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TOPICAL REVIEW

Coal transitions—part 1: a systematic map and review of case study learnings from regional, national, and local coal phase-out experiences

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Keywords: climate change mitigation, coal transitions, evidence synthesis, political economy, systematic map

Abstract

A rapid coal phase-out is needed to meet the goals of the Paris Agreement, but is hindered by serious challenges ranging from vested interests to the risks of social disruption. To understand how to organize a global coal phase-out, it is crucial to go beyond cost-effective climate mitigation scenarios and learn from the experience of previous coal transitions. Despite the relevance of the topic, evidence remains fragmented throughout different research fields, and not easily accessible. To address this gap, this paper provides a systematic map and comprehensive review of the literature on historical coal transitions. We use computer-assisted systematic mapping and review methods to chart and evaluate the available evidence on historical declines in coal production and consumption. We extracted a dataset of 278 case studies from 194 publications, covering coal transitions in 44 countries and ranging from the end of the 19th century until 2021. We find a relatively recent and rapidly expanding body of literature reflecting the growing importance of an early coal phase-out in scientific and political debates. Previous evidence has primarily focused on the United Kingdom, the United States, and Germany, while other countries that experienced large coal declines, like those in Eastern Europe, are strongly underrepresented. An increasing number of studies, mostly published in the last 5 years, has been focusing on China. Most of the countries successfully reducing coal dependency have undergone both demand-side and supply-side

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transitions. This supports the use of policy approaches targeting both demand and supply to achieve a complete coal phase-out. From a political economy perspective, our dataset highlights that most transitions are driven by rising production costs for coal, falling prices for alternative energies, or local environmental concerns, especially regarding air pollution. The main challenges for coal-dependent regions are structural change transformations, in particular for industry and labor. Rising unemployment is the most largely documented outcome in the sample. Policymakers at multiple levels are instrumental in facilitating coal transitions. They rely mainly on regulatory instruments to foster the transitions and compensation schemes or investment plans to deal with their transformative processes. Even though many models suggest that coal phase-outs are among the low-hanging fruits on the way to climate neutrality and meeting the international climate goals, our case studies analysis highlights the intricate political economy at work that needs to be addressed through well-designed and just policies.

1. Introduction

A rapid coal phase-out is a key step to achieve the goal of keeping global warming well below 2 °C. Several elements make the global energy transition away from coal the main road to achieve climate targets. Coal accounts for about a third of global CO_2 emissions (Friedlingstein *et al* 2019), is the most carbon intensive fossil fuel, has significant negative externalities on human health and environment, and it is easier to replace than oil and gas (Luderer *et al* 2018). Phasing out coal is thus becoming a priority on the agenda of many countries and political debates increasingly focus on how coal exits can be organized over the next few decades (Garg and Steckel 2017). However, current national emission reduction commitments (nationally determined contributions—NDCs) of major coal-producing and -consuming countries fall short of the required ambition and do not include clear clauses for a coal exit. A global coal phase-out remains the elephant in the room of international climate negotiations (Edenhofer 2015).

It is possible to identify four main arguments as to why phasing out coal may prove, in practice, extremely challenging (figure 1). First, coal is historically and even currently abundant, based on established technologies, and relatively easy to handle (Steckel *et al* 2020). Coal use also allows many developing countries, where electrification is still in progress, to access affordable and reliable electricity (Kalkuhl *et al* 2019). Its relative accessibility and distribution across the globe make it attractive for many countries as the real societal costs of coal (i.e. environmental degradation, air and water pollution, forced relocations, and global heating) are not fully internalized (Muller *et al* 2011, Cardoso 2015, Sovacool *et al* 2021). Environmental and health benefits alone would outweigh the direct policy costs of a coal phase-out (Rauner *et al* 2020). However, not taking all these societal costs into consideration, coal is often falsely perceived as cheap. In addition, costs of renewable energies are decreasing but are penalized by high capital costs, especially in the Global South (Schmidt 2014, Hirth and Steckel 2016). Alternatives to coal have a higher capital intensity per Megawatt, making them less attractive for low- and middle-income countries (Steffen 2020). Finally, the majority of the operating coal fleet is located in regulated or semi-regulated markets and still benefits from direct or indirect fossil fuel subsidies (Edenhofer 2015, Bodnar *et al* 2020). This creates an economic and regulatory lock-in, decreasing the attractiveness of alternative sources, even when competitive and cheaper.

