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

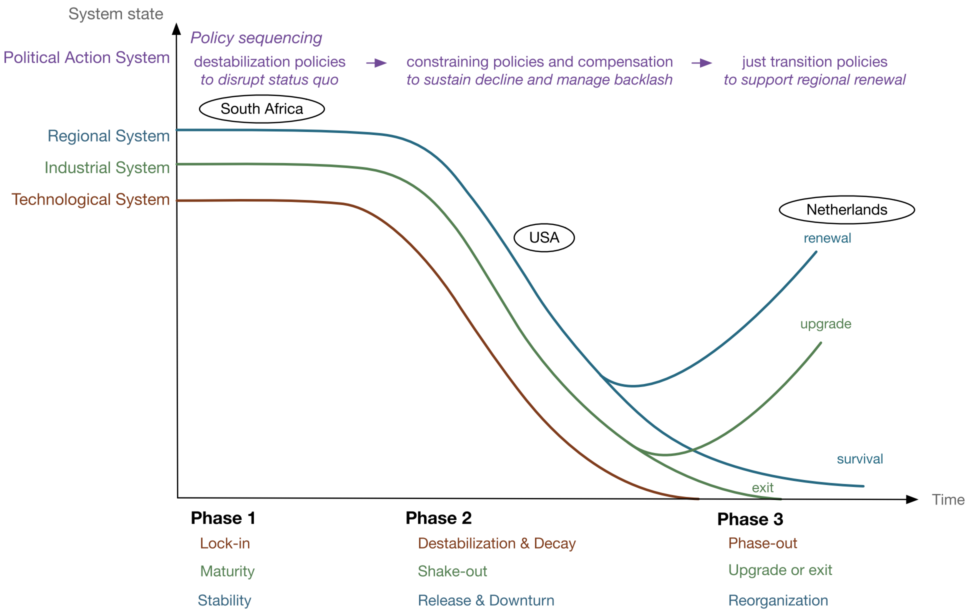
Lola Nacke[1,*], Aleh Cherp[2,3] and Jessica Jewell[1,4,5,*]

[1]Department of Space, Earth and Environment, Chalmers University of Technology, Chalmersplatsen 4, 421 96 Gothenburg, Sweden
[2]Department of Environmental Sciences and Policy, Central European University, Quellenstraße 51. A-1100 Vienna, Austria
[3]The International Institute for Industrial Environmental Economics, Lund University, Tegnérsplatsen 4, 223 50 Lund, Sweden
[4]Centre for Climate and Energy Transformation & Department of Geography, University of Bergen, Postboks 7802, 5020 Bergen, Norway
[5]Advancing Systems Analysis, International Institute for Applied Systems Analysis, Schlossplatz 1, 2361 Laxenburg, Austria
*Correspondence address. Department of Space, Earth and Environment, Chalmers University, Chalmersplatsen 4, 421 96 Gothenburg, Sweden.
Tel: +46-73-856-7792; E-mail: jewell@chalmers.se; lolan@chalmers.se

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 reorganization 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

