down- and up-stream industries and thus exacerbated unemployment effects.

Regional economic development and employment

In the case of the decline of a major regional industry, the development of other industries within this region is crucial. The success of any regional economic development strategy is often measured through employment or wage growth [97]. However, empirically, scholars have found that coal-intensive regions continue to lag behind their peers even decades after a coal industry has been closed: in the Yorkshire region, unemployment rates are higher than on the UK average even years after coal mines have closed [16].

A variety of place-specific factors have been shown to influence whether regions economically develop. For example, resource endowments or availability of space for factories influence a region's ability to attract alternative industries and withstand decline [43, 95]. Regions also vary on economic and institutional structures with some offering better financial incentives for entrepreneurship through the availability of financing, skilled labor and a market for certain products (or proximity to such a market) [43, 44]. There is also evidence that declining industries can leave their footprint on emerging ones: in the USA, there are bigger firms and fewer start-ups close to mines [98]. More generally, diversity and competition within the regional industry are important to stimulate innovation and productivity [97, 99]. For example, Alder *et al.* [99] argue that a lack of competition between firms in the steel, automobile and rubber markets in the US Rust Belt led to a lack of investments and productivity growth, thus contributing to the economic decline of the region.

Regional population: Communities and demographics

Whether regions thrive is also indicated by whether regional populations grow or decline [43]. Reduced employment opportunities are likely to lower the quality of life and lead to outmigration. Stognief *et al.* [57] for instance highlight outmigration from the Lusatia region following the decline of coal mining. Often, young and well-educated residents emigrate, which may further drive the decline of the regional system [43] and can lead to an overall aging of the population as a whole. In turn, outmigration may especially affect regions where there already was an ongoing population decline due to aging of the population [57].

Outmigration can further erode the tax revenue of the regional government [43], which is often already falling due to the declining industry [57]. The willingness of regional inhabitants to move away, or work in another industry, may be influenced by local identities and cultures in addition to factors related to the skills of the workforce. Johnstone and Hielscher [16] for instance describe the Yorkshire region in the UK, where the prominence of coal technologies over time had 'transformed and shaped the region, embedding cultural traditions and social identities' (p. 640). Other residents, who are not directly employed by these industries, also may have their cultures and identities shaped in part by the long history of carbon-intensive practices in the region [16, 57].

Regional responses

Regional responses to counteract socio-economic decline may thus include resistance, if local identities and cultures are threatened, and regional economies are dependent on the declining industry. They may however also include renewal. Renewal strategies may include finding a new economic niche, attracting economic opportunities disconnected from the declining industry or taking advantage of an emerging technology. For example, local subsidies for hiring or for industry may attract new businesses and increase employment in the region [31, 43, 100]. Stognief *et al.* [57] suggest that increasing the attractiveness for residents through establishing cultural sites can help counteract population decline. If renewal strategies are not successful, regions may fall into the poverty trap [57, 91]. This may initiate a survival mode and may lead to the need for continuous subsidies and transfers. The success of these strategies is influenced by the political and institutional context within the region, such as the degree of regional autonomy and the mode of operation of local authorities [43, 44]. Additionally, there is usually a strong connection between dominant industries and regional authorities through both tax revenues and through votes of workers and their families [16, 57, 86].

Diagnostic second- and third-level variables for regional decline and renewal

The variables for diagnosing regional systems may be grouped into (i) regional legacy, which includes immutable characteristics that are either static or change only slowly; (ii) regional dynamics; and (iii) regional strategies.

Regional legacy includes regional geography such as location, connectedness, infrastructure and available natural resources. It also includes regional economy, particularly its degree of dependence on the fossil fuel industry, economic diversity and wealth. Thirdly, regional legacy includes demography such as population age and general level of education. Finally, institutional and political factors affect regional responses in the face of decline [43, 44].

Regional dynamics includes economic, employment and migration trends. Though these trends may not change the fundamental characteristics of the regions overnight, they create important expectations and self-reinforcing processes that may differentiate between the 'downward' and 'upward' spirals.

Regional strategies include responses by governments, communities, companies and other regional actors to coal decline. Often, these strategies include choices that are key in determining the future of the region. For example, the literature shows regions with policies supporting businesses are more likely to grow rather than decline [43, 101].

Regional lifecycle phases

Current thinking on regional development draws on the idea of the adaptive cycle from socio-ecological literature where a system is classified according to its potential and resilience [57, 91, 102, 103]. Potential (accumulated resources) within a region include firms' competences and capital, infrastructure and workers' skills, whereas a region's resilience is defined as its ability to respond to shocks, commonly associated with system flexibility [91].

Over time, the variation in these two aspects go through distinct phases but are not necessarily in sync. Researchers distinguish the 'exploitation phase' where potential (accumulated resources) is slowly increasing and resilience (flexible networks that can adapt to changes in the external environment) is high; it is during this phase that economic growth occurs [91]. In the 'conservation phase', resources are accumulated to their highest level but resilience has fallen as mature networks and institutional structures have decreased the flexibility for different actors [91]. If a shock occurs and the system is not able to adapt, it may enter the 'release phase' where accumulated resources become irrelevant and resilience drops; this can be thought of as the beginning of decline [91]. The region may then enter the 'reorganization and restructuring phase', where resilience grows as the region begins to restructure, and new resources start to get accumulated [91]. Here, we distinguish three regional phases during decline: **stability**, **release and downturn** and **reorganization** characterized by either renewal or survival.

Political action system and policy sequencing

Easton [48] defines PASs as 'those actions more or less directly related to the making of binding decisions for a society' (p. 185). In the context of our analysis, we are specifically interested in those actions and decisions that affect the use of fossil fuels. Naturally, these actions and decisions are part of a broader PAS that deals with such diverse issues as regulations of electricity markets, energy security, environmental and climate protection, etc.

Mechanisms of the political action system

While the PAS does not undergo lifecycles like technological, industrial and regional systems, it co-evolves with these systems as fossil fuel use declines due to several mechanisms.

On the one hand, the PAS generates outputs, such as policies or regulations, that either support or suppress fossil fuel-based technologies. Support for the use of domestic resources (as in Spain through preferential merit order for domestic coal from 2010 to 2014) may increase their competitiveness [33], while policies such as carbon pricing or cap-and-trade schemes can decrease their competitiveness. Kivimaa and Kern [13] highlight the importance of deliberate destabilization policies such as withdrawal of subsidies for fossil fuel-based technologies and support for their competitors (see also [10, 11]). Environmental regulations such as emission control policies may also affect the profitability of a national industry [86].

On the other hand, PASs are themselves affected by inputs, such as demands or support from actors participating in the political debate. As fossil fuels decline, feedback may be triggered that negatively affects destabilization policies, such as backlash from industrial lobbies, companies, labor organizations or regional representatives. This sensitivity to feedbacks differentiates the PAS from the broader socio-political setting which contains immutable characteristics that are unlikely to change in response to fossil fuel decline (see 'Economic and political settings').

Public opinion and anti-fossil fuel norms can also pressure national and regional governments to either institute policies that penalize fossil fuels [104], or to choose clean options, for their investment and electricity [12]. These trends can lead to the loss of technological legitimacy, particularly in the face of concerns about negative externalities arising from fossil fuels and their connection to climate change. Decline may however be slowed by equally passionate concerns on the other side of the political agenda when fossil fuels are connected to employment and national competitiveness. Energy security concerns related to growing energy demand, e.g. in emerging economies like India or China, may also result in increased legitimacy of fossil fuels. The polarization of this debate may make it hard to reach a consensus on national strategies to support declining regions.

Recent literature suggests that one way to address mechanisms that hinder stringent climate mitigation policies is policy sequencing. The core idea behind policy sequencing is that 'policies at an early stage can be conducive to implementing more stringent policies at a later stage' [105] (p. 141) as barriers to climate mitigation policies are loosened [24, 25, 105]. Meckling *et al.* [25] for instance find that green innovation and industrial policies pave the way for more stringent carbon pricing policies in many contexts as they help decrease the technology costs of low-carbon alternatives to fossil fuels. One possibility to pave the way for more stringent policies may be compensating affected actors [105]. However, Leipprand et al. [105] find that there are limits to the extent to which policies affect actors in other systems. Our diagnostic framework can thus support policy sequencing approaches by identifying the state of technological, industrial and regional systems at different phases of decline, to better understand the main risks and what policies are needed at each phase.

Economic and socio-political settings

While the PAS closely co-evolves with the technological, industrial and regional systems, all of these systems are also embedded in larger economic and socio-political settings that influence developments in the systems but do not co-evolve to the same extent and in the same timeframes. Here, we review the key contextual mechanisms affecting technologies, industries and regions in decline and the variables characterizing these mechanisms. These settings can be grouped into (i) broader economy and (ii) broader policies and institutions.

National economy and energy markets

Wealth, growth and inequality

The national economic setting shapes regional phase-out in a myriad of ways. At the moment, coal phase-out is furthest along in countries that are part of the Organisation for Economic Co-Operation and Development (OECD). These countries are wealthier and thus have the capacity to deal with potential inequities arising from phase-out [56]. For example, in the German coal phase-out plan, the national government pledged EUR40 billion to regions [106]. Economic growth provides economy-wide opportunities for finding employment and attracting investments to recover from the negative impacts of coal decline on job availability and regional tax base. Finally, more unequal economies are likely to be less responsive to inequalities arising because of coal decline.

Energy markets

Energy markets affect coal decline more directly. For example, the electricity market liberalization in the UK is partly credited with contributing to the decline of British coal [11]. Another important factor is growing energy demand, which can be a barrier to the decline of fossil fuels for electricity generation [34]. This barrier may be especially hard to overcome in cases where alternative energy sources, such as nuclear, face opposition, e.g. in Germany [79]. On the other hand, stagnating or declining electricity demand may enable faster decommissioning of carbon-intensive assets [33, 56]. Del Río [33] for instance highlights how, in Spain, overcapacity combined with sluggish energy demand supported coal decline. Another relevant energy market dynamic is global energy trade and import dependence. Governments may aim to limit import dependence and thus continue to support domestic production of resources even if they are less profitable [33]. Domestic resource depletion can spur decline if extraction becomes unprofitable, as was one of the factors driving coal decline in the UK [79]. The case of South Africa (see 'Phase 1 - South Africa') also shows that growing international coal demand can influence domestic coal availability [107].

Broader policies and institutions

Institutions and policies within different countries also influence decline pathways. Jewell et al. [56] find that states with more transparent and effective governance are more likely to phase out coal, expaining that these states are better equipped to balance between concentrated and diffuse interests. Rentier et al. [90] zoom in on different types of democracies in Europe and find that between the four they examine, the liberal market economy of the UK phased out coal the fastest, arguably because domestic coal in the UK was less protected than in the other countries. The extent to which different actors are able to affect the course of decline depends on the influence each of these actors has on decision-making processes in political systems that vary from one state to another. For example, in systems where unions exert more political control, they are able to slow decline [15, 90].

Finally, fossil fuel decline is affected not only by policies directly targeting a specific resource or its competitors but also by broader regulations and institutions in the electricity and energy markets. For example, energy market rules such as power purchasing agreements may trigger institutional lock-in, as they may set a timespan for energy production using a specific resource or practice [55]. Another example of rules potentially inhibiting technology change are technology standards, favoring incumbent technologies [9].

Summary

In this section, we summarize the characteristics of co-evolving systems (top-level variables) important for understanding fossil fuel decline, and the second- and third-level variables that are relevant in diagnosing decline in these systems (Table 2). Technological, industrial and regional systems are distinguished by how their boundaries are drawn and how system elements are connected. Yet, one and the same actor (or artifact) may belong to the technological, industrial or regional system depending on the analytical angle. This is similar to how a particular artifact can be part of socio-technical, techno-economic or political systems [36]. Firms, for instance, are relevant actors in the technology system, as they engage with artifacts, knowledge and practices. Firms are also contained in the industrial system, which they affect through their respective shake-out or stake-out strategies. Finally, they are also embedded within regional systems, where they generate tax revenue and employ local workers.

We also consider mechanisms that shape the evolution of the three systems. Once again, many mechanisms are not confined to a single system alone but bind them together. For example, stalling renewal of the industrial

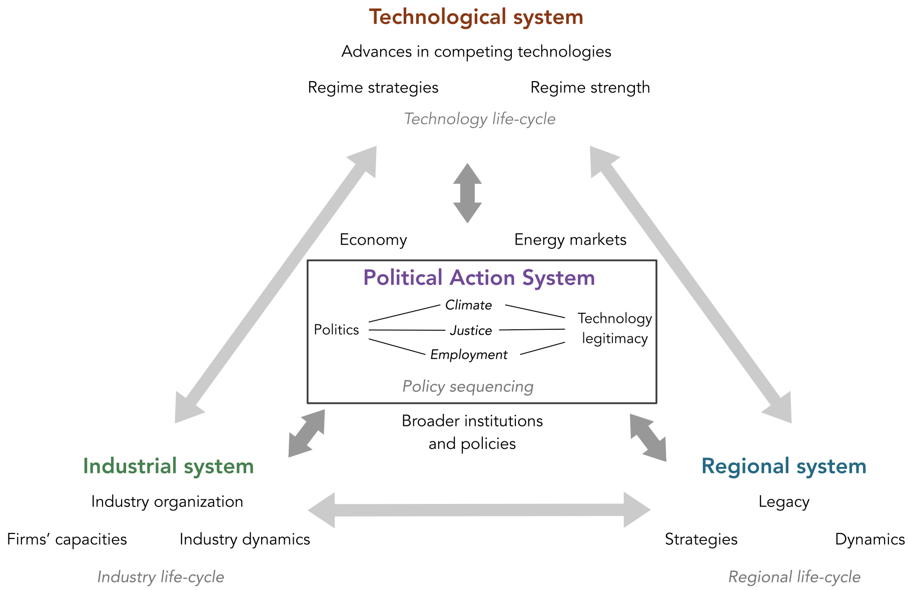

Figure 1. Top-level variables (four systems) and second-level variables for four systems and economic and socio-political setting

sector (industry system) leads to the loss of innovativeness (technology system) and a lack of opportunities for young people (regional system). One illustration of this is that after the German reunification, Lusatian coal could not compete with more efficient and cheaper coal from the West. As a result, coal production declined, and many firms left the region, leading to a rise of unemployment [57]. Thus, many variables, which we propose for diagnosing coal regions in decline (summarized in Fig. 1), can arguably belong to more than one system. Where exactly they belong is less important, rather than that no important variables are missed in a comprehensive diagnostic analysis. Figure 1 shows the four systems, the economic and socio-political setting and their respective second-level variables. These are the most important explanatory variables. Table 2 also shows the third-level variables that are relevant in most cases of decline.