Second, 60% of all coal power plants, mostly constructed in the Global South, are younger than 20 years. Coal-fired power plants require high initial capital costs, which have to be amortized along the average life of the plant. These lifetimes can even extend to half a century or more. Early retirement would imply sunk investments for a large part of the coal fleet, making coal plants stranded assets (Caldecott *et al* 2016).

Third, the coal industry is deeply rooted in the culture and the economy of territories. Economic and employment impacts from coal phase-out policies are highly localized, making the phase-out a sensitive issue in specific areas and for specific communities. Local and national policymakers are therefore under increasing pressure to guarantee a 'just transition' (Sartor 2018). This implies the management of short- and medium-term costs of the phase-out through the provision of an effective social security system, a shift in the economic structure of coal regions through well designed investment plans, and the development of a new collective territorial and cultural identity (Jabob *et al* 2020b, Oei *et al* 2020, Pai *et al* 2020).

Fourth, the coal industry is a powerful economic stakeholder with significant vested interests and lobbying power. The coal mining industry employs about 7.3 million people worldwide, with a global market size of $698bn per year (IBISWorld 2019). Moreover, coal-dependent economies often share

Figure 1. Four common arguments why phasing out coal is difficult.

an institutional design more susceptible to vested interests and corruption (Lamb and Minx 2020).

Against this background, Paris-consistent mitigation scenarios provided by Integrated Assessment Models (IAMs) generally envisage a rapid and substantial decline of coal in the next 30 years (Rogelj *et al* 2018, Cui *et al* 2019, Minx *et al* 2022). Even if the trajectories arising from different scenarios and different models are extremely heterogeneous, a consensus is rising on the possibility of phasing out coal fairly quickly and relatively easy compared to other fossil fuels (Kriegler *et al* 2018). Although helpful in translating mitigation targets into policy actions, these scenarios cannot capture the full complexity of coal phase-out dynamics and their political economy aspects. These models usually adopt a cost-effective approach that does not take into account the distinct patterns of constraints linked to coal dependency. Politics often must face trade-offs in terms of feasibility and ease of implementation which may lead to less cost-effective solutions. Even if not explicitly introduced in the models, political economy constraints should be kept in mind while interpreting policy scenarios. Another limitation of model-based evidence comes from the fact that most of the models ignore climate damages as well as the potential co-benefits of actions to limit warming, as, for example, health and environmental benefits, that in the case of a coal phase-out are extremely relevant. Other issues include the limited geographical resolution of IAMs, which generally model the global economy and energy system divided into tens of regions, rather than hundreds of countries. This lack of disaggregation and granularity makes it hard to rescale the results to the national or subnational level, while, as explained, transitions away from coal impact, in particular, specific territories and communities with geographical imbalances of losses and benefits constituting further important challenges and barriers for the transition. Finally, as a general remark, it is important to consider that scenario projections are run under a wide range of uncertainties, ranging from implementation of climate actions, availability and costs of technologies, and socio-economic and lifestyle changes. The degree to which emissions can be reduced in the short-medium run ultimately depends on the political willingness, the plurality of interests, and technology and demand patterns that are crucial in shaping the opportunity costs of the phase-out. Therefore, while evidence coming from IAMs suggests a rapid coal phase-out, there is a potential wedge between policy actions that are efficient and effective, as suggested by models, and the ones that are feasible[1].

Linking model-based scenarios and political economy considerations is thus important for identifying viable pathways to climate change mitigation. To provide solution-oriented knowledge it is useful to draw on historical evidence of previous coal transitions, to understand common patterns and key lessons from countries that have already experienced declines in coal production and/or consumption. Despite the relevance of the topic, evidence remains fragmented throughout different research fields, and not easily accessible. Some recent works on coal transitions have provided a series of case-studies evidence on coal phase-outs in major coal-consuming economies (Caldecott *et al* 2017, Sartor 2018). While these have been important early efforts, the number of countries and case studies considered is limited, specifically selected, and the work is undertaken with no employment of systematic methods for assessing the literature. To address this gap, this paper provides a systematic map and comprehensive review of the literature on historical coal transitions, with a specific

[1] For a comprehensive assessment of scenario evidence on coal transitions in mitigation scenarios consistent with the Paris Agreement see part 2 of this review (Minx *et al* 2022).