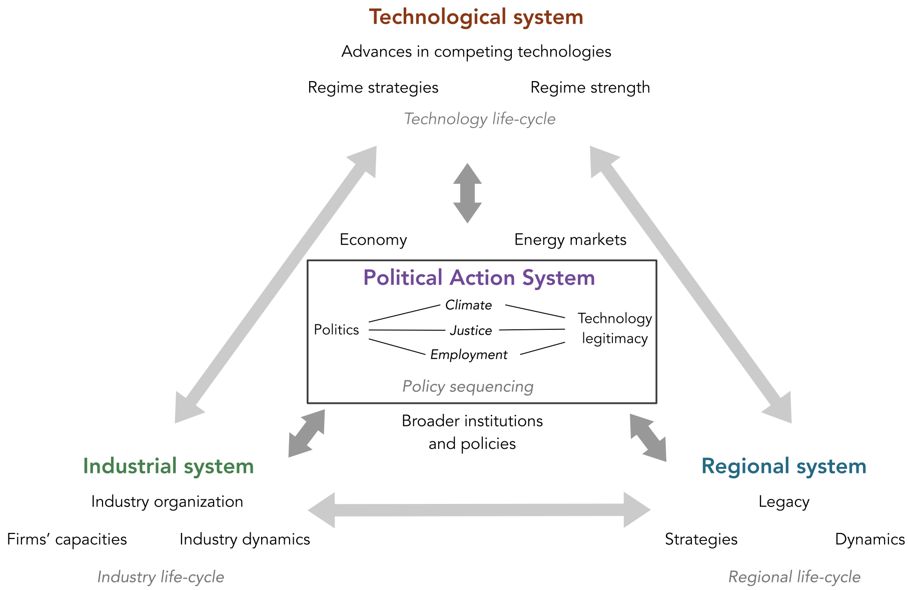

Figure 1. Top-level variables (four systems) and second-level variables for four systems and economic and socio-political setting

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

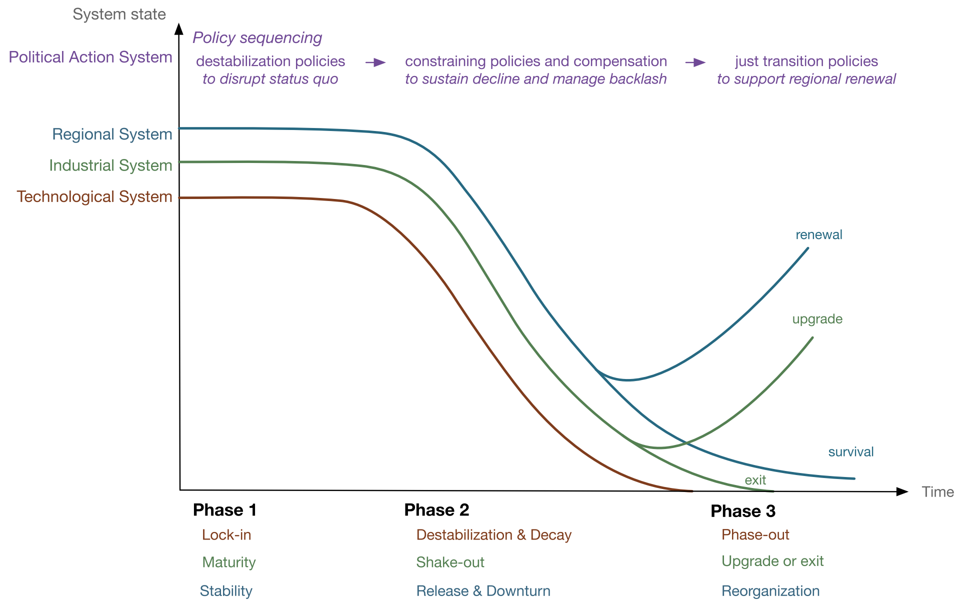

Figure 2. Phases of decline, policy-sequencing and the co-evolution of technological, industrial and regional systems

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 outmigration 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.

DATA AVAILABILITY STATEMENT

No new data were generated or analyzed in support of this research.