DIAGNOSING THE PHASES OF DECLINE

The proposed diagnostic approach aims to facilitate cross-case comparisons, draw lessons and inform policy sequencing for managing the rapid decline and phase-out of fossil fuels such as coal. While there is an emerging literature on policy sequencing for climate policies [24, 25, 105] and lessons of coal phase-out and other carbon-intensive industries [30–32], our framework strengthens these literatures by offering a systematic approach to characterize the state of technological, industrial and regional systems throughout decline. It is not only the socio-economic and political contexts [56, 76] that shape decline dynamics in any given case but also how far along a given decline process is (Fig. 2). The nature and strengths of mechanisms change over the phases of decline, thus policy and strategies applied at one phase may not work at another phase. Consequently, at the core of our diagnostic approach is identifying the phase of decline for each system in a particular case to inform the sequencing of policies throughout fossil fuel decline.

Identifying the phase of decline

Identifying the phase of decline of each system is done by examining the key second- and third-level variables listed in Table 2 and the strengths of mechanisms that they reflect. Here, we describe the hallmarks of each phase for each system, summarized in Table 3. We use the example of coal combustion for electricity generation as the technological system in decline.

Phase 1: Technological lock-in, industrial maturity and regional stability

The hallmark of Phase 1 is stability and slow change in the underlying systems.

In the technology system, the regime is strong which is characterized by a high value of assets. There are either no or limited competing technologies and those that exist do not have a clear competitive advantage. The regime may begin to experience pressure, either in the form of public campaigns or increasing regulations. The technology can usually incrementally improve (e.g. through pollution control) in response to these criticisms. The regime successfully reproduces and incrementally adjusts.

In Phase 1, the industrial system is mature which is reflected in a relatively constant number of firms, firm ownership and firm capacity. There may be modest growth with new firms entering the industry. This phase is also characterized by strong unions who oppose downsizing or reorientation of existing firms.

The regional system in Phase 1 is strongly linked to the technological and industrial systems and oriented toward preserving the local industry. There is also likely relative stability in the key socio-political, economic or demographic characteristics of the region, determined

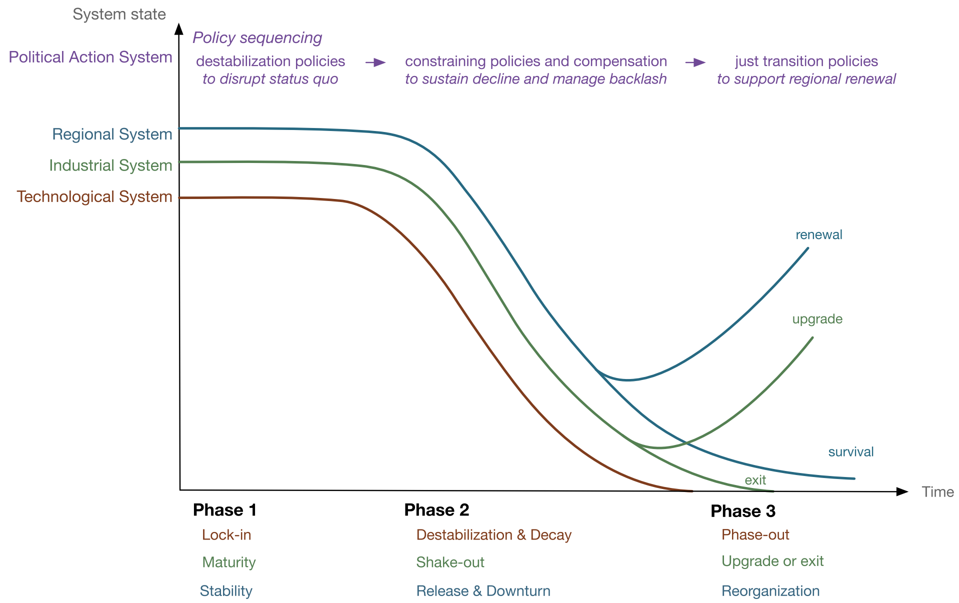

Figure 2. Phases of decline, policy-sequencing and the co-evolution of technological, industrial and regional systems

by the underlying legacy such as location and geography, political autonomy, economic diversity and demographics.

In the broader economic and socio-political setting, several pressures may emerge which advance decline to Phase 2. Economic pressures may include stagnating demand, depletion of resources and increasing imports, whereas political pressures may include waning policy support particularly when combined with support for alternatives, and legitimacy of the technology being increasingly challenged in media and public opinion, including through international opinion channels.

The biggest risk of Phase 1 is continuation of the status quo through continuous renewal of infrastructure and recruitment of new actors. The stability of technology, industry and region and the strong interlinkages between the three systems makes this phase particularly persistent [11, 13]. This phase comes to an end either through the evolution of the underlying systems (e.g. through aging assets and lack of renewal in new fossil fuel infrastructure) or through external pressure within the broader setting.

Phase 2: Technological destabilization and decay, industrial shakeout and regional release and downturn

Phase 2 is characterized by destabilization and decay in technologies and industries and growing resistance from affected firms as their survival and the status quo is challenged.

In the technology system, we see a lack of new developments in the coal industry and either stagnation or decline in Phase 2. The value of associated assets also begins to decrease as the infrastructure ages and costs of competing technologies continue to fall. Competing technologies can also rapidly expand and gain political power. The diversity of regime actors also declines and those that remain pursue incremental adjustments to ensure their survival.

In the industrial system, there is a lack of new entrants and a decline in the number of firms, possibly accompanied by divestment and a decrease in firm sales, as the overall industry becomes less profitable and more competitive. Increasing pressures on the industry often lead to large-scale industrial re-organization either through nationalization, privatization or a growing number of mergers. Firm capacity declines as profits fall, though there may be an emergence of a greater number of firms investing in innovations or proximate industries as a strategy for survival.

The regional system in Phase 2 is characterized by economic decline, rising unemployment, outmigration and a falling tax base. Regional strategies during Phase 2 range from clinging to the old technology to searching for renewal strategies, sometimes with support from national governments or supranational entities (such as the EU). At the same time, the decline at the regional level can trigger backlash and resistance as regions cast fossil fuels as intimately linked to their identities.

In the broader setting, there are several markers that signal mounting pressure in Phase 2. There also may be further loss of legitimacy. Policies favoring competing technologies may get stronger while political debates over coal (or the declining technology) may increasingly polarize society.

The biggest risk during Phase 2 is backlash from the regime as well as affected workers and communities against decline. As the status quo is destabilized and decline unfolds, actors lose revenue or market share (firms), employment (workers) or their culture and identities feel threatened (residents of regions). Their active resistance becomes a risk to further sustain technology decline and eventually realize phase-out.

Table 3. Phases, characteristics and markers of three co-evolving systems, the PAS and the broader setting

	Phase 1	Phase 2	Phase 3
Technology	**Lock-in**	**Destabilization and decay**	**Phase-out**
Regime strength	Value of assets is high and a recent increase or stability of industry	No new developments, aging infrastructure, diversity of regime actors (e.g. utilities) declines	Retirement of coal plants or related infrastructure, closing mines
Advances in competing technologies	Competing technologies are limited and do not have obvious advantages	Competing technologies are widely available and cheaper than coal; their market share increases and may gain political power	
Regime strategies	Regime reproduction and successful incremental improvements in response to pressures	Pursuing incremental adjustments (e.g. clean coal and capacity markets for supporting intermittent renewables)	Most of regime actors exit or switch to other technologies
Industry	**Maturity**	**Shake-out**	**Upgrade or exit**
Industry organization	The number and ownership of firms is largely constant	Decline in number of firms and structural changes in ownership (e.g. nationalization, privatization or mergers)	Number of firms is substantially lower and much of industry may have been re-organized
Firms' capacities	Stable capacity	Capacity and profitability decline. Some firms diversify either through R&D or investment in proximate industries	Firm capacity continues to decline but a subset of firms may take off in similar industries
Industrial dynamics	Industry is steady or in some aspects growing with strong union opposition to downsizing	Less new entrants, possibly accompanied by divestment, asset and company sales	Industrial actors exit, re-orient, sell assets; unions weaken
Regions	**Stability**	**Release and downturn**	**Reorganization**
Legacy	Location and geography (natural resources for other industries, agriculture, tourism) Political autonomy, capacity and resources of regional government Economic diversity, wealth, employment, industrial structure, dependence on coal Demography (age, education, urbanization)		
Dynamics	Stability of main characteristics	Economic decline, increasing unemployment, outmigration, falling tax base and investments	Poverty/rigidity trap or renewal of economic activities and identities
Strategies	Oriented toward preservation of coal industry	Mixed: clinging to old identity and industry, survival, renewal	Focused on survival or renewal
Political Action System	**Destabilize status quo** Continuous support (e.g. subsidies) increasingly contested Support for competitors and destabilization policies emerging International finance for coal phase-out	**Manage backlash** Constraining policies (bans, taxes) balanced with compensation or support for phase-out	**Support regional renewal** Industrial and regional restructuring policies
Setting			
National economy and energy markets	Stagnating demand, depleting resources, increasing imports		
Broader policies and institutions	Transparency of government, decision-making processes Trust in government		

Phase 3: Technological phase-out, industrial upgrade or exit and regional reorganization

In Phase 3, the technology is nearing phase-out and the related firms either move to other regions or find ways to reinvent themselves. Regions, which do not have an option to flee, search for strategies of survival or renewal.

In the technological system, Phase 3 can be recognized by massive retirements of coal assets and a weakened regime with actors exiting or switching to new technologies. Additionally, coal phase-out may be accompanied by fuel substitution as in the case of the Netherlands and the USA where biomass (the Netherlands) and natural gas (the USA) substitutes a large portion of the coal power fleet [108, 109]. Competing technologies are now widely available and cheaper than their coal counterparts and dominate the market.

The industrial system in Phase 3 is characterized by a low number and diversity of firms and potentially an ongoing reorganization. In general, the firms that remain search for new strategies to survive—either by investing in innovations and different technologies (upgrade) or through fleeing to new markets (exit).

The regional system in Phase 3 faces the challenge of reinventing itself. Following a recent decline, the region likely has an older population and has lost the tax base that it used to rely on. In the worst case, the region falls into the poverty trap with a downward spiral of victimization, stigmatization, economic and social decline and dependence on subsidies and transfers. In the best case, the region undergoes a renewal with new economic activities and a renewed identity.

The broader setting at this phase sees a turn to industrial and regional restructuring and may see a growing concern for declining regions.

The main risk in the third phase is the inability of regional economies to adapt and recover from technological and industrial decline, leading to regional despondence. Many regional economies have been built around fossil fuels and re-inventing these economies faces distinct challenges.

Co-evolution and non-ideal types

The description of decline phases above portrays ideal types where co-evolution is synchronized across the three systems. In many real situations synchronization of the three systems is highly likely, particularly in Phases 1 and 2 that have a starting point of tightly coupled technologies, industries and regions. During the tight coupling in Phases 1 and 2, changes in one system tend to also lead to changes in the others.

At the same time, it is possible to observe the three systems out of synch, even in Phases 1 and 2. This can happen due to more rapid changes in one system, or simply because there is more inertia in one system than the others. For example, a technology may not have declined but coal-dependent regions anticipate such a decline leading to outmigration, falling tax revenues and the region advancing to Phase 2. Another potential trigger of such de-synchronization can be the loss of legitimacy of coal internationally combined with regions observing the experience of their counterparts in other countries. For example, in South Africa, coal continues to be the primary source of electricity generation with limited signs of decline, but there is already an active just transition movement raising concerns about what a coal phase-out would mean for coal dependent regions (see 'Phase 1 - South Africa'). Thus, when diagnosing a case, it is important to keep in mind that the phases of different systems can be in or out of sync and thus each system should be first diagnosed independently before their phases are compared.

Policy sequencing for feasible decline pathways

Policy sequencing is an approach to respond to policy problems over time, by introducing less stringent policies at first to relax or remove barriers and thus enable more stringent policies later [24, 25, 105]. Such barriers may include technology costs of low-carbon alternatives or opposing interests within and outside of government [24, 105]. While most literature on policy sequencing assumes that all barriers relax over time [24, 25], more recent work finds that ramping up climate policies can trigger opposition and resistance [105]. We argue that the strength of different barriers varies throughout the phases of decline, and diagnosing which phase a system is in can help understand which barrier poses the highest risk to sustained fossil fuel decline and can inform the most effective policy sequence.

During Phase 1, the highest risk is the continuation of the status quo, i.e. a sustained use of fossil fuels for power generation. The most appropriate policies at this stage aim for creative destruction [13] and destabilization [10, 12] by unsettling the status quo for instance by withdrawing subsidies, installing bans and supporting competing technologies. During Phase 2, the highest risk is backlash and opposition to phase-out. If this risk is not addressed, this may lead to negative feedback in the PAS and rejection of policies that support decline. To prevent this, policies need to balance mounting pressures on the polluting technology and support new opportunities for the regions and industries associated with this technology. It is crucial not to prolong the phase-out while at the same time managing backlash. This may include financial support for companies to continue phasing out fossil fuels and for workers to retrain.

During Phase 3, the key risk is regional despondence, and the most salient issue becomes the renewal of the affected region, in order to prevent it from falling into a poverty trap with high levels of unemployment and out-migration combined with continued or rising discontent, harkening back to the past and populism among the population. Under this path, its strategies focus on dealing with the economic, political and social despondence and the region may become excessively reliant on transfers and subsidies. The policies at this phase should focus on supporting renewal with new or renewed industries leading to falling unemployment and higher levels of social cohesion.

Depending on the development of the industry, we can imagine two desirable outcomes requiring different policy responses that would lead to regional recovery but accomplished through different means.

- **Industrial upgrade and regional renewal:** under industrial upgrade, firms reinvest in the region and the renewed industry attracts new jobs. The example of coal mining phase-out in the Netherlands (see 'Phase 3 - Netherlands'; Table 4) illustrates this, where the state-owned mining company began to invest in alternative business branches such as chemicals and substituted coal for gas. A policy response may be to support the upgrade of the industry.
- **Regional de-coupling:** regional de-coupling from both the declining industrial and technological systems may become the case if firms exit the region in search of a better market or go bankrupt (the latter has for instance occurred in coal regions within the USA; see 'Phase 2 - USA'). A policy response may be to support other firms or regional governments.

Successful decline—both in terms of phase-out of polluting fossil fuels and safeguarding justice—depends on de-coupling co-evolving systems of technology, industry and regions. Policy sequencing may support de-coupling by addressing the most salient risks at each phase of decline.