focus on the different political economy dimensions associated with a sustained decline in coal production or consumption. To the best of our knowledge, this is the first attempt to systematically characterize the literature landscape on past coal transitions. In the spirit of our systematic exercise, the paper develops around the following main research question: *what evidence exists on previous coal transitions?* The goal is to retrieve the evidence available in English to (a) understand main transition patterns across countries and identify knowledge gaps and knowledge clusters and (b) provide an overview of different political economy aspects of the transitions that have been mentioned by previous studies. To deal with the vast amount of literature and the rapid expansion of evidence across disciplines, we rely on computer-assisted techniques and machine learning algorithms to find, screen, and identify the relevant literature (Haddaway *et al* 2020). We identified 194 publications from 42 713 search results using a supervised active learning approach that trained a support vector machine model using 1–2 word ngrams from the article abstracts[2]. From these publications we coded 278 studies, collecting information on type of transition experienced, drivers and barriers, outcomes, and policy instruments. In the first part of the analysis we map the literature on historical episodes of declines in coal production and consumption in different periods and locations to answer the following question: *what happened, where, and when?* The aim is to identify common trends and transition waves across countries and periods and to detect knowledge clusters and knowledge gaps, by confronting the literature landscape with data on coal production and consumption. In the second part of the paper we want to shed light on political economy aspects and answer the following research questions: *what were the main drivers and barriers for past coal transitions? What have been the main outcomes of previous coal-phase outs? Which actors have been involved and which policy instruments have been adopted to address the transformative processes required by the transition?* Answering these questions can provide useful policy insights and contribute to the understanding of how to manage the rapid coal phase-out needed to address the challenges at hand of global climate stability.

The remainder of the paper is organized as follows. Section 2 provides an overview of the current state and trends of coal production and consumption; section 3 describes the research design adopted in the paper; sections 4 and 5 present the results of our systematic map of the literature; section 6 discusses the main findings and provides some concluding remarks.

[2] For an overview of this approach and its replicability see O'Mara-Eves *et al* (2015).

2. Coal production and consumption: current trends and historical declines

Global coal production and consumption has increased three-fold over the past 50 years (figure 2). Coal is the second-largest energy source after oil, accounting for 27% of primary energy consumption (BP 2020), and is the primary source for electricity generation (IEA 2020a). Despite a growing awareness of climate change, as well as progressive climate policy in some nations, the fastest period of global coal growth occurred in the early 2000s (figure 2). This 'renaissance of coal' was led by China, but also took place in many rapidly growing economies (Steckel *et al* 2015, Jiang and Guan 2016).

Nonetheless, most coal production and consumption remains concentrated in a small number of countries. Looking at the distribution of coal production we see that seven countries, namely China, Indonesia, the United States, Australia, India, the Russian Federation, and South Africa account for almost 90% of world production (figure 3). The consumption of coal is similarly concentrated: China is the major consumer, followed by India and the United States, which, together with Japan, South Africa and the Russian Federation, make up 80% of the total consumption (figure 4)[3]. The strong demand for coal in Asia favors the Pacific exporters: looking at the coal trade balance, Australia and Indonesia account for more than half of the total coal export, with China being the major coal importer, followed by India (IEA 2020a).

Global growth in coal production and consumption stabilized between 2010 and 2019 (figure 2). This triggered much speculation on whether global CO_2 emissions may have peaked around 2016, which turned out to be premature when emissions started to rise in subsequent years (Jackson *et al* 2016, Figueres *et al* 2018, Peters *et al* 2020). The underlying trend was strongly driven by coal dynamics, particularly in China, which experienced a slowdown in economic growth after 2010 and limited the investment in new coal capacity (Friedlingstein *et al* 2019, Peters *et al* 2020).

Whether or not a peak in coal production and consumption has been reached depends on a regional outlook and balance of trends. Coal production and consumption are following a declining trend in the United States and in most of the European countries, however this decrease is offset by a larger production and consumption by Asian economies, in particular Indonesia. Europe is rapidly reducing coal consumption dependency. In 2015, the UK, formerly 'king coal', was a frontrunner in announcing an explicit

[3] These six countries, together with the Republic of Korea, Indonesia, Germany, Vietnam, Poland, Australia, Turkey, and Kazakhstan (in order or consumption) account for 90% of global coal consumption.