References

1. IPCC *Global Warming of 1.5°C Summary for Policymakers*, 2018. http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf
2. UCCCU *End of Coal in Sight at COP26*, 2021. https://ukcop26.org/end-of-coal-in-sight-at-cop26/ (15 November 2021, date last accessed)
3. PPCA *Members Powering Past Coal Alliance*, 2021. https://poweringpastcoal.org/about/Powering_Past_Coal_Alliance_Members. (4 January 2022, date last accessed).
4. Neagu B, Taylor K *Romania Commits to Phase Out Coal by 2032*, 2021. EurActiv. https://www.euractiv.com/section/energy/news/romania-will-phase-out-coal-by-2032/. (4 January 2022, date last accessed).
5. PPCA *New PPCA Members Tip the Scales towards 'Consigning Coal to History' at COP26*, 2021. https://www.poweringpastcoal.org/news/press-release/new-ppca-members-tip-the-scales-towards-consigning-coal-to-history-at-cop26 (18 November 2021, date last accessed)
6. UCCCU *Statement on International Public Support for the Clean Energy Transition*, 2021. https://ukcop26.org/statement-on-international-public-support-for-the-clean-energy-transition/ (18 November 2021, date last accessed)
7. UCCCU *Supporting the Conditions for a Just Transition Internationally*, 2021. https://ukcop26.org/supporting-the-conditions-for-a-just-transition-internationally/ (15 November 2021, date last accessed)
8. Seto KC, Davis SJ, Mitchell RB *et al.* Carbon lock-in: types. *Annu Rev Energy Environ*. 2016;**41**:425–52
9. Unruh GC. Understanding carbon lock-in, Energ. *Policy*. 2000;**28**: 817–30
10. Geels FW. Regime resistance against low-carbon transitions: introducing politics and power into the multi-level perspective. *Theory Cult Soc*. 2014;**31**:21–40
11. Turnheim B, Geels FW. Regime destabilisation as the flipside of energy transitions lessons from the history of the British coal industry (1913–1997). *Energy Policy*. 2012;**50**:35–49
12. Turnheim B, Geels FW. The destabilisation of existing regimes: confronting a multi-dimensional framework with a case study of the British coal industry (1913–1967). *Res Policy*. 2013;**42**: 1749–67
13. Kivimaa P, Kern F. Creative destruction or mere niche support? *Res Policy*. 2016;**45**:205–17
14. Markard J. The next phase of the energy transition and its implications for research and policy. *Nat Energy*. 2018;**3**:628–33
15. Abraham J. Just transitions for the miners: labor environmentalism in the Ruhr and Appalachian coalfields. *New Polit Sci*. 2017;**39**:218–40
16. Johnstone P, Hielscher S. Phasing out coal, sustaining coal communities? Living with technological decline in sustainability pathways. *Extr Ind Soc*. 2017;**4**:457–61
17. Henry MS, Bazilian MD, Markuson C. Just transitions: histories and futures in a post-COVID world. *Energy Res Soc Sci*. 2020;**68**:101668
18. Newell P, Mulvaney D. The political economy of the 'just transition'. *Geogr J*. 2013;**179**:132–40
19. Jenkins KEH, Sovacool BK, Błachowicz A *et al.* Politicising the just transition: linking global climate policy, nationally determined contributions and targeted research agendas. *Geoforum*. 2020;**115**:138–42
20. International Labour Organization *ILO Welcomes COP26 Just Transition Declaration*, 2021. Ilo.Org. https://www.ilo.org/global/about-the-ilo/newsroom/news/WCMS_826717/lang--en/index.htm (12 November 2021, date last accessed)
21. European Commission. *The Just Transition Mechanism: Making Sure No One is Left Behind*. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/finance-and-green-deal/just-transition-mechanism_en (12 November 2021, date last accessed)
22. Galgóczi B. Just transition on the ground: challenges and opportunities for social dialogue. *Eur J Ind Relat*. 2020;**26**:367–82
23. Rinscheid A, Rosenbloom D, Markard J *et al.* From terminating to transforming: the role of phase-out in sustainability transitions. *Environmental Innovation and Societal Transitions*. 2021;**41**: 27–31 https://doi.org/10.1016/j.eist.2021.10.019
24. Pahle M, Burtraw D, Flachsland C *et al.* Sequencing to ratchet up climate policy stringency. *Nat Clim Chang*. 2018;**8**:861–7
25. Meckling J, Sterner T, Wagner G. Policy sequencing toward decarbonization. *Nat Energy*. 2017;**2**:918–22
26. Ostrom E Doing institutional analysis: digging deeper than markets and hierarchies. In: Menard C, Shirley MM, (eds.), *Handbook of New Institutional Economics*. Dordrecht: Springer, 2005, 819–48
27. Ostrom E, Janssen MA, Anderies JM. Going beyond panaceas. *Proc Natl Acad Sci USA*. 2007;**104**:15176–8
28. Ostrom E. Institutional rational choice: an assessment of the institutional analysis and development framework. *Theories of the Policy Process*. 2019;**21**:68
29. Ostrom E. A diagnostic approach for going beyond panaceas. *Proc Natl Acad Sci USA*. 2007;**104**:15181–7
30. Brauers H, Herpich P, von Hirschhausen C *et al. Coal Transition in Germany*, 2018. IDDRI, Climate Strategies. https://coaltransitions.files.wordpress.com/2018/09/coal_germany_final.pdf (28 February 2022, date last accessed)
31. Oei P-Y, Brauers H, Herpich P. Lessons from Germany's hard coal mining phase-out: policies and transition from 1950 to 2018. *Clim Pol*. 2020;**20**:963–79
32. Normann HE. Conditions for the deliberate destabilisation of established industries: lessons from U.S. tobacco control policy and the closure of Dutch coal mines. *Environ Innov Soc Transit*. 2019;**33**:102–14