ILLUSTRATIVE APPLICATION OF FRAMEWORK TO THREE CASES

Phase 1: South Africa

Coal power generation and coal mining in South Africa are in Phase 1 of decline. **Technological lock-in** is high indicated by a **strong regime** retrofitting and expanding its coal fleet [110] along with new coal mining capacity and infrastructure [107] despite plans for decommissioning few older plants by 2030 [110]. By 2030, coal is still envisioned to provide 43% of installed capacity [110] despite **advances in competing technologies** such as solar and wind power [111]. **Regime strategies** focus on prolonging the use of coal. Some argue that Eskom and energy-intensive companies have influenced energy demand forecasts, leading to an increase in planned coal capacity [112]. Instead, electricity demand has stagnated leading to overcapacity of the electricity system, which Eskom uses to argue for delaying additional renewables deployment.

The maintenance of the status quo is also indicated by stable **industry organization** and **industrial maturity**. Independent producers emerged in response to a governmental program to increase renewables capacity [113]. Nevertheless, Eskom maintained its monopoly over electricity production, distribution and transmission [114] and **industry dynamics** remained stable as Eskom refused to sign power purchasing agreements with the independent producers. Support for coal was also demanded by the union of coal transport workers that saw increasing renewable capacity as a danger to their employment [107]. At the same time, Eskom is indebted and struggles with corruption as well as poor contract management with the five main national mining companies [110] that produce coal for both domestic use and export. To make a higher profit, mining companies chose to sell coal abroad, leading to a shortage of available coal and contributing to the electricity supply crisis [107]. This indicates that Eskom lacks the financial and institutional **capacity** to innovate and diversify.

One relevant coal region is Mpumalanga, where mining is the largest contributor to regional GDP and more than 80% of South Africa's coal is mined [107]. The region also has several power plants that are planned to be decommissioned between 2020 and 2026 due to aging [115]. **Regional dynamics** currently seem **stable** but point toward a potential decline, since employment in the coal sector has already decreased due to mechanization [107]. The **legacy** of strong economic dependence on the coal sector makes this especially threatening for the region. For example, more than half of businesses operating in the Steve Tshwete Local Municipality in Mpumalanga offer services to either coal mines or coal power plants [115]. Capacities of companies and workers may support the region in adjusting to coal decline [107, 115]. Financial and institutional capacities of regional governments are limited, and **strategies** of regional governments are mainly focused on providing public services and supporting urban development [114, 116].

In the **PAS**, some pressures on Eskom have emerged. The Integrated Resource Plan 2019 formulated by the Department of Mineral Resources and Energy outlines a plan to unbundle Eskom and separate its generation, transmission and distribution functions [110]. However, the implementation and impact of this plan are still unclear. In addition, regulations in support of renewables emerged in response to an energy supply crisis in 2007 and attracted international finance as well as interest from domestic companies and joint ventures with Chinese and Indian firms to deploy renewables [113].

Together with Eskom's decreasing capacity to supply electricity and decreasing global coal demand in the broader setting, this may eventually push the technology system in Phase 2 of decline. Additionally, concerns over looming coal demand and its regional and national socio-economic consequences have led to several just transition initiatives, focused on how to manage coal decline [117]—this may indicate a de-synchronization of the three systems, as regional systems may advance to release coal before decline in the technological system materializes.

However, the case of South Africa also highlights the risk of preserving the status quo: even as pressures on coal grow, the technology remains locked-in in the face of mature industry. In November 2021 at COP26, the UK, the USA, France and Germany agreed to pay international aid of US$8.5 billion to South Africa to support 'the decarbonization of the electricity system' [118]. How exactly this money will be spent has not yet been disclosed, but the current phase of decline suggests that it may

Table 4. Diagnostic variables for coal decline in South Africa, the USA and the Netherlands

	South Africa	USA	Netherlands (mining)
Technology	**Lock-in**	**Destabilization and decay**	**Phase-out**
Regime strength	Aging coal fleet Plans for retrofits and additional capacity	Aging coal fleet No additional capacity planned	Decline of revenue from coal mining
Advances in competing technologies	Decline of renewables costs globally	Discovery of shale gas Decline of renewables costs globally	Discovery of Slochteren gas field in 1959 Cheaper foreign coal
Regime strategies	Self-reproduction Refusal to sign power purchasing agreements with renewables producers Influencing energy demand projections	Investment in CCS or renewables Some investment in coal mining Lobbying for support to export coal	Abandonment of coal mining
Industry	**Maturity**	**Shake-out**	**Upgrade or exit**
Industry organization	State-owned utility Eskom maintains monopoly over electricity production Five main coal mining companies	Declining number of firms in mining sector Declaration of bankruptcies	Declining number of firms as private mining companies exit
Firms' capacities	Eskom: indebted, struggles with corruption, poor contract management	Utilities: diversification, investment in other technologies, e.g. gas, wind	DSM: knowledge in gas distribution, revenues from chemicals business
Industrial dynamics	Plans to unbundle Eskom but implementation unclear Transporters' unions actively resisting coal phase-out	Mining: (weak) union resistance to decline Utilities, e.g. PSEG, sell coal assets	Workers' unions supported phase-out and reindustrialization DSM upgraded from coal to gas and chemical industry
Regions	**Stability**	**Release and downturn**	**Reorganization**
Legacy	Economic dependence on coal, mining largest GDP contributor Majority of companies are in or supply coal sector	Remoteness from industrial centers, lack of skilled workforce, economic dependence on coal industry	Only partly dependent on coal industry, little autonomy of regional government
Dynamics	Stability in unemployment, poverty rates	Decline of regional tax base as coal industry declines	No significant increase in unemployment New companies settle
Strategies	Provide and manage coal infrastructure, urban development	Plans to lobby for support of coal mining for export, expansion of infrastructure	Attraction of alternative industries, establishment of public offices in the region
PAS	**Destabilize status quo** Support for renewables from some government agencies Just transition working groups	**Manage backlash** Polarized debate on coal decline Support for coal workers and regions	**Support regional renewal** Subsidies for regional infrastructure, economy, for retraining of workers
Setting			
National economy and energy markets	Supply crisis in energy market High unemployment and poverty rates	Stagnating energy demand Declining coal export demand	Oversupply in 1960s This changed with ensuing oil and economic crisis in 1970s/80s
Broader policies and institutions	Coal and energy intensive companies have strong influence in policy-making processes Lack of capacities on local governmental level	Mix of federal and state-level energy and transition policies	Relatively little independence of regional government Close interaction between unions, industry, government

be important to focus on further destabilizing the status quo and support initiatives in regions to move away from coal.

Phase 2: USA

Coal in the USA provides an example of Phase 2 of decline. Even though there are no official phase-out plans, the technological system has been **destabilized** and is in decay. One indication and key reason is the **advance of natural gas** which has seen significant cost reduction for shale gas combined with cost reductions and increased deployment of renewables [119]. Other pressures from the broader socio-political and economic setting include stagnating domestic energy demand and stagnating global demand for coal [119, 120]. A decline of **regime strength** is also indicated by the aging coal power plant fleet: the average capacity weighted age in 2020 was 41 years [109] and there is no additional planned coal capacity [121]. **Regime strategies** differ: in power generation, there is some investment in CCS [109, 122]; in other words, an adjustment strategy, but also in nuclear and renewables [123], which indicates a diversification strategy. In coal mining there are ambitions to increase coal exports as domestic demand declines [109, 122].

The **shake-out** of the industrial system is indicated by changes in **industry organization**, such as a declining number of firms, especially among coal mining companies [119, 121]. Even though this decline already occurred in 2013/14, and some companies were able to stay afloat through write-offs of liabilities and divestment [119], the trend has not been reversed. In 2019, a company in the Powder River Basin (PRB) abruptly filed for bankruptcy [122]. This indicates that mining companies' capacities to innovate and diversify may be low. Among utilities, examples such as PSEG divesting from its coal assets and investing in wind and natural gas technologies indicate capacities to innovate [123]. Jobs in the coal sector are usually unionized and well paid [124], leading to some resistance to coal decline. However, Abraham [15] argues that unions, specifically in Appalachia, are not well equipped to influence coal decline pathways.

There are several coal regions in the USA. Many studies focus on Appalachia and the PRB which are experiencing negative **dynamics** due to US-wide decline of coal. The regional tax base in both regions is decreasing indicating **regional downturn** [122, 124]. Even though coal mined in Appalachia and PRB is of different quality and differently impacted by environmental regulations, both regions face similar challenges due to their **legacy**: remoteness from industrial centers, lack of skilled workforce, an economic dependence on the coal industry and local identities, cultures and expectations connected to the coal industry [119, 122, 125]. **Regional strategies** differ, as some regions, such as the PRB, aim to find new opportunities for coal mining through coal exports [119, 122, 125], whereas others introduce legislation to end power generation from coal and plan a coal phase-out [125].

Nevertheless, the case of the USA highlights the risk of backlash to coal decline: both regions and the industry have lobbied for support of coal in the face of decline, which has affected the **PAS** [119, 122]. Attempts to manage this backlash include the 'Partnerships for Opportunity and Workforce and Economic Revitalization (POWER) Initiative' and the 'Assistance to Coal Communities' [125]. However, the debate around coal decline remained highly polarized, with strong support for Donald Trump coming from some coal regions due to his support of the industry [122]. While not directly supporting the industry, he revoked some environmental regulations that had previously decreased the competitiveness of coal [119, 120].

Phase 3: Netherlands

One country that has already undergone phase-out of coal mining is the Netherlands. Phase-out of coal power generation is currently underway. Coal mining phase-out in the Netherlands serves as an example of industrial upgrade and regional renewal.

One driver of coal phase-out was the **advance in competing resources** as the Groningen gas field was discovered in 1959. Additionally, foreign coal was economically more competitive than domestic coal [32, 126]. Other pressures from the broader economic and socio-political setting included a general overcapacity of the European coal industry and cheaper oil imports [32]. One of the most important actors in the mining regime was the company Dutch State Mines (DSM) which was involved not only in coal production but also in the production of chemicals, and gas as a by-product of coal coking [127, 128]. The decline of **regime strength** may have been indicated by the decline of revenue from coal mining compared with the revenue from these other activities [32]. Initially, coal mining actors adopted a **strategy** of resistance to the coal phase-out and aimed to lobby for state subsidies. However, this strategy changed to one of adjustment by substituting coal for gas within DSM [32, 128].

The **organization** of the industrial system was dominated by the state-owned DSM as the largest mining company, even though there were several smaller private companies [126, 129]. Workers in the coal mining sector were unionized and powerful. They supported the phase-out and were involved in negotiations with both DSM and politicians [126, 130]. DSM's diversified business model and several revenue streams ensured there was financial **capacity** to innovate and diversify even as revenues from coal mining declined [32]. As DSM was also previously involved in distributing the gas that was the by-product from coking coal to municipal district heating, it had the capacity and resources to engage in natural gas distribution [127]. The **industry dynamics** changed insofar as private mining companies exited the industry, whereas DSM **upgraded** by remaining in the gas and chemicals sectors [127].

The main coal mining region in the Netherlands was Limburg. Relevant aspects of the **regional legacy** to decline include that the region is located relatively far away from other industrial centers and cities in the country, but right at the border with Belgium and Germany, among others with the German Ruhr area which is also a coal mining region [129]. The economy in the eastern part of the region was dependent on the coal sector, whereas diversified DSM was situated in the western part [126, 129]. Local government had little autonomy for the most part of the decline [129]. Only in 1977 when the last coal mines were closed were more capacities transferred to the region. For the most part, decline was thus managed by the national government [129], and **regional strategies** of innovativeness and **reorganization** only became relevant later. Whether regions are on the path of renewal or survival may be indicated by **dynamics** such as unemployment rates and migration trends. In the beginning of the phase-out, there were seemingly little to no redundancies, as many workers could be reemployed in DSM's chemical operations, could move to other companies or could move to Germany [126, 129]. New companies, such as a car manufacturer, settled in the region, diversifying the economy [129]. However, developments within the broader economic and socio-political setting influenced this pathway: during the ensuing oil and economic crisis in the 1970s, unemployment rose more significantly in Limburg than in the rest of the Netherlands, leading to further required policy intervention and support.

The **PAS** supported the transition through financially compensating private mines in exchange for closing them early [126]. It was also a government decision to allocate the rights to exploit gas reserves to DSM, thus enabling the later upgrade of the firm [32]. In addition, subsidies were allocated to the retraining of workers, to infrastructure improvements in the region and to making the region more attractive to investors such as through reducing the costs of land [32, 126].

The relative success of the early regional development pathway may be attributed to governmental, company and union strategies that all seemed to be aligned toward renewal and innovation rather than lobbying for continued support for the coal sector. Even though there were challenges to Limburg's renewal pathway and the risk of regional despondence was present especially in the context of a larger economic crisis, the Dutch case can serve as an example of de-coupling of industry and regions from declining technologies.

CONCLUSION

Phasing out fossil fuels simultaneously creates two policy problems: managing the transformation of affected industries and ensuring socio-economic recovery in the regions dependent on fossil fuel resources and industries. Here, we propose a practical tool to inform policy sequencing to address these interconnected policy problems. Three bodies of literature have addressed these problems and their associated systems: socio-technical transitions literature studies change or persistence of technological systems, business and management literature studies the transformation of industrial systems and regional geography and economics literature addresses the recovery of regional systems. To use Elinor Ostrom's terminology, these systems constitute top-level variables. We derived second- and third-level variables from the literature that reflect mechanisms driving or blocking decline in each of these systems.

We propose a diagnostic framework that shows how these variables evolve during different phases of decline and illustrate this framework using three different examples of national coal decline. We show that the strength of each policy problem varies throughout the phases of decline, giving rise to different risks and making different policies necessary at each phase. This is captured in the PAS containing rules and regulations that affect the three systems and which at the same time responds to feedbacks from these systems.

This defines a research agenda of 'policy sequencing for feasible decline'. Today's policy landscape includes both efforts to compensate affected actors of decline while at the same time withdrawing all financial support from incumbents [2, 7, 131, 132]. However, how these policies should be combined is unclear. We believe that diagnosing the phase of technological, industrial and regional decline can answer this question and inform policy sequencing for decline based on the strengths of risks and mechanisms at different phases. Empirically, testing the validity of our proposal for policy sequencing for decline, as has been done in clean energy [25], offers a fruitful research direction.

In addition, our diagnostic approach offers further avenues for future research.

First, we believe our approach will be particularly useful in cross-case comparisons and in drawing lessons from such studies. Identifying which strategies for decline are transferable and under what conditions is a crucial step to formulating empirically and theoretically sound policy advice. When examining a case of coal decline (or persistence), we believe positioning the case in the phase of decline is just as important as considering its geographic and socio-political setting. This framework could also be applied to other cases of carbon-intensive decline, such as steel manufacturing, or oil phase-out, where similar policy problems emerge and interact. The relevant top-level variables may have to be modified depending on the implicated systems [133].

Second, it would be useful to better understand when, where and how the regional system de-couples from the industrial and technological system. Here, it is important to pay attention to the path of the regional system because that is where policy has the potential to have the most impact. Recovery for fossil fuel dependent regions can be the result of new industries arriving after the fossil fuel industry has fled, or the result of a renewed industry from the very same firms. Understanding what leads to these different pathways and the role of policy in ensuring successful renewal is key to supporting feasible fossil fuel decline pathways.

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CONFLICT OF INTEREST

None declared.

AUTHORS' CONTRIBUTIONS

J.J. and A.C. conceptualized the article. L.N. conducted the literature review and case studies. L.N. and J.J. wrote the original article. All authors revised the article. J.J. supervised the work.

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Paper II

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

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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*

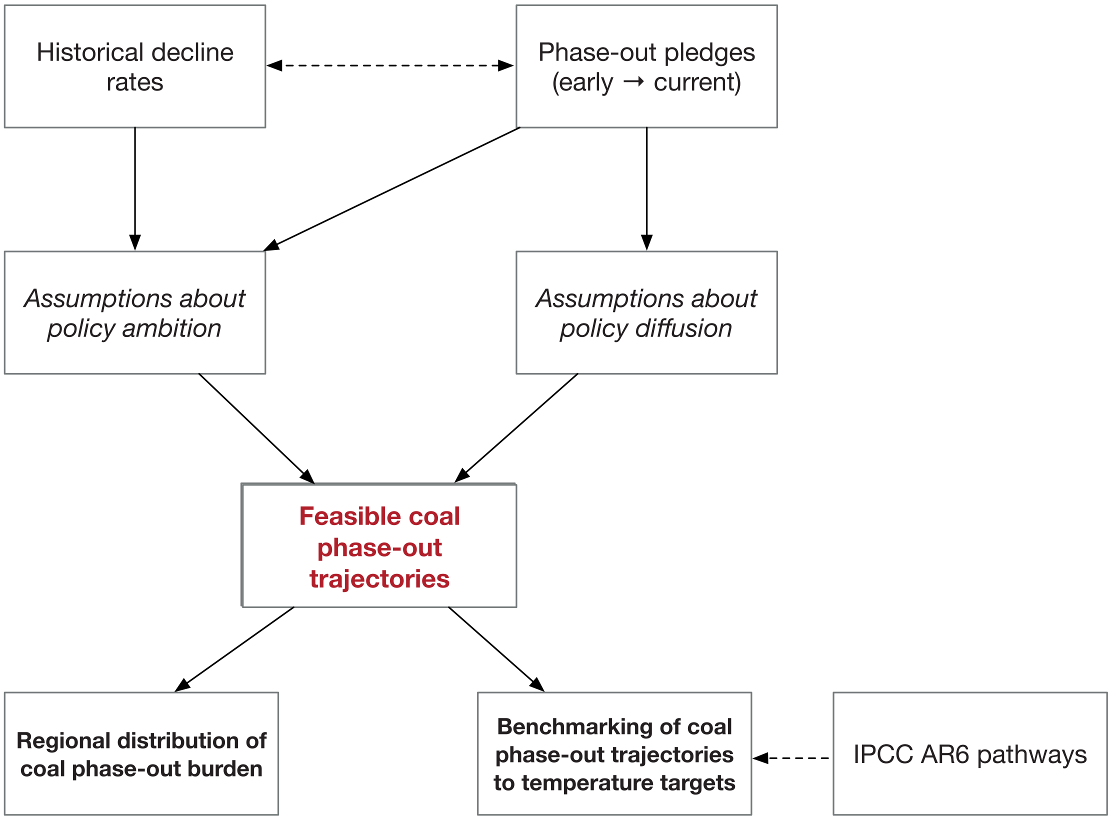

Figure 1. Organisation of research in this article. Plain text—inputs, *italic*—assumptions used in building coal phase-out trajectories, bold—results. Dashed lines—use of contextual information for analysis and benchmarking.

[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

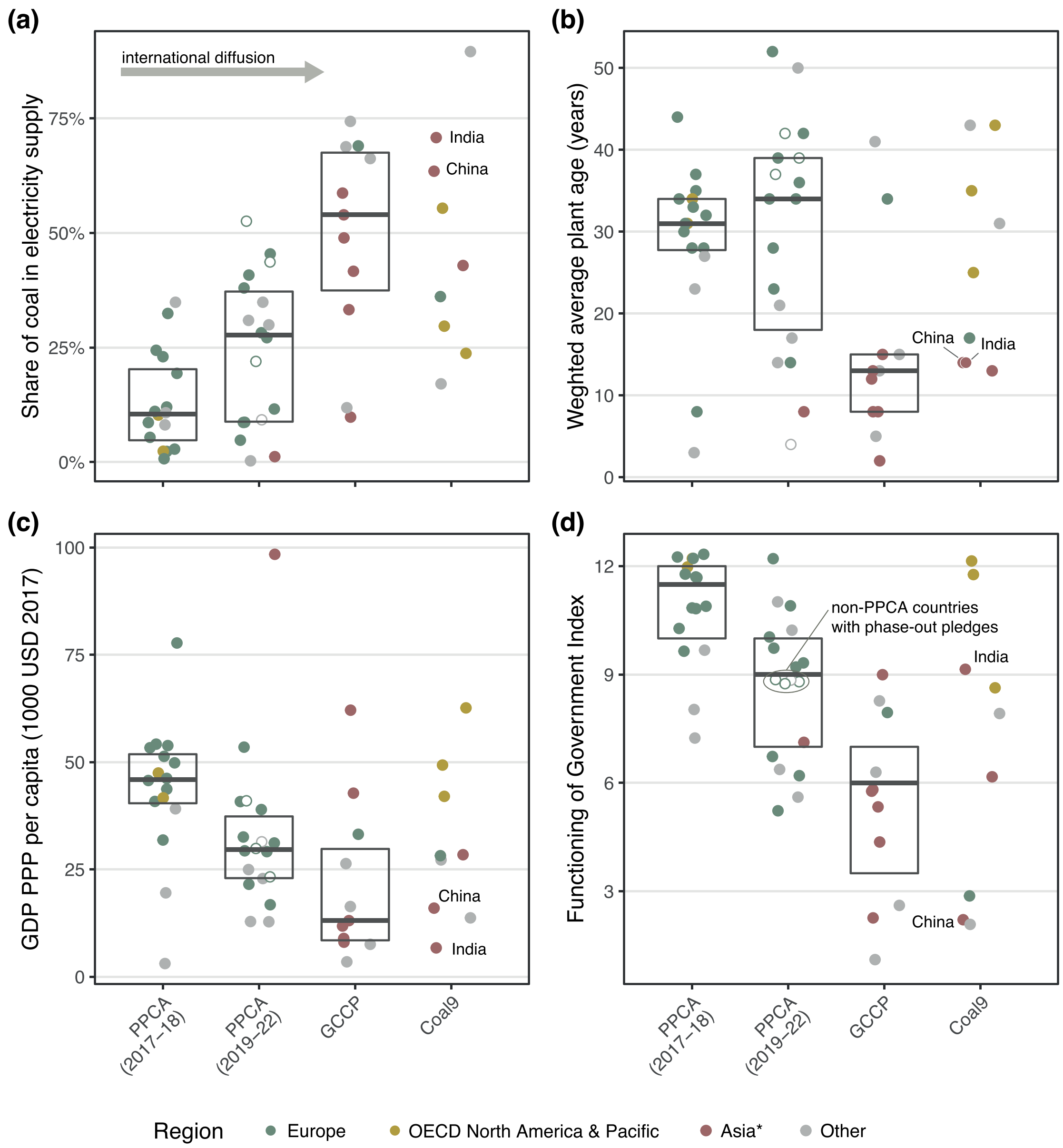

Figure 2. Characteristics of countries with different timing and type of coal phase-out pledges as well as without pledges. (a) Share of coal in the electricity supply. (b) Average age of coal power plant units, weighted by capacity. (c) GDP PPP per capita. (d) Functioning of Government index. See note 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

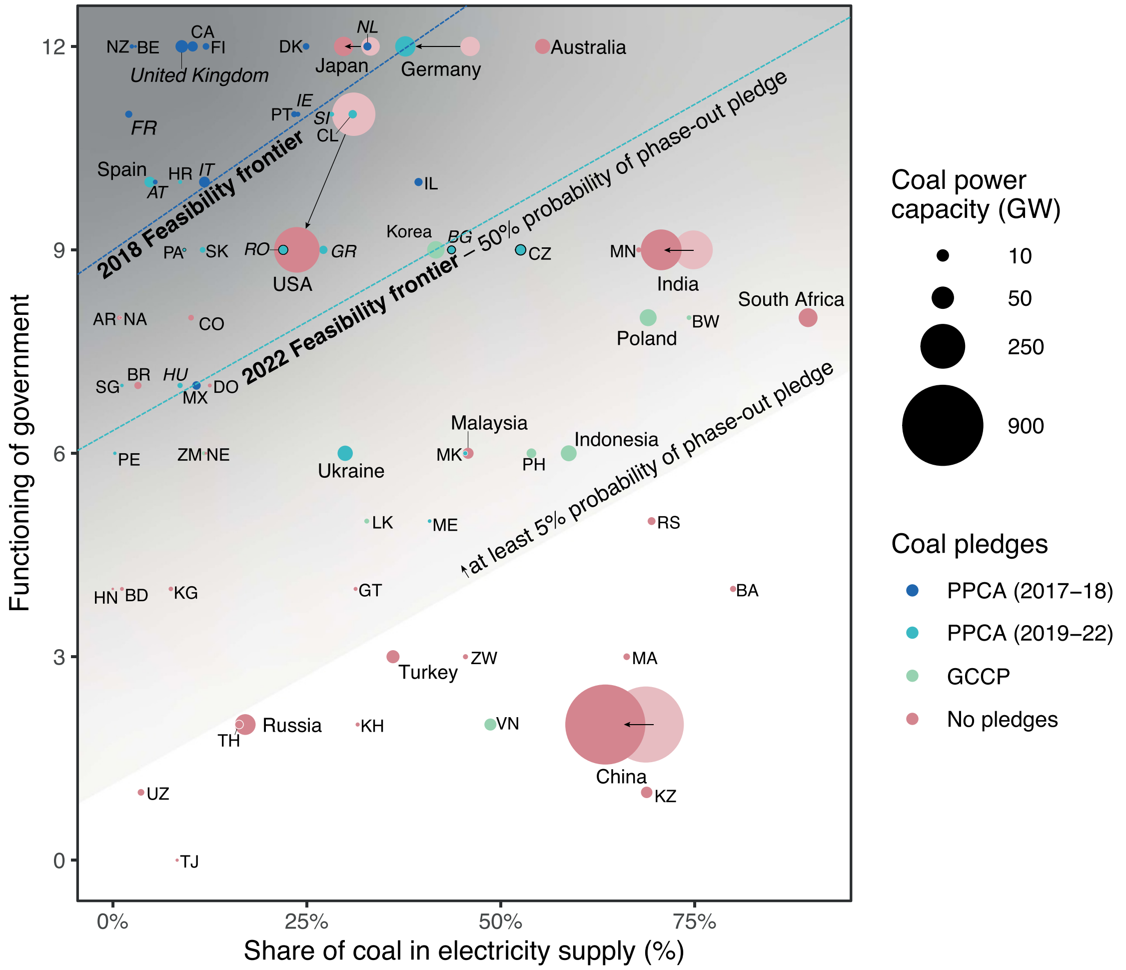

Figure 3. The evolution of the feasibility space for coal phase-out pledges. The two feasibility frontiers correspond to 50% probability of being a PPCA member based on the logistic regression analysis of PPCA membership in 2018 from [11] and in 2022 (our calculations) respectively, using percentage 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

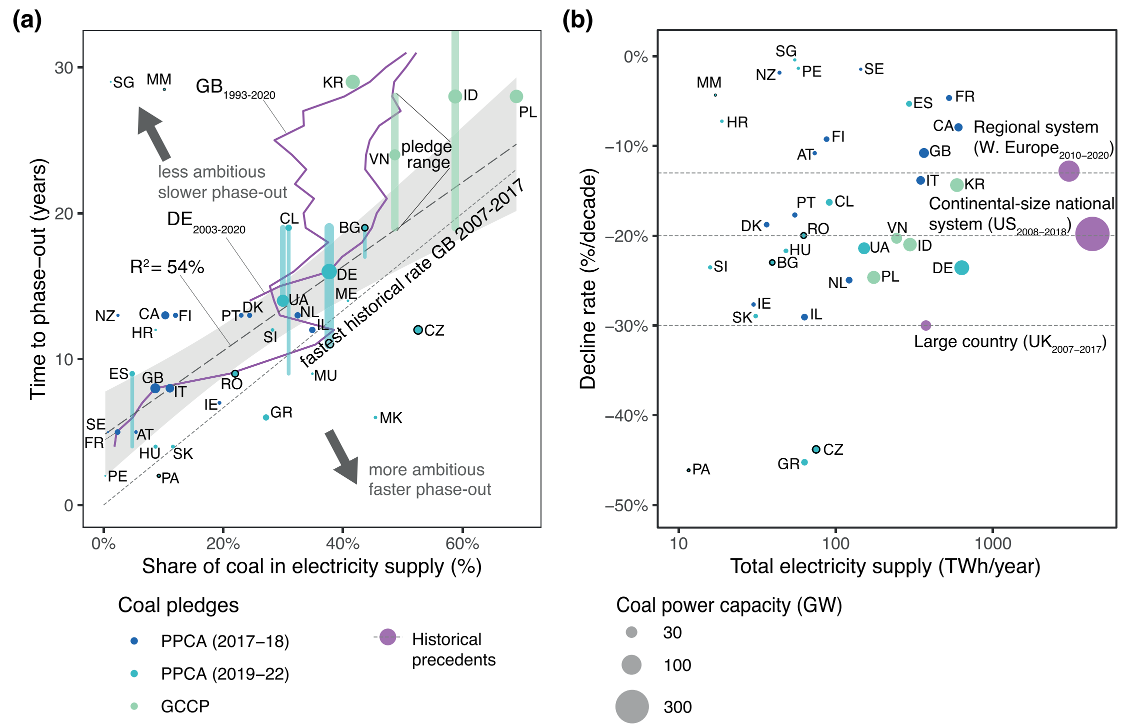

Figure 4. The pledged phase-out time as a function of share of coal in electricity and total electricity supply and coal decline rates implied in the phase-out pledges. Both panels include all countries with electricity production from coal >1% and coal phase-out pledges, except for countries with total 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