33. del Río P *Coal Transition in Spain*. IDDRI, Climate Strategies, 2017. https://www.iddri.org/en/publications-and-events/report/coal-transition-spain (28 February 2022, date last accessed).
34. Fothergill S *Coal Transition in the United Kingdom*. IDDRI, Climate Strategies, 2017. https://www.iddri.org/en/publications-and-events/report/coal-transition-united-kingdom (28 February 2022, date last accessed).
35. Foxon TJ. A coevolutionary framework for analysing a transition to a sustainable low carbon economy. *Ecol Econ*. 2011;**70**: 2258–67
36. Cherp A, Vinichenko V, Jewell J *et al.* Integrating techno-economic, socio-technical and political perspectives on national energy transitions—a meta-theoretical framework. *Energy Res Soc Sci*. 2018;**37**:175–90
37. Utterback JM *Mastering the Dynamics of Innovation*. Boston, Massachusetts: Harvard Business School Press, 1994
38. Anderson P, Tushman ML. Technological discontinuities and dominant designs: a cyclical model of technological change. *Adm Sci Q*. 1990;**35**:604–33
39. Loorbach D, Frantzeskaki N, Avelino F. Sustainability transitions research: transforming science and practice for societal change. *Annu Rev Environ Resour*. 2017;**42**:599–626
40. Peltoniemi M. Reviewing industry life-cycle theory: avenues for future research. *Int J Manag Rev*. 2011;**13**:349–75
41. Klepper S. Industry life cycles. *Ind Corp Chang*. 1997;**6**:145–82
42. Harrigan KR. Strategy formulation in declining industries. *Acad Manag Rev*. 1980;**5**:599–604
43. Breinlich H, Ottaviano GIP, Temple JRW. Chapter 4 regional growth and regional decline. *Handb Econ Growth*. 2014;**2**:683–779
44. Glaeser EL, Rosenthal SS, Strange WC. Urban economics and entrepreneurship. *J Urban Econ*. 2010;**67**:1–14
45. Norgaard RB *Development Betrayed*. London; New York: Routledge, 1994, http://www.bokus.com/bok/9780415068628/development-betrayed/
46. Nelson RR. Co-evolution of industry structure, technology and supporting institutions, and the making of comparative advantage, Int. *J Econ Bus*. 1995;**2**:171–84
47. Freeman C, Louca F *As Time Goes by: From the Industrial Revolutions to the Information Revolution*. Oxford: Oxford University Press, 2001
48. Easton D. An approach to the analysis of political systems. *World Polit*. 1957;**9**:383–400
49. Edmondson DL, Kern F, Rogge KS. The co-evolution of policy mixes and socio-technical systems: towards a conceptual framework of policy mix feedback in sustainability transitions. *Res Policy*. 2019;**48**:103555
50. McGinnis M, Ostrom E. Social-ecological system framework: initial changes and continuing challenges. *Ecol Soc*. 2014;**19**:30.
51. CORDIS *Carbon Intensive Regions in Transition—Unravelling the Challenges of Structural Change*, 2021. https://cordis.europa.eu/project/id/884539 (11 April 2021, date last accessed)
52. Carlsson B, Stankiewicz R. On the nature, function and composition of technological systems. *J Evol Econ*. 1991;**1**:93–118
53. Binz C, Truffer B. Global innovation systems—a conceptual framework for innovation dynamics in transnational contexts. *Res Policy*. 2017;**46**:1284–98
54. Wang W, Li Z, Cheng X. Evolution of the global coal trade network: a complex network analysis. *Resour Policy*. 2019;**62**: 496–506
55. Trencher G, Rinscheid A, Duygan M *et al.* Revisiting carbon lock-in in energy systems: explaining the perpetuation of coal power in Japan. *Energy Res Soc Sci*. 2020;**69**:101770