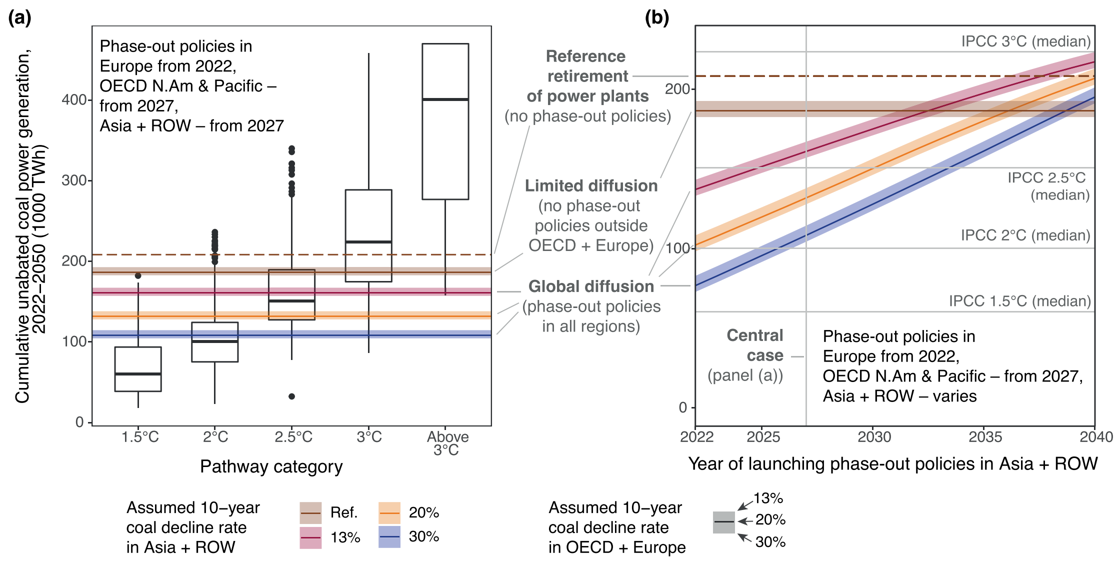

Figure 5. Global cumulative power generation from unabated coal in counterfactual coal decline scenarios compared to IPCC AR6 pathways (2022–2050) and the effect of the speed of policy diffusion. Colours represent different decline rates in *Asia + ROW*. Ranges of the same colour represent different 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

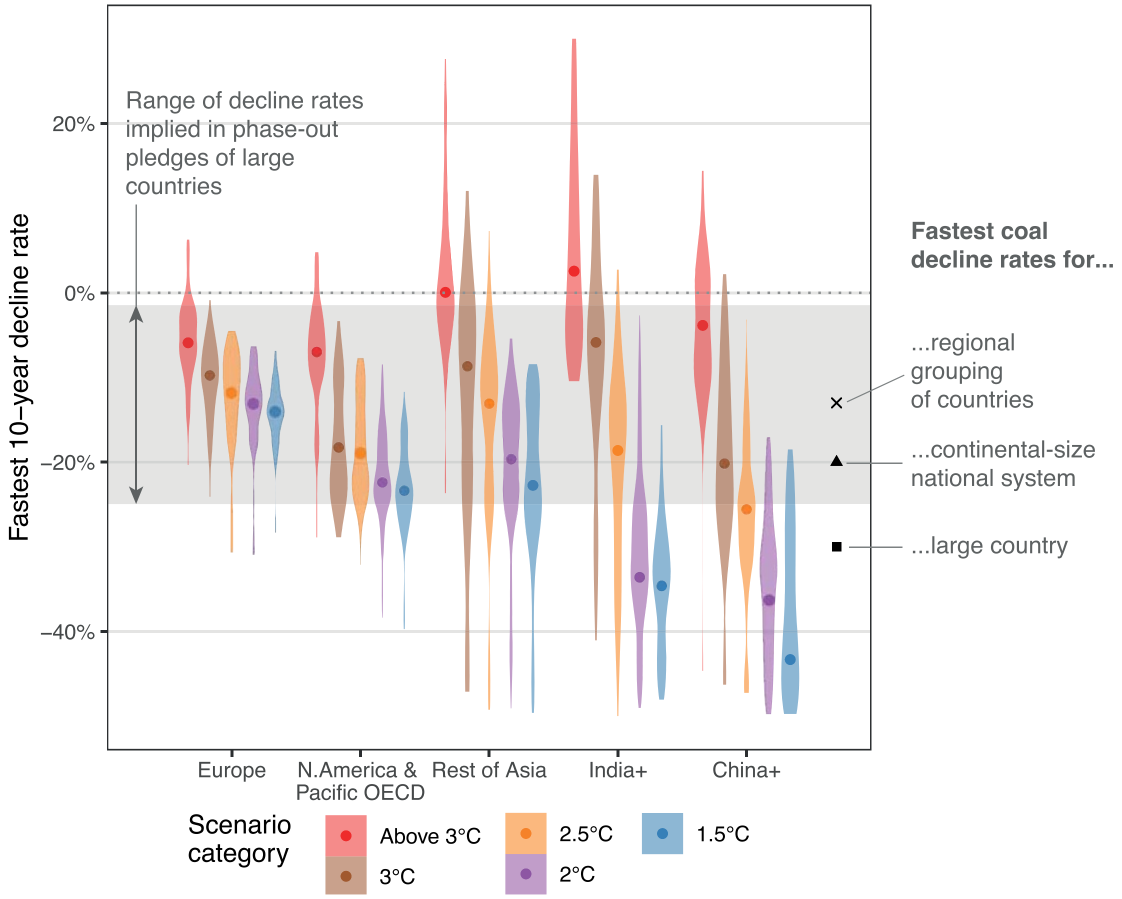

Figure 6. Fastest regional coal decline rates in IPCC AR6 pathways consistent with different temperature targets as compared to historical benchmarks. Fastest ten-year decline rates expressed as percentage of total electricity supply (note S1) are calculated for major coal-using regions in each pathway 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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Paper III

Socio-political cost of accelerating coal phase-out

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Socio-political cost of accelerating coal phase-out

Lola Nacke[a], Vadim Vinichenko[a], Aleh Cherp[b,c], Avi Jakhmola[a], Jessica Jewell*[,a,d,e]

Abstract

While macroeconomic models highlight rapid coal phase-out as an urgent climate mitigation measure, its socio-political feasibility is unclear. The negative impacts of coal phase-out for companies, workers and coal-dependent regions, and the unequal global distribution of the coal phase-out burden has triggered resistance and calls for just transitions. Here, we construct a database of domestic and international just transition policies and partnerships that compensate affected actors of coal phase-outs. By comparing coal phase-out in countries which have compensation plans with those that don't, we show that compensation policies are essential to realizing premature retirement of coal. The cost we estimate associated with these policies clarifies the financial cost of making coal phase-out politically feasible. We find that compensation costs are proportional to avoided emissions resulting from coal phase-out and are generally consistent with recent carbon prices. We find that the cost of implementing similar compensation policies in case of 1.5°C -consistent coal phase-out for China and India is 17 times higher than all existing compensation, and roughly comparable to global Official Development Assistance in 2021. We show that in the case of coal phase-out, political will and social acceptance have a tangible economic component which should be factored in to assessing the feasibility of achieving climate targets.

Introduction

Ending the burning of coal for power production is one of the most urgent climate mitigation measures[1]. However, coal phase-out can trigger socio-economic hardship for coal-dependent regions[2,3] and political backlash from coal workers and companies[4,5]. Governments are tackling these challenges with 'just transition' strategies, which are believed to increase the political feasibility of coal phase-out[6–8]. Just transition strategies often include financial compensation to support actors who bear the costs of the transition to a low-carbon economy[3,6]. This compensation offers a unique empirical window into how much it could cost to make worldwide coal phase-out politically feasible.

With cheaper renewable electricity already available in many markets[9], phasing out coal is technically and economically feasible. Nevertheless, some believe the rapid coal phase-out depicted in many climate scenarios is infeasible due to technological inertia and socio-political barriers[10–12]. What would it take to overcome these barriers? We build the first database of all compensation packages including the most prominent international just energy transition partnerships to quantify the cost of a politically feasible worldwide coal phase-out.

Our analysis also brings evidence to the debate on fairness of energy transitions[7,13–15]. While there is general agreement on the need for a just transition, what exactly this should entail is contested. For example, some hailed Germany's €56 billion ($66 billion) compensation package as a landmark policy making coal phase-out politically feasible[16] while others attacked it as imposing an unjust burden on German taxpayers[17]. By comparing the existing compensation

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schemes we clarify whether the understanding of fairness varies across countries with different socio-economic and political circumstances and thus whether it can be projected for countries such as India and China that have not yet started decisive coal phase-out.

In this way, today's compensation policies shed light on the potential future cost of transnational compensation for just transitions. The COP26 accord calls for "targeted support [for coal phasedown] to the poorest and most vulnerable in line with national circumstances and recognizing the need for support towards a just transition"[18]. Such support is critical to reaching our climate targets since over 80% of coal power is located in emerging markets and developing economies[7]. International partnerships have been created to support coal phase-out in Indonesia[19], Vietnam[20], and South Africa[21] (Supplementary Note 1). If China and India, the two countries with the biggest coal fleets, adopt compensation policies similar to existing policies, how much compensation would be required to keep them on a 2°C or 1.5°C pathway?

To answer these questions, we calculate the compensation within national and international policies per ton of avoided CO_2 emissions. We find that despite some variation, the cost of compensation per avoided CO_2 emissions is consistent with carbon prices over the last five years. We then use this result to estimate the cost of compensation that might be implied if India and China commit to coal phase-out consistent with a 1.5°C or 2°C target. We find that the cost of compensation for China and India along 1.5°-consistent pathways would be 17 times higher than the cost of all currently operating compensation policies.

Building a database of compensation policies for coal phase-out

In spite of increasing interest in just transitions, there has been little quantitative and comparative analysis of just transition policies, in particular of financially compensating regions, workers and companies for coal phase-out. We construct a database of all national coal phase-out commitments and just transition policies which compensate actors negatively affected by coal phase-out. We identify 24 countries with plans for financial compensation, and 23 countries where these plans are accompanied by a national coal phase-out pledge (Table 1, Methods). To characterize the financial compensation flows and beneficiaries for each policy, we code the respective amount of compensation, the origin of the funds, and beneficiaries based on government sources and where necessary third-party reports (Table 1, Supplementary Table 1, Supplementary Figure 1). In cases where there is uncertainty in pledged compensation, either because a reported pledge could not be confirmed in official government documentation, or because a measure is contingent upon future developments like the approval of just transition plans submitted to the EU, we provide both a lower and upper estimate and use the average of the two as our central case (Methods, Supplementary Table 1). We are able to estimate financial compensation for 20 countries with coal phase-out commitments and for South Africa which receives financial support under its Just Energy Transition Partnership (JETP) but does not have a coal phase-out commitment (Table 1, Methods).

To evaluate the intensity and speed of national coal phase-out commitments, we calculate avoided emissions from coal phase-out policies. We do so by comparing the total emissions of national coal power plant fleets in two scenarios: (1) a reference scenario where coal power plants are retired when they reach the average national retirement age for coal plants and (2) a policy scenario where coal power plants are phased-out in line with national commitments (Methods, refs.[22],[15]).

Figure 1. Countries with coal phase-out and/or compensation plans. a) All countries with coal phase-out commitments by installed capacity of coal power plants[23], avoided emissions and size of compensation package (Methods, Supplementary Table 2). b) Countries with coal compensation by avoided emissions and total compensation cost (Methods). Error bars on panel (b) represent the uncertainty range for avoided emissions and compensation (Table 1, and Supplementary Table 1 and 2).

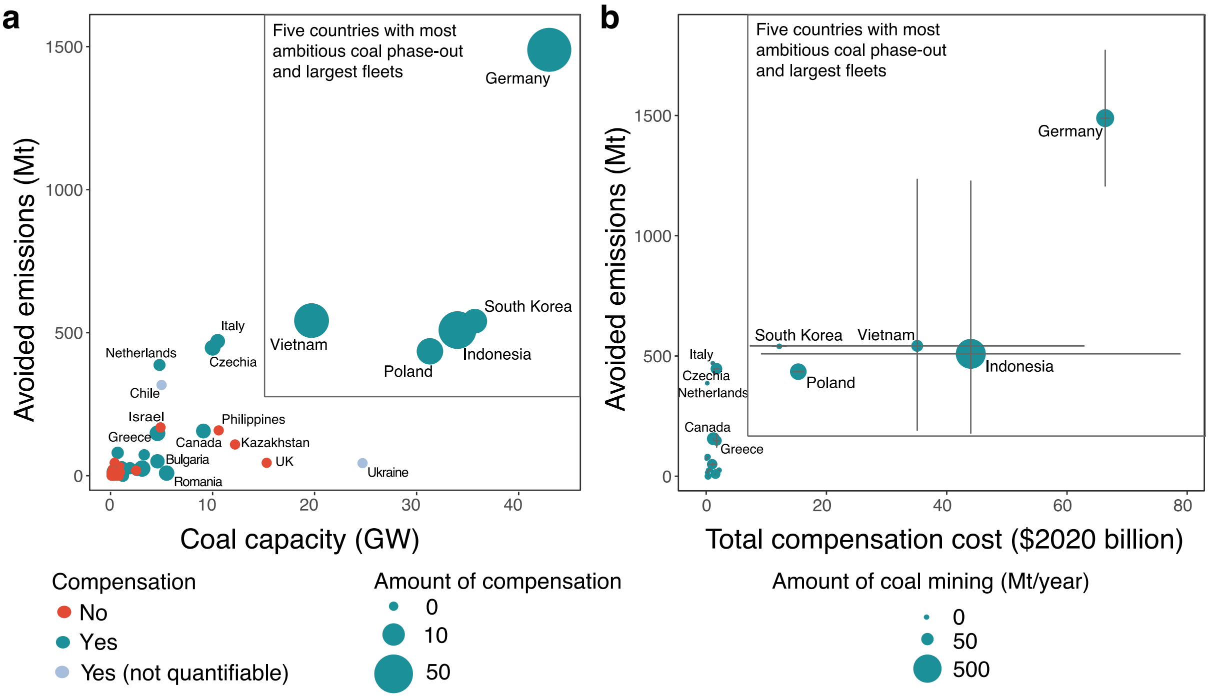


Table 1. Coal phase-out compensation, origins, and beneficiaries of compensation. Central estimate for compensation is reported followed by the full uncertainty range in parentheses (Methods). For “Origins of transfers”, national funds are indicated by plain text and international funds by italics. In cases where the origin of national funds could not be identified, we indicate this with “NA”. *South Africa’s JETP is included, however since there is no national coal phase-out commitment, we could not estimate a full uncertainty range. **Chile and North Macedonia have coal phase-out compensation plans but have not disclosed the amount of compensation. ***Ukraine has a coal phase-out commitment as well as a planned just transition and coal sector restructuring scheme. However, since the outbreak of the Russo-Ukrainian war, it is unclear when and whether these plans will be implemented, which is why we exclude Ukraine from further analysis. See Supplementary Table 1 for detailed estimates and sources.

Country	Compensation ($billion)	Origins of transfers	Beneficiaries and purposes of transfers
Germany	65 (62-69)	Redirecting regional infrastructure funds (national) *Just Transition Fund (EU)*	Economic and environmental recovery of coal regions, compensation for coal companies, assisting laid-off workers
Indonesia	44 (9-79)	*Just Energy Transition Partnership*	Support closure of coal plants, increasing renewables capacity, support for regions
Vietnam	35 (7-63)	*Just Energy Transition Partnership*	Support closure of coal plants, increasing renewables capacity, support for regions
Poland	13 (11-16)	Revenues from carbon pricing, transmission tariff, redirected development fund (national) *Just Transition Fund (EU)*	Compensation for coal companies Economic recovery of coal regions
South Korea	12 (11-13)	Mobilized from the treasury (national)	Economic recovery of coal regions Support for laid-off workers
South Africa*	9	*Just Energy Transition Partnership*	Support closure of coal plants, increasing renewables capacity, support for regions
Spain	2.1	Funds managed by Just Transition Institute, Institute for Energy, Fundación Biodiversidad (national) *Just Transition Fund (EU)* *Recovery and Resilience Facility (EU)*	Infrastructure, environmental and economic recovery of coal regions Support for laid-off workers
Greece	1.8 (1.2-2.3)	Reinvesting carbon pricing revenues (national) *Just Transition Fund (EU)*	Infrastructure and economic recovery of coal regions
Czechia	1.7 (1.2-2.2)	*Just Transition Fund (EU)* *Recovery and Resilience Facility (EU)*	Increasing renewables capacity Economic recovery of coal regions
Romania	1.6	*Just Transition Fund (EU)* *Recovery and Resilience Facility (EU)*	Increased renewables capacity Economic recovery of coal regions
Canada	1.2	Repurposed Green Infrastructure funding from Budget 2017 (national) Reinvesting carbon pricing revenues (regional - Alberta)	Infrastructure, economic recovery, skills development in coal regions Assisting laid-off workers (Alberta)
Italy	1.1 (0.9-1.3)	*Just Transition Fund (EU)*	Infrastructure and economic recovery in coal regions
Bulgaria	1 (0.3-1.7)	*Just Transition Fund (EU)* *Recovery and Resilience Facility (EU)*	Infrastructure and economic recovery in coal regions
Slovakia	0.6 (0.5-0.8)	NA (national) *Just Transition Fund (EU)*	Compensating coal mining company for environmental recovery of region and support of workers, economic recovery of coal regions
Portugal	0.3	NA (national) *Just Transition Fund (EU)*	Infrastructure and economic recovery in coal regions
Hungary	0.3	NA (national) *Just Transition Fund (EU)*	Infrastructure and economic recovery in coal regions
Finland	0.2 (0.2-0.3)	Redirected from tendering scheme for renewable electricity (national)	Subsidies to power companies to invest in alternatives to coal

Country	Compensation ($billion)	Origins of transfers	Beneficiaries and purposes of transfers
Slovenia	0.2 (0.2-0.3)	NA (national) *Just Transition Fund (EU)*	Infrastructure and economic recovery in coal regions
Netherlands	0.2 (0.1-0.3)	NA (national)	Compensation for coal companies Economic recovery of coal region in Colombia
Croatia	0.2 (0.1-0.2)	NA (national) *Just Transition Fund (EU)*	Infrastructure and economic recovery in coal regions
France	0.1	Program 174: Energy, climate and post-mining (national)	Assisting laid-off workers, economic and environmental recovery of regions
Chile**	NA	NA	Remuneration for power plants and coal workers
North Macedonia**	NA	NA	Support for coal workers and coal regions, investment in renewables
Ukraine***	NA	State budget	Planned measures on restructuring coal sector and closing coal mines
Total	**186 (118-253)**	Total National: 92 (90-95) *International: 94 (29-158)*	-

Estimating and mapping financial flows for compensation of coal phase-out

Globally, total compensation flows for coal phase-out account for $186 billion (central estimate – $118-253 billion full range). Coal phase-out compensation policies range from $0.07 billion to $66 billion (central estimates – $0.06-79 billion full range) per country. We find that all countries with ambitious coal phase-out commitments also plan compensation for coal phase-out (Figure 1). The five countries (South Korea, Poland, Indonesia, Vietnam, and Germany) with the most ambitious coal phase-out commitments and largest coal fleets (> 20 GWe) plan compensation more than $10 billion each and account for over 95% of today's compensation. Most of these countries also have coal mining. Countries with smaller coal fleets (≤10 GWe) and no or little coal mining plan compensation less than $1 billion (Figure 1, Supplementary Table 2).

Half of all compensation is international (50% central estimate; 24%-63% – full uncertainty range), and the other half national. There are three international financial compensation programs with provisions for coal phase-out compensation (Table 2). For EU recipient countries, the bulk of international funding comes from the EU Just Transition Fund (JTF) but some countries also receive funding for coal phase-out from the Recovery and Resilience Facility (RRF) designed to facilitate recovery from the COVID-19 pandemic. Additionally, different coalitions of developed countries have signed Just Energy Transition Partnerships (JETPs) with Indonesia, Vietnam, and South Africa and there are talks of JETPs with India and Senegal (Supplementary Note 1).

Overall, compensation amounts to about 0.001%-0.6% of GDP (Figure 3) with nationally funded compensation ranging from zero (for countries which rely fully on international funding) to 0.1% of GDP. The majority of countries which plan compensation for coal phase-out receive some international funding. Only two non-EU countries (Canada and South Korea) and three EU countries without active coal mining (Netherlands, Finland, and France) do not receive international funding. The EU's JTF is funded from the EU budget 2021-2027 and from its Covid recovery instrument, which also includes the RRF[24]. For the JETPs, it is not clear how donor countries plan to fund compensation. National and sub-national funds are mobilized from a variety of sources such as regional infrastructure funds (Canada and Germany), climate and energy funds (Finland, France, and Spain), and carbon tax revenues (Canada and Greece) – Table 1.

The main purpose of compensation policies is to fund the economic and environmental recovery of coal regions by increasing the deployment of renewables technologies and industries, and support laid-off coal workers (Table 1, Supplementary Table 1). We found that the majority of national financial flows are received by regional authorities in regions where coal mining or coal-based electricity production is located. In ten cases, coal companies are among the direct beneficiaries and in six cases workers are among the direct beneficiaries (Table 1). Funding targeted at companies is designed to compensate for foregone revenues from coal plant closures and to support coal companies to develop their capacities in low-carbon technologies. International funding goes directly to national and regional governments of recipient countries which are in turn likely to use it for similar purposes.

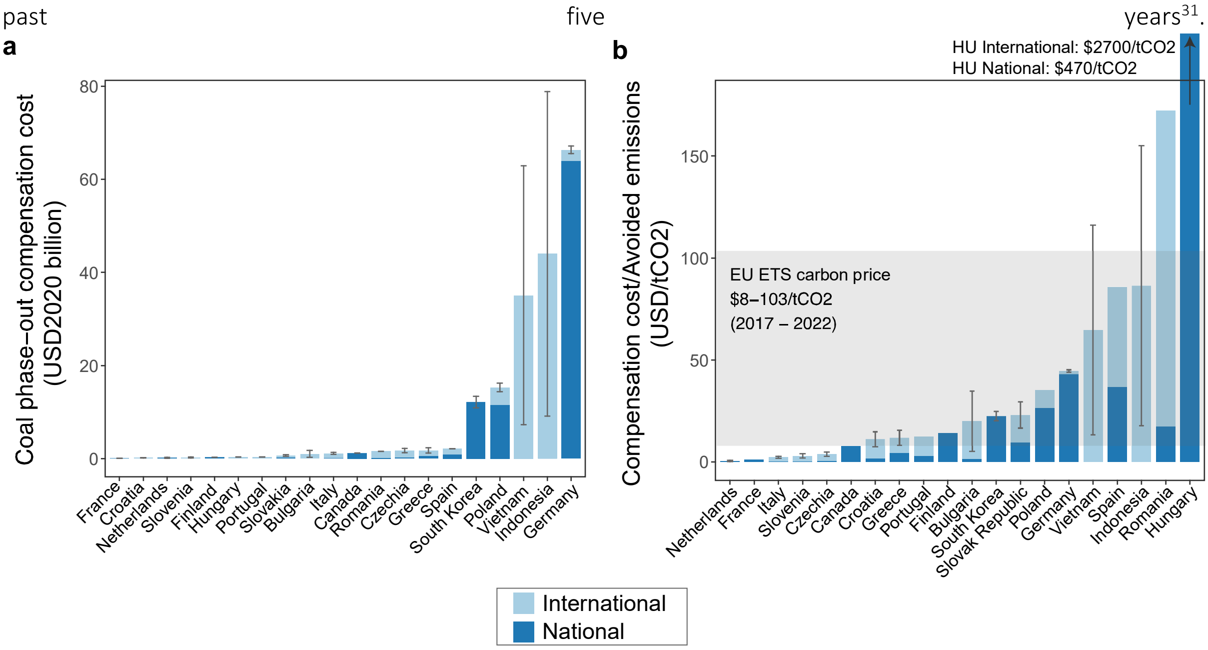
Table 2. International compensation programs. The Just Transition Fund and Recovery and Resilience Facility in this table only include funds which are likely to be used to support coal phase-out in recipient countries. The JETPs aim to support decarbonization in the recipient countries, with phasing down coal power-generation as one of the major challenges. For the upper estimate, we extrapolate currently committed flows (indicated in bold) over the entire duration of the coal phase-out (Supplementary Table 1, Supplementary Note 1). We calculate the central estimate as the mean of the currently committed and extrapolated amounts.

Financial compensation program	Total amount ($billion)	Recipients	Funders	Description
Just Transition Fund	9 (7-11)	Bulgaria, Croatia, Czechia, Germany, Greece, Hungary, Italy, Poland, Portugal, Romania, Slovakia, Slovenia, Spain[25,26]	EU	EU support for member states with regions vulnerable to negative effects of the climate transition.
Recovery and Resilience Facility	1	Bulgaria, Czechia, Spain, Romania[27]	EU	EU support for member states to recover from the impact of the Covid pandemic and make their economies more resilient and sustainable.
Just Energy Transition Partnership	**9**	South Africa[21,28]	EU, France, Germany, UK, US	Accelerate decarbonization, focusing on the electricity system and help achieve South Africa's NDC. Currently committed "over the next 3-5 years […,] with a view to longer term engagement"[21] .
	44 (**9**-79)	Indonesia[19]	Canada, Denmark, EU, France, Germany, Italy, Japan, Norway, UK, US	Support achievement of Net Zero by 2050 and transitioning away from on and off-grid coal-powered electricity. Currently committed over the next 3-5 years, considering "policy reforms aimed at facilitating greater levels of investment"[19].
	35 (**7**-63)	Vietnam[20]	Canada, Denmark, EU, France, Germany, Italy, Japan, Norway, UK, US	Support the achievement of Vietnam's Net Zero 2050 goal, and the transition away from fossil fuels. Currently pledged over the next 3-5 year. "The continuation of the partnership is expected to be contingent on [conditions outlined in the JETP]"[20]
Total	*98 (33-163)*			

Compensation consistent with carbon prices and proportional to ambition of coal phase-out

To evaluate the financial effort needed for compensation policies in the context of the energy transition, we calculate the cost of compensation per ton of avoided emissions. We find that while at first glance, the variation in compensation per tCO_2 seems quite large (interquartile range \$7-50/tCO2), it is consistent with the EU ETS carbon price over the last five years (Figure 2). Countries with compensation below the carbon price tend to have no active coal mining (e.g. Italy, France and the Netherlands) or a particularly small coal fleet (e.g. Slovenia). Hungary is a clear outlier – while its total compensation is comparable to Finland and Portugal, its coal phase-out affects one coal plant that has already been in operation for more than 50 years and a small coal mining industry[29,30].

Figure 2. National and international compensation plans. Dark blue, compensation from national funds; light blue international compensation. Bars represent the central estimate and error bars represent the uncertainty range (Methods, Table 1). **a)** Total compensation. **(b)** Compensation normalized to ton avoided emissions (Methods). The grey range in panel (b) shows the carbon price under the EU emissions trading scheme over the past five years[31].



We also calculate compensation per GW of installed coal power capacity (Supplementary Figure 2) to test how compensation costs compare to the cost of a new coal power plant. One would expect compensation to be less than the cost of a new power plant, since in most cases older plants are retired which don't have the same value as a new one. For most countries this is true, however we find that Germany's compensation policy is equivalent to the cost of new plants and if international transfers to Vietnam and Indonesia continue until the planned phase-out, their compensation cost may also be similar to the recent cost of a new plant. In the case of Germany, this may reflect the plan to phase out young plants such as the newly built Datteln IV which featured heavily in the negotiations for coal phase-out[32,33] and in the case of Vietnam and Indonesia, it may reflect the relatively young coal fleet and distant phase-out (see Supplementary Table 2).

Finally, we test the possibility of predicting compensation based on the ambition of national coal phase-out commitments, characteristics of the coal sector, and national contexts with a multiple variable regression analysis (Methods, Supplementary Note 2). To characterize the ambition of national coal phase-out commitments we measure avoided emissions which is proportional to stranded coal capacity. For the coal sector, we test the effect of the size and power generation from the coal fleet, value-added of the coal sector, and the presence of coal mining. To characterize the national context, we test the effect of the size of an economy, its wealth, and level of democracy. We find that avoided emissions is the best predictor of compensation policies, particularly when we control for coal mining and either the size of a country's economy or how democratic a country is (Supplementary Note 2). This means that compensation packages are generally proportional to the ambition of coal phase-out commitments.