56. Jewell J, Vinichenko V, Nacke L *et al.* Prospects for powering past coal. *Nat Clim Chang*. 2019;**9**:592–7
57. Stognief N, Walk P, Schöttker O *et al.* Economic resilience of German lignite regions in transition. *Sustainability*. 2019;**11**:5991
58. Kaplan S, Tripsas M. Thinking about technology: applying a cognitive lens to technical change. *Res Policy*. 2008;**37**:790–805
59. Murmann JP, Frenken K. Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. *Res Policy*. 2006;**35**:925–52
60. Erickson P, Kartha S, Lazarus M *et al.* Assessing carbon lock-in. *Environ Res Lett*. 2015;**10**:84023
61. Fouquet R, Pearson PJG. Past and prospective energy transitions: insights from history, Energ. *Policy*. 2012;**50**:1–7
62. Griliches Z. Hybrid corn: an exploration in the economics of technological change. *Econometrica*. 1957;**25**:501
63. Hagerstrand *Innovation Diffusion as a Spatial Process*. Chicago: The University of Chicago Press, 1967
64. Grubler A. The rise and fall of infrastructures dynamics of evolution and technological. *Change*. 1990;**1**:316
65. David PA. Clio and the economics of QWERTY. *Economic History*. 1985;**2**:332–7
66. Arthur BW. Competing technologies, increasing returns, and lock-in by historical small events. *Econ J (London)*. 1989;**99**: 116–32
67. Unruh GC. Escaping carbon lock-in, Energ. *Policy*. 2002;**30**: 317–25
68. Creutzig F, Roy J, Lamb WF *et al.* Towards demand-side solutions for mitigating climate change. *Nat Clim Chang*. 2018;**8**: 260–3
69. Grubb M, Drummond P, Hughes N *The Shape and Pace of Change in the Electricity Transition*, 2020. https://www.wemeanbusinesscoalition.org/wp-content/uploads/2020/10/Shape-and-Pace-of-Change-in-the-Electricity-Transition-1.pdf (28 February 2022, date last accessed).
70. Geels FW, Schot J. Typology of sociotechnical transition pathways. *Res Policy*. 2007;**36**:399–417
71. Cherp A, Vinichenko V, Jewell J *et al.* Comparing electricity transitions: a historical analysis of nuclear, wind and solar power in Germany and Japan. *Energ Policy*. 2017;**101**:612–28
72. Markard J, Geels FW, Raven R. Challenges in the acceleration of sustainability transitions. *Environ Res Lett*. 2020;**15**:081001 https://doi.org/10.1088/1748-9326/ab9468
73. Markard J. The life cycle of technological innovation systems. *Technol Forecast Soc Change*. 2020;**153**:119407
74. Marchetti C, Nakicenovic N *The Dynamics of Energy Systems and the Logistic Substitution Model*. RR-79-13. Laxenburg, Austria: International Institute for Applied Systems Analysis, 1979
75. Grubler A, Nakićenović N, Victor DG. Dynamics of energy technologies and global change. *Energ Policy*. 1999;**27**:247–80
76. Jakob M, Flachsland C, Steckel JC *et al.* Actors, objectives, context: a framework of the political economy of energy and climate policy applied to India. *Energy Res Soc Sci*. 2020;**70**:101775
77. Klepper S, Simons KL. Innovation and industry shakeouts. *Bus Econ Hist*. 1996;**25**:81–9
78. Unruh GC, Carrillo-Hermosilla J. Globalizing carbon lock-in. *Energ Policy*. 2006;**34**:1185–97
79. Brauers H, Oei P-Y, Walk P. Comparing coal phase-out pathways: the United Kingdom's and Germany's diverging transitions. *Environ Innov Soc Transit*. 2020;**37**:238–53
80. Lieberman MB. Exit from declining industries: 'shakeout' or 'stakeout'? *RAND J Econ*. 1990;**21**:538–54
81. Agarwal R. Technological activity and survival of firms. *Econ Lett*. 1996;**52**:101–8