Compensation for coal phase-out in China and India might strain domestic and international budgets

In spite of the global diffusion of coal phase-out and just transitions policies, neither China nor India, the two countries with the largest coal fleets, has pledged to phase-out coal. China has pledged to slow coal expansion and "start phasing down coal use from 2026"[34] and to stop funding coal power plants abroad[35], however China's coal fleet is still expanding with 86 GW coal capacity in construction and another 106 GW permitted[36]. Additionally, China's net-zero target (2060) is two to three decades later than the coal phase-out depicted in IPCC 1.5°C and 2°C compatible pathways (Table 3, Methods). In India, discussions are underway for a national just transition strategy[37] and Just Energy Transition Partnership[38], however the country's net zero target (2070) is also several decades after coal phase-out in IPCC 1.5°C and 2°C compatible pathways (Table 3, Methods). All in all, we find that the avoided emissions to reach 1.5°C and 2°C targets required in India+ and China+ are 13-18 times higher than all countries with coal phase-out commitments globally[15].

If China and India adopt compensation strategies similar to existing policies, how much compensation would be required to keep these two countries on a 2°C or 1.5°C pathway? We answer this question using our empirical model of existing compensation policies (Supplementary Note 2) and the avoided emissions implied by 1.5°C and 2°C pathways for the China+ and India+ regions (Table 3, Methods). We use avoided emissions from the China+ and India+ regions to estimate compensation in China and India respectively, since each country accounts for at least 97% of coal power generation in their respective region (Methods). After controlling for the effect of mining and national characteristics, we find that in China, a compensation strategy similar to existing policies would result in $2.3 trillion (central estimate, IQR range and $1.7-2.6 trillion) for 1.5°C, $1.7 trillion ($1.5-2.2 trillion) for 2°C, and in India $1 trillion ($0.8-1.1 trillion) for 1.5°C and $0.8 trillion for 2°C ($0.6-0.9 trillion) (Table 3). Compensation for China and India for 1.5°C-consistent pathways would thus be roughly 17 times higher than all currently committed compensation, and roughly 13 times higher for 2°C-consistent pathways.

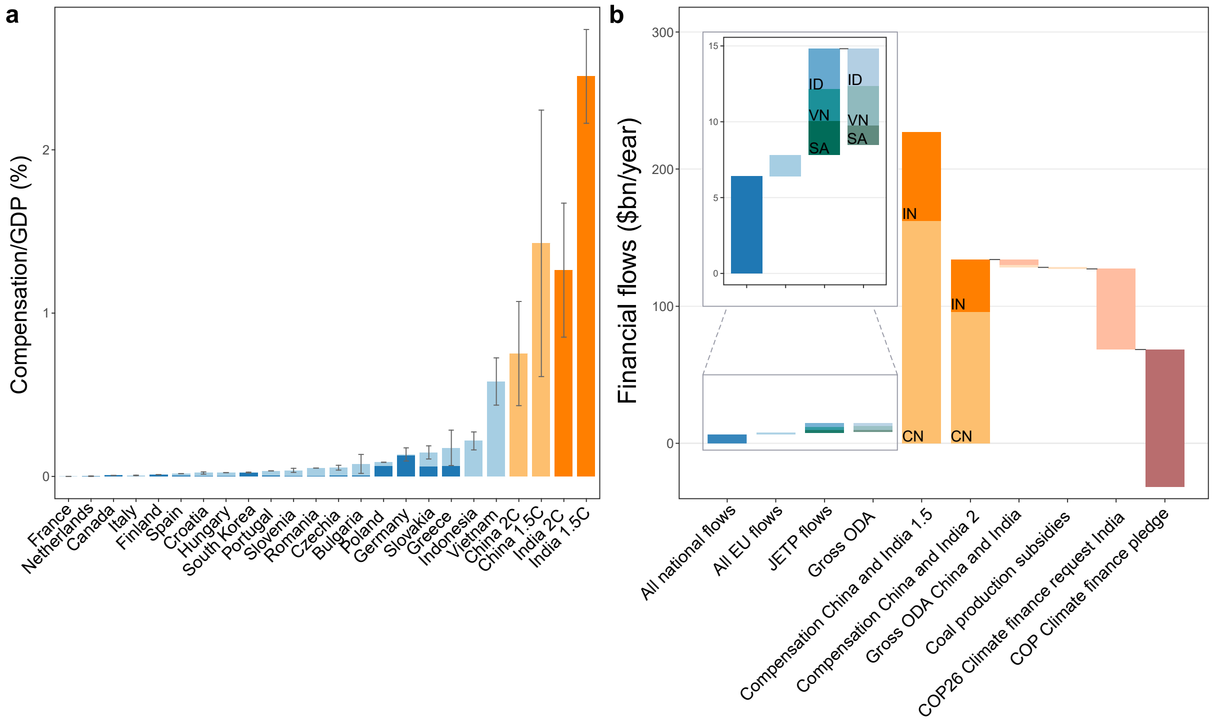
Table 3. Coal phase-out dates, avoided emissions, and estimated compensation. Data for Indonesia and Vietnam are based on their GCCP coal phase-out commitment, and estimated compensation is based on the JETPs and our extrapolation (Methods, Supplementary Note 1, Supplementary Table 1). Net zero targets for both countries are those stated in the JETP agreements. Data for all other coal compensation countries includes coal phase-out data for all other countries in our dataset. For all values, we present the central estimate first, lower and upper estimates in the brackets. Data for India+ and China+ is scenario-based on our empirical model and AR6 IPCC climate change stabilization pathways[39]. For the date of coal phase-out for China and India, we calculate the date when unabated coal power generation falls below 1% in respective IPCC AR6 pathways (Methods, ref.[15]). The range in each column represents the range we calculate based on the IQR of avoided emissions in IPCC AR6 pathways.

Region/Country	Coal phase-out year		Gt avoided emissions		Estimated compensation		Net zero targets
Coal phase-out commitments and compensation plans							
Indonesia	2045 (2040-2050)		0.51 (0.18-1.2)		$0.04 trn (0.01-0.08)		2050
Vietnam	2045 (2040-2049)		0.54 (0.19-1.2)		$0.04 trn (0.01-0.06)		2050
All other countries with compensation	2036 (2022-2050)		4.2 (3.8-4.7)		$0.11 trn (0.1-0.11)		2035-2050
Total	-		*5.3 (4.2-7.1)*		*$0.19trn (0.13-0.25)*		-
Scenario-based	1.5°C	2°C	1.5°C	2°C	1.5°C	2°C	
India+	2038 (2035-2041)	2045 (2040-2045)	26 (21 -30)	21 (17 -25)	$1 trn (0.8–1.1)	$0.8 trn (0.6-0.9)	2070
China+	2035 (2030-2040)	2040 (2035-2045)	60 (42 - 69)	43 (36 - 57)	$2.3 trn (1.7-2.6)	$1.7 trn (1.5-2.2)	2060
Total	-	-	*86 (63-99)*	*64 (53-82)*	*$3.3 trn (2.5-3.7)*	*$2.5trn (2.1-3.1)*	-

Given the high economic burden on both China and India (Figure 3), international funding is likely required to support such compensation. For example, compensation programs may draw on international climate finance such as that pledged under the Paris Climate Agreement or the recently requested support by India's Prime Minister[40] (Figure 3). However, this would require using most of the pledged international climate financing to fund compensation for coal phase-out in China and India (Figure 3). Additionally, so far, only about half of annually pledged transfers under the Paris Climate Agreement have been mobilized [41]. Additionally, the funding for Just Energy Transition Partnerships in Indonesia and Vietnam is comparable to the Official Development Assistance (ODA) for these countries and in the past, a proportion of ODA has been earmarked for climate change mitigation[42] (Figure 3). In contrast, in India, annual funding required for coal phase-out in line with climate targets is at least ten times the amount it receives in gross ODA, and in China compensation is at least 30 times higher than its gross ODA. In 2021, total ODA globally was $176 billion[42] (Methods) - roughly comparable to estimated coal phase-out compensation for China and India in line with 2°C climate pathways.

In terms of domestic flows, there are some opportunities for funding particularly in China. The country mobilized domestic funding to support re-employment of workers in heavy industries who lost jobs due to overcapacity[43,44]. And there may also be potential to mobilize funding through cutting coal subsidies (Figure 3, Supplementary Figure 3), which in China are higher than tax revenues[45], but still far smaller than the required amounts for compensation (Supplementary Figure 3).

Figure 3. Coal phase-out compensation in the national and international context. **(a)** Blue bars represent our central estimate for coal phase-out compensation plans – dark blue from national sources and light blue from international sources – and error bars our uncertainty range. Annual compensation is the total compensation divided by the number of years between the phase-out pledge and the pledged phase-out date normalized to GDP in the year each phase-out commitment was made. Orange bars represent the median of our scenario-based estimates of potential coal phase-out compensation cost for India and China to stay on a 1.5°C- and 2°C- consistent pathways with the error bars representing the IQR range. For China and India, we calculate annual compensation for each individual 1.5°C or 2°C-compatible pathway and normalize it to GDP in 2021[46] (Methods). **(b)** Central estimates for planned national (dark blue bars) and international (light blue and green bars) compared to Official Development Assistance[42] for JETP countries, scenario-based compensation (orange bars), coal production subsidies in China and India[47], the climate finance request by India's Prime Minister at COP26[40], and the climate finance pledge first made at COP15[41]. (Methods, Supplementary Table 3, Supplementary Figure 4). "ID" stands for Indonesia, "VN" for Vietnam, "SA" for South Africa, "IN" for India, and "CN" for China.



Discussion and conclusion

Our results have direct policy implications for existing and planned JETPs and other international agreements regarding clean energy transitions. Our research suggests that compensating affected actors is necessary for accelerated coal phase-out and that the amount of compensation is proportional to the ambition of coal phase-out commitments. While some have criticized compensation schemes as unjust support for fossil fuel interests[17], our findings indicate that such policies are essential to ensure sufficient support for sustainable energy transitions[48,49]. However, we also show that international compensation for coal phase-out in China and India – the two countries with the largest coal fleets – would be so large as to exceed the total amount of the currently pledged international climate financing, if the ambition is ramped up to meet climate targets and if compensation rates are similar to existing policies.

Our findings indicate that the need for compensation will likely increase, rather than diminish, as coal phase-out policies diffuse to economies with weaker institutions. However, providing internationally-funded compensation to governments that lack democratic accountability creates the additional risk that aid flows intended to support just transitions will be captured by vested interests and thus fail to resolve the 'speed' versus 'justice' tension[50] inherent in coal phase-out.

More generally, our research serves as a model for quantifying the social and political concerns of rapid transitions[51,52] so that they can be considered on par with economic aspects. In spite of the cost-effectiveness of coal phase-out, its feasibility is often challenged on socio-political grounds[10,11,15,22,53]. We show that political will and social acceptance have a tangible economic component which can be at least partially quantified in monetary terms. This approach can be used to better estimate the real costs of climate policies to governments, and could be extended to other climate actions mired by socio-political obstacles.

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Methods

Identifying countries with coal phase-out commitments and compensation packages

To build a database of coal phase-out commitments and planned compensation for coal phase-out, we first identify countries with coal phase-out commitments and then identify which of these countries plan compensation (Figure 1).

For coal phase-out commitments, we build on a database from ref.[15] which includes coal phase-out commitments for all countries with installed coal capacity at the time the commitment was made. This database was built through a systematic review of national and international documents including National Energy and Climate Plans (NECPs); National Recovery and Resilience Plans (NRRPs) submitted by member states to the EU; Nationally Determined Contributions (NDCs) submitted under the Paris Agreement; the Powering Past Coal Alliance (PPCA); the Global Coal to Clean Power Statement (GCCP); as well as other policy statements. It covers all explicit national coal phase-out commitments (but does not include coal phase-out implied by national net-zero targets or other climate targets since such plans may or may not feature coal phase-out).

To identify compensation plans, we conducted a systematic search and expert consultations. For the systematic search, we searched for “coal phase-out”, “coal”, “just transition” and “coal compensation” for each country with a coal phase-out commitment (Supplementary Table 2). Based on our analysis, we identified 23 countries that have both coal phase-out commitments and related compensation plans. To confirm our case selection, we consulted experts in two surveys and three workshops. The first survey was conducted in September 2021 with a selection of 15 coal phase-out experts and the second survey was conducted in January and February 2022 and distributed to the same contacts as in our first survey and via Twitter. In both versions of the survey, we presented respondents with our criteria for case selection and initial set, and asked them two questions:

1. Are you aware of any governments not included in the list above that are planning to phase out coal and compensate affected actors?
2. Are you aware of any other governments that compensate affected actors of coal sector declines without a deliberate coal phase-out policy?

We asked the same two questions to attendees at three online workshops on fossil fuel decline – two associated with the CINTRAN project[54] and one associated with the Contractions project[55]. Through the expert consultations, we found that while Poland has not finalized its law, the country has plans for compensation.

We also include international funding through the EU Just Transition Fund (JTF) and the JETPs both of which were announced during our analysis. At the time of writing, there are three JETPs: with South Africa[21], Indonesia[19] and Vietnam[20] (Supplementary Note 1). Indonesia and Vietnam have coal phase-out commitments, but South Africa does not have a coal phase-out date. We thus include the JETP for South Africa in our analysis (Table 1), but do not consider the country as a case in our empirical model since there is no phase-out commitment.

Quantifying and mapping financial compensation

To quantify and map financial flows associated with compensation, we code each compensation plan for: the amount of compensation; the beneficiary(ies) and purpose(s); and the origin of compensation (Supplementary Table 1). In the majority of our cases we rely on official governmental and international sources (Supplementary Figure 1).

Our governmental sources include laws, national budgets, strategies, plans and press releases. To identify government sources, we search national and ministerial websites for each of our country cases with the search terms 'coal phase-out', 'coal', 'just transition' and 'compensation'. We use these search terms in the English version of government websites, and where English versions are not available, we translate these terms into the national language, and translate the search results into English using Google translate.