82. Agarwal R, Tripsas M Technology and industry evolution. In: *Handbook of Technology and Innovation Management*, Hoboken, New Jersey: Wiley-Blackwell, 2008, 1–55
83. Goods C. A just transition to a Green economy: evaluating the response of Australian unions. *ABL*. 2013;**2**:13–33
84. Hicks C, McGovern T. Product life cycle management in engineer-to-order industries. *Int J Technol Manag*. 2009;**48**: 153–67
85. Deily ME. Exit strategies and plant-closing decisions: the case of steel. *RAND J Econ*. 1991;**22**:250–63
86. Rector J. The Spirit of black Lake: full employment. *Mod Am Hist*. 2018;**1**:45–66
87. Ghemawat P, Nalebuff B. The devolution of declining industries. *Q J Econ*. 1990;**105**:167–86
88. Markard J, Bento N, Kittner N *et al.* Destined for decline? *Energy Res Soc Sci*. 2020;**67**:101512
89. Klepper S. Nano-economics, spinoffs, and the wealth of regions. *Small Bus Econ*. 2011;**37**:141
90. Rentier G, Lelieveldt H, Kramer GJ. Varieties of coal-fired power phase-out across Europe. *Energ Policy*. 2019;**132**:620–32
91. Simmie J, Martin R. The economic resilience of regions: towards an evolutionary approach. *Camb J Econ Soc*. 2010;**3**:27–43
92. Paasi A. The resurgence of the ‘region’ and ‘regional identity’: theoretical perspectives and empirical observations on regional dynamics in Europe. *Rev Int Stud*. 2009;**35**: 121–46
93. Hughes TP The evolution of large technological systems. In: Bijker WE, Hughes TP, Pinch T, (eds.), *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, Cambridge, Massachusetts: The MIT Press, 2012, 45–76
94. Sovacool BK, Lovell K, Ting MB. Reconfiguration. *Sci Technol Stud*. 2018;**43**:1066–97
95. Yoon C. Estimating a dynamic spatial equilibrium model to evaluate the welfare implications of regional adjustment processes: the decline of the Rust Belt. *Int Econ Rev*. 2017;**58**: 473–97
96. Martin R, Sunley P. Path dependence and regional economic evolution. *J Econ Geogr*. 2006;**6**:395–437
97. Porter M. The economic performance of regions. *Reg Stud*. 2003;**37**:549–78
98. Glaeser EL, Kerr SP, Kerr WR *Entrepreneurship and Urban Growth: An Empirical Assessment with Historical Mines*, 2012. https://www.nber.org/papers/w18333, (28 February 2022, date last accessed)
99. Alder S, Lagakos D, Ohanian L. The decline of the US Rust Belt:. A Macroeconomic Analysis (August 1, 2014). FRB Atlanta CQER Working Paper No. 14-5, Available at SSRN: https://ssrn.com/abstract=2586168 or http://dx.doi.org/10.2139/ssrn.2586168
100. Kline P, Moretti E. Place based policies with unemployment. *Am Econ Rev*. 2013;**103**:238–43
101. Holmes TJ. The effect of state policies on the location of manufacturing: evidence from state borders. *J Polit Econ*. 1998;**106**: 667–705
102. Holling CS. Understanding the complexity of economic, ecological, and social systems. *Ecosystems*. 2001;**4**:390–405
103. Courvisanos J, Jain A, Mardaneh KK. Economic resilience of regions under crises: a study of the Australian economy. *Reg Stud*. 2016;**50**:629–43
104. Green F. Anti-fossil fuel norms. *Clim Chang*. 2018;**150**:103–16
105. Leipprand A, Flachsland C, Pahle M. Starting low, reaching high? *Environ Innov Soc Transit*. 2020;**37**:140–55
106. BMWi *Strukturstärkungsgesetz Kohleregionen*, 2020. https://www.bmwi.de/Redaktion/DE/Textsammlungen/Wirtschaft/strukturstaerkungsgesetz-kohleregionen.html (11 April 2021, date last accessed)
107. Burton J, Caetano T, McCall B. Coal transitions in South Africa, IDDRI and climate. *Strategies*. 2018; https://www.iddri.org/en/publications-and-events/report/coal-transitions-south-africa (28 February 2022, date last accessed).
108. Tsalidis G-A, Joshi Y, Korevaar G *et al.* Life cycle assessment of direct co-firing of torrefied and/or pelletised woody biomass with coal in the Netherlands. *J Clean Prod*. 2014;**81**:168–77
109. Hauenstein C, Holz F. The U.S. coal sector between shale gas and renewables: last resort coal exports? *Energ Policy*. 2021;**149**:112097
110. Department of Mineral Resources and Energy *Integrated Resource Plan*, 2019. http://www.energy.gov.za/IRP/2019/IRP-2019.pdf (28 February 2022, date last accessed).
111. Jain S, Jain PK. The rise of renewable energy implementation in South Africa. *Energy Procedia*. 2017;**143**:721–6
112. Baker L, Newell P, Phillips J. The political economy of energy transitions: the case of South Africa. *New Political Economy*. 2014;**19**:791–818
113. Power M, Newell P, Baker L *et al.* The political economy of energy transitions in Mozambique and South Africa: the role of the rising powers, energy res. *Soc Sci*. 2016;**17**:10–9
114. Hanto J, Krawielicki L, Krumm A *et al.* Effects of decarbonization on the energy system and related employment effects in South Africa. *Environ Sci Policy*. 2021;**124**:73–84
115. Semelane S, Nwulu N, Kambule N *et al.* Evaluating available solar photovoltaic business opportunities in coal phase-out regions—an energy transition case of Steve Tshwete local municipality in South Africa. *Energ Policy*. 2021;**155**:112333
116. Strambo C, Burton J, Atteridge A *The End of Coal? Planning a Just Transition in South Africa*, 2019. Stockholm Environment Institute. https://www.sei.org/wp-content/uploads/2019/02/planning-a-just-transition-in-south-africa.pdf (28 February 2022, date last accessed).
117. Coal LA *What is the Just Transition?* 2021. https://lifeaftercoal.org.za/about/just-transition#:~:text=Just%20Transition%20in%20South%20Africa&text=It%20is%20in%20response%20to,Just%20Transition%20from%20fossil%20fuels (10 April 2021, date last accessed)
118. UCCCU *Political Declaration on the Just Energy Transition in South Africa*, 2021. https://ukcop26.org/political-declaration-on-the-just-energy-transition-in-south-africa/ (16 November 2021, date last accessed)
119. Mendelevitch R, Hauenstein C, Holz F. The death spiral of coal in the U.S.: will changes in U.S. policy turn the tide? *Clim Pol*. 2019;**19**:1310–24
120. Coglianese J, Gerarden TD, Stock JH. The effects of fuel prices. *Energy J*. 2020;**41**:2008–16
121. USEIA *Annual Coal Report*, 2020. US Department of Energy, Washington, DC. https://www.eia.gov/coal/annual/ (28 February 2022, date last accessed).
122. Cha JM. A just transition for whom? *Energy Res Soc Sci*. 2020;**69**:101657
123. Anderson J. *US Coal-Fired Power Output Decline Continues with Last PSEG Coal Plant Retirement*. 2021. S&P Global Platts. https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/060121-us-coal-fired-power-output-decline-continues-with-last-pseg-coal-plant-retirement (25 June 2021, date last accessed)