Our international sources include the JETPs[19,20,28], the EU JTF Allocation[25,26], NRRPs[56–58], and EU case law[59,60]. The JETP agreements include both donor and recipient countries, compensation amounts for the next 3-5 years, and allude to plans of continued support (see Table 2). We only include public finance to enable consistent comparison across different types of compensation plans and since private investment is likely to be motivated by other reasons. The EU JTF allocation includes support for regions in EU member states that are likely to be negatively affected by climate mitigation measures such as coal phase-out[26]. We quantify this funding using European Commission documentation to identify which countries are likely to receive funding related to coal phase-out[26]. There is some uncertainty in this funding for two reasons: first, some Territorial Just Transition Plans (TJTPs) have not yet been approved, thus we include these amounts in the upper estimate. Second, JTF documentation does not always specify which parts of the funding are related to the coal phase-out, and which parts are related to other climate change mitigation measures. We capture the latter uncertainty by calculating a lower estimate as a reasonable share of the overall funding based on nationally-specific documentation, and an upper estimate of the entire amount of compensation. These assumptions are described for each country in Supplementary Table 1. We also include NRRPs because the Recovery and Resilience Facility supports not only economic recovery from the Covid 19 pandemic, but also "mak[es] European economies and societies better prepared for the challenges and opportunities of the green [transition]"[27]. In their NRRPs, countries specify which purposes they intend to use the funding for. We include flows that are specifically related to coal phase-out.

In four cases (Poland, Netherlands, Greece, and for Germany's auction system) we found evidence of compensation but could not identify a government source. In these cases, we used the following third-party sources: for Poland, we used a report identified through our expert consultations written by a consultancy which had accessed a draft coal phase-out plan in Polish[61]; for Greece and the Netherlands, we identified reports through our systematic Google search of coal phase-out and compensation documents described in the previous section; and for Germany's auction system, we included an estimate from a newspaper article written during the time of the political negotiations[32] and a scientific article published since[62].

In 13 cases there is uncertainty surrounding pledged compensation, so we establish a lower and upper estimate (Supplementary Table 1):

- The lower estimate includes compensation plans we could verify in government sources and which are not dependent on national action or future developments. For Vietnam and Indonesia it includes the amount already pledged under the JETPs.
- The upper estimate includes compensation plans we could only verify in third-party sources and preliminary or uncertain EU Just Transition Fund allocation. For Vietnam and Indonesia, this is an extrapolation of a constant annual compensation to the pledged phase-out date (Supplementary Note 1).
- We also calculate a central estimate as the mean of the upper and lower estimates.

We excluded three items for which the situation has substantially changed since the announced compensation plan. For Germany we excluded potential compensation to electricity consumers dependent on future electricity price changes due to the coal phase-out since this pledge was made prior to the Russo-Ukrainian war and the resulting spikes in electricity prices from the current energy crisis; given the current situation it is difficult to quantify this flow and highly uncertain whether it should be attributed to coal phase-out. Second, in the Netherlands we excluded requests for compensation from two coal power plant owners since they have been struck down by the courts. Additionally, we excluded Ukraine from our analysis. While Ukraine declared coal phase-out in 2020 and specified costs of compensation to coal companies in its 2022 budget[63], the start of the war in February 2022 has made implementation of these plans highly uncertain.

We could not quantify compensation for two countries: Chile pledges to compensate power companies based on a capacity mechanism but does not specify how this capacity mechanism is to be calculated[64–66]. North Macedonia's NECP mentions funds to be allocated to coal phase-out and a just transition but has not yet specified how much or the source of these funds[67].

All compensation is reported in USD2020 using the exchange rate[68] and GDP deflator[46] for the respective year and country. We used the year in which the compensation is numerated in, if specified, or the year in which the respective document was published.

To map the origin, beneficiaries, and purpose of compensation, we build on the national and international documents described above and government budgets. We search government budgets for the years of and following coal phase-out commitments (for example, we retrieve government budgets for the years 2017-2021 for France since France's coal phase-out commitment was made in 2017). We search government budgets for the term "coal" (or its equivalent in the national language, for example "charbon" in French) and code budget entries specifically related to coal phase-out.

Calculating avoided emissions from coal phase-out

We follow the method developed in references[15,22] to calculate the avoided emissions from coal phase-out resulting from national pledges and for India and China in 1.5°C and 2°C consistent IPCC pathways[39,69]. Avoided emissions from phase-out is the difference between emissions from coal-fired generation in a reference scenario where coal plants follow a natural retirement trajectory and a phase-out scenario where plants are retired following phase-out commitments. Given that avoided emissions are proportional to stranded coal capacity[70,71], we take this as a proxy for the ambition level of the coal phase-out commitment.

For the reference scenario, we assume that operating plants begin retiring from 2022 and are retired by their expected lifetime, based on the historical national lifetime and its standard deviation, and estimated using truncated normal distribution (see ref.[22]). For the countries that adopted a pledge before 2019, we use the coal-fired fleet as of 2018 and assume retirement from 2019 as in ref.[22], since this better represents the expected effect of the pledges at the moment of taking them. We calculate the average historical lifetime of coal power plants since 2001 in each country using the World Electric Power Plants (WEPP) database[72]. If a country has fewer than four retirement events in that period, we use the global average lifetime (42 years), except for Asian countries where we use a regional average which is markedly shorter (30 years)[15,22].

In the phase-out scenario, we assume that plants retire according to the same logic until the pledged retirement date, when all remaining plants are abruptly retired. For countries with ranges in their coal phase-out commitment, we calculate several phase-out scenarios. For example, Vietnam and Indonesia, pledge to phase out coal "in the 2040s"[73], thus we assume an optimistic phase-out by 2040, a central phase-out by 2045, and a pessimistic phase-out by 2049. For Germany, the phase-out scenarios correspond to the multi-stage coal phase-out plan proposed by the Coal Commission, and the new phase-out year envisioned by the current government[74] (Supplementary Text 4 in ref.[22]).

For each country we calculate avoided generation from each plant prematurely retired due to phase-out by multiplying its capacity by the number of years between the retirement under the reference and phase-out scenarios and accounting for the historical national load factor. We then apply technology-specific efficiencies and emission rates for the thermal content of different coal types to convert avoided generation into avoided emissions (see ref. [22] for more details).

For avoided emissions in China and India under 1.5°C and 2°C pathways[39], we use the methodology developed by ref.[15]. We first calculate emissions under a reference scenario for all countries in the China+ and India+ regions from the set of ten regions (R10) using the same approach we describe above. We use the China+ and India+ regions to approximate avoided emissions and coal phase-out dates for China and India respectively, since these countries account for 97%% and 98% of coal power generation in their respective regions.

We calculate unabated coal power generation under 1.5°C and 2°C consistent pathways as the difference between total electricity generation from coal (variable "Secondary Energy|Electricity|Coal") and generation from coal with CCS ("Secondary Energy|Electricity|Coal|w/ CCS"). For 1.5°C consistent pathways, we use categories C1 (no/low overshoot) and C2 (high overshoot) and for 2°C consistent pathways categories C3 (likely below 2°C) and C4 (below 2°C). We convert unabated coal generation to emissions using the same emission intensity as in the reference scenario for the respective region. We approximate required avoided emissions starting in 2022 by calculating the difference between coal emissions under the reference scenario and estimated emissions under each 1.5°C and 2°C consistent IPCC AR6 pathway, seeing the latter as a necessary emission budget for coal generation.

We also approximate the coal phase-out year in the China+ and India+ regions in climate mitigation pathways with the median (and interquartile range) of the first reported year when unabated coal power generation falls below 1% for each region across the sets of 1.5°C and 2°C consistent pathways respectively (see Table 3).

Multivariable regression analysis

To investigate the role different mechanisms play in compensation, we conduct a multivariable regression analysis (see Supplementary Note 2). We test several models with a combination of independent variables. We limit the number of independent variables in each test to avoid using too many independent variables for a relatively small sample (20 countries) and to limit multicollinearity. Our dependent variable is our central estimate of coal phase-out compensation. We chose independent variables based on theoretical and empirical evidence of mechanisms that may affect the amount of compensation paid (see Supplementary Note 2 for details). Our variables fall into two main categories: (1) those characterizing the ambition of national coal phase-out and characteristics of the coal sector and (2) those characterizing the overall national context:

Ambition of national coal phase-out and characteristics of coal sector:

1. avoided emissions (Mt CO2) *Source:* own calculation as described above.
2. installed capacity of operating coal power (GW) in the year of the phase-out commitment *Source*: WEPP database[72].
3. average of coal power generation (2016-2020). We use an average since coal power generation fluctuates due to e.g. energy demand changes or availability of hydropower resources. *Source*: IEA[75].
4. average of coal mined (Mt). We use the average over the last five available years due to fluctuations in annual coal production. *Source*: Enerdata[76] for most countries, IEA[77] for Greece, Bulgaria and Slovakia, and national statistics[78] for Vietnam.
5. value added (VA) of the coal power and mining industries. *Source*: own calculation, described in Supplementary Note 3.

National context and government capacity:

6. the size of the national economy (GDP). We use GDP for the year in which coal phase-out was pledged converted to USD2020. *Source*: IMF World Economic Outlook[46].
7. quality of democracy as measured with the electoral democracy index ‘polyarchy’ from V-Dem. ‘Polyarchy’ measures the fairness of elections that affect the composition of a country’s executive, freedom for political and civil society organizations, freedom of expression, and independence of the media. *Source:* V-Dem [79].
8. GDP/capita (PPP). *Source*: Penn World Table[80].

We test the correlation between each pair of variables, and choose a maximum of three independent variables with a correlation below 0.7 for each regression model (Supplementary Note 2). This results in a total of nine models which we rank according to the Aikaike Information Criterion (AIC) and Adjusted R2 (Supplementary Table 6).

Modelling compensation for China and India under 1.5°C and 2°C consistent pathways

We estimate compensation for China and India under climate targets using IQR of avoided emissions and phase-out dates under IPCC 1.5°C and 2°C consistent pathways combined with equations from our best regression models:

$$Y_A = 13342 + 36.9*X_1 + 49*X_2 - 21949*X_3$$

$$Y_B = -3826 + 33.9*X_1 + 57.4*X_2 + 0.001*X_4$$

Where

- Y_A = Coal phase-out compensation retrieved from Model A
- Y_B = Coal phase-out compensation retrieved from Model B
- X_1 = Avoided emissions under specific IPCC AR6 pathway
- X_2 = Mt coal mined
- X_3 = Polyarchy
- X_4 = GDP

To calculate a range of plausible coal phase-out compensation for both countries, we calculate compensation estimates using avoided emissions under each individual 1.5°C- and 2°C-degree consistent IPCC AR6 pathway. We calculate 164 compensation estimates for each country under 1.5°C-consistent pathways, and 314 compensation estimates under 2℃-consistent pathways. We exclude ten cases in which 2°C-consistent IPCC AR6 pathways return negative avoided emissions since these models project a coal build-out which has been criticized in the literature[81].

Benchmarking compensation within national and international contexts

We also benchmark compensation against several domestic and international financial flows. We retrieve carbon prices under the EU emissions trading scheme from emission spot primary market auction reports for 2017 to 2022[31] and normalize compensation to our avoided emissions from coal phase-out. For recently-built coal plant costs, we identify all recently-constructed coal plants from the WEPP database[72] (in EU between 2010-2022) and conduct a systematic Google search for them using the terms: “coal power plant name” + “construction cost” + “year of construction” (Supplementary Table 5). To compare these costs to compensation, we normalize compensation to the installed coal capacity in the year the coal phase-out pledge was made[72].

We also compare both annual and cumulative empirical versus modelled compensation estimates. For annual compensation rates in countries with empirical observations, we divide the upper and lower estimates for compensation by the number of years from the announcement of a coal phase-out commitment to the year of planned coal phase-out. For countries with uncertainty in the pledge date (Supplementary Table 2) we use the longer coal phase-out duration for the lower estimate and the shorter duration for the upper estimate, assuming that more ambitious pledges would be accompanied by higher compensation. For annual compensation rates in China+ and India+, we divide pathway-specific coal compensation based on our empirical model by pathway-specific phase-out dates (the first year in which unabated coal power generation declines below 1%).

We also compare our compensation estimates to several national and international financial flows. For all flows we include only public finance so that it is possible to compare governmental effort for accelerated coal phase-out and since private investment is likely driven by a different logic:

- Average annual Official Development Assistance (ODA) paid over ten years (2010-2020) covering gross ODA paid by Development Assistance Committee (DAC) and non-DAC countries and the EU. *Source:* OECD[42].
- Climate finance pledged by developed countries to developing countries at COP15[41].
- Climate finance request from India's prime minister for $1 trillion at COP26[40]. To compare this to annual compensation estimates (Figure 3), we divide the request by the median duration of coal phase-out in line with 1.5°C and 2°C consistent pathways.
- Coal production subsidies paid to coal producers. We do not include coal consumption subsidies, since compensation for coal phase-out focuses on producers (companies, workers, and regions) rather than consumers. We do not include investments in state owned enterprises in our main estimate because such investments are made under the assumption that enterprises are operational and will return a profit, while compensation is paid without an expected return. We identified data on coal subsidies from at least one source for all countries except Vietnam, Bulgaria, Croatia and Romania. *Source*: OECD[47] and IISD[82].

Limitations

Our analysis is based on coal phase-out commitments and compensation pledges, both of which are still evolving. This dataset needs to be continuously updated as new countries develop compensation plans, and more information about the design and implementation of such schemes can be collected. Additionally, given the early implementation of such policies it is not possible to evaluate the use of compensation, which should be addressed in future research. In particular, it is important to understand how regions, workers and industries supported by compensation schemes fare in the long term, and compared to regions where coal was historically phased out without a deliberately planned just transition policy.

Additionally, while the policy documents we review provide some information on how compensation schemes are financed, it is likely that compensation originates from additional sources. Where we could not access national policy documents in a language known by the authors, we reached out to country experts (such as in the case of Poland) or retrieved information from international organizations (such as in the case of Greece) to minimize the effect of language barriers on our data collection. However, it is possible that additional resources may be accessible to native speakers for some countries.

Finally, the predictive power of statistics tends to increase with the number of cases. Currently, a relatively small number of countries have both coal phase-out commitments and an associated compensation scheme. As more countries may be added to the database in the future, it is important to update the regression analysis to understand whether the relationship we currently observe between avoided emissions and amount of compensation remains stable, or whether new mechanisms emerge.

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Competing interests

The authors declare no competing interests.

Data availability

All data generated during this study are included in this published article. All secondary data used for the analysis are cited in the article and publicly available.

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Author contributions

JJ & AC conceived the study. JJ, AC and LN developed the Methodology. LN led investigate and data curation. LN, VV, and AJ conducted formal analysis. LN and JJ wrote the original draft with contributions from AC. All authors contributed to visualisation. JJ provided supervision and LN project administration. JJ acquired funding.