124. Carley S, Evans TP, Konisky DM. Adaptation, culture, and the energy transition in American coal country, energy res. *Soc Sci*. 2018;**37**:133–9
125. Roemer KF, Haggerty JH. Coal communities in the U.S. energy transition: a policy corridors assessment. *Energy Policy*. 2021;**151**:112112
126. Gales B, Hölsgens R. *Coal Transition in the Netherlands. A Historical Case Study for the Project 'Coal Transitions: Research and Dialogue on the Future of Coal'*. 2017. IDDRI and Climate Strategies. https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue%20Iddri/Rapport/201706-iddri-climatestrategies-coal_nl.pdf (28 February 2022, date last accessed).
127. Kaijser A (ed). From Slochteren to Wassenaar: the creation of a natural gas regime in the Netherlands, 1960–1963. *NEHA-Jaarboek*. 1996;**59**:330–63
128. Jeannet J-P, Schreuder H. *From Coal to Biotech: The Transformation of DSM with Business School Support*. Berlin, Heidelberg: Springer, 2015. https://doi.org/10.1007/978-3-662-46299-7
129. Kasper H, Maastricht University, Etil BV *The Aftermath of the Closure of the Dutch Coal Mines in South Limburg*, 2012. https://nowa-energia.com.pl/wp-content/uploads/2013/03/raport_uniwersytet_w_maastricht_en.pdf (28 February 2022, date last accessed).
130. Hölsgens HNM *Energy Transitions in the Netherlands*. Groningen: University of Groningen, 2016
131. Diluiso F, Walk P, Manych N *et al.* Coal transitions—part 1: a systematic map and review of case study learnings from regional, national, and local coal phase-out experiences. *Environ Res Lett*. 2021;**16**:113003
132. UCCCU *Global Coal to Clean Power Transition Statement*, 2021. https://ukcop26.org/global-coal-to-clean-power-transition-statement/ (15 November 2021, date last accessed)
133. Roelfes M, Wehnert T, Mölter H *et al.* Specification of regional challenges/typology of highcarbon industry regions. 2018. Climate-KIC, Wuppertal. https://re-industrialise.climate-kic.org/wp-content/uploads/2020/01/Re-Industrialise_Regional-challenges-final.pdf
134. Geels FW, Berkhout F, van Vuuren DP. Bridging analytical approaches for low-carbon transitions. *Nat Clim Chang*. 2016;**6**:576–83
135. Riahi K, Kriegler N, Johnson C *et al.* Locked into Copenhagen pledges – Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol Forecast Soc*. 2015;**90**:8–23 https://doi.org/10.1016/j.techfore.2013.09.016
136. Rogelj J, Shindell D, Jiang K *et al.* Mitigation pathways compatible with 1.5°C in the context of sustainable development. 2018. Special Report on Global Warming of 15°C (SR15). http://www.ipcc.ch/report/sr15/.
137. Gilabert P, Lawford-Smith H. Political feasibility: a conceptual exploration. *Polit Stud (Oxf)*. 2012;**60**:809–25
138. Rosenbloom D, Rinscheid A. Deliberate decline: an emerging frontier for the study and practice of decarbonization. *Wiley Interdiscip Rev Clim Chang*. 2020;**11**:e669 https://doi.org/10.1002/wcc.669
139. Martin R. Roepke lecture in economic geography—rethinking regional path dependence: beyond lock-in to evolution. *Econ Geogr*. 2010;**86**:1–28