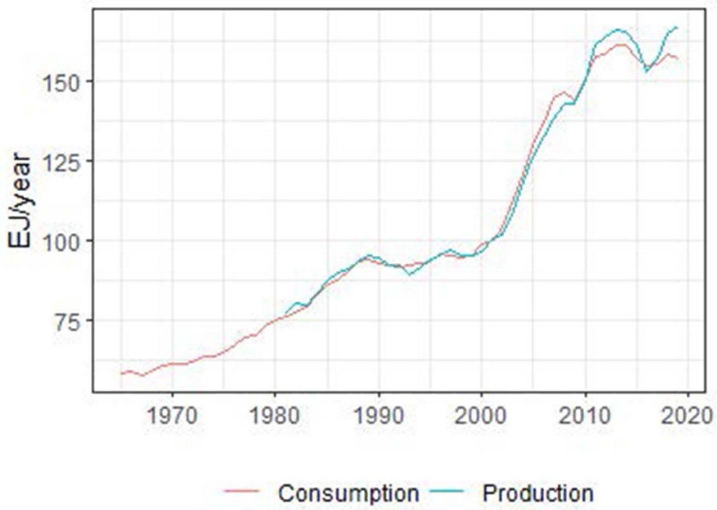

Figure 2. Global coal production and consumption. Source of data: BP (2020). Production refers to commercial solid fuels only, i.e. bituminous coal and anthracite (hard coal), and lignite and brown (sub-bituminous) coal, and other commercial solid fuels. It includes coal produced for coal-to-liquids and coal-to-gas transformations.

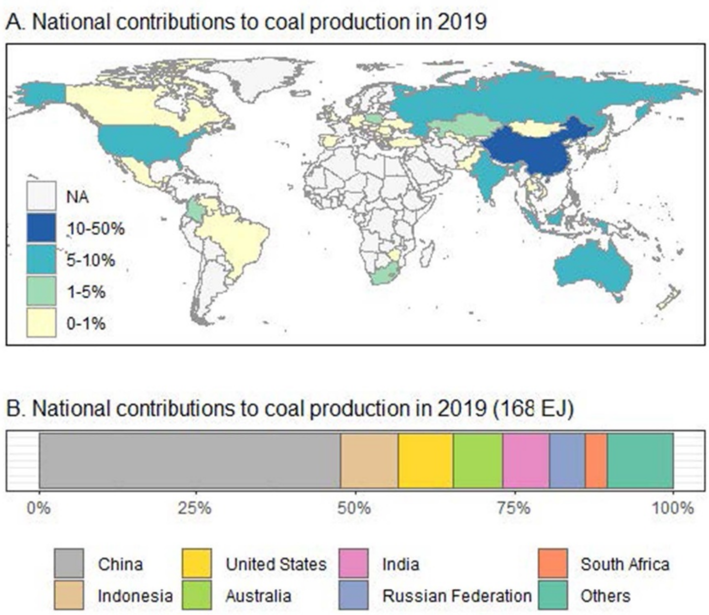

Figure 3. Coal production worldwide. Panel (A) shows country coverage and national contributions to global coal production (%). Panel (B) lists the countries that account for more than 90% of global coal production. Source of data: BP (2020). Production refers to commercial solid fuels only, i.e. bituminous coal and anthracite (hard coal), and lignite and brown (sub-bituminous) coal, and other commercial solid fuels. It includes coal produced for coal-to-liquids and coal-to-gas transformations. NA values in panel A do not necessarily indicate 0 coal production, but missing data where BP has aggregated smaller producers into an 'other' category where individual national values cannot be distinguished.

coal phase-out (Brauers *et al* 2020). Since then, 14 other European countries committed to phase-out coal generation by 2030 (EMBER 2019). Exceptions are Belgium, which managed to become coal-power-free already in 2016, as well as Germany and Czech Republic, which agreed on a phase-out by 2038 (even if in Germany there is the possibility of bringing the phase-out date forward to 2035).

The United States did not declare a phase-out date but showed no plans to build new coal plants either. The coal-fired capacity in the United States has been declining since 2011, after many plants retired or switched to other fuels and the utilization rate of running plants was reduced (EIA 2020). Nevertheless, about 500 GW of new coal-fired power plants are globally planned or already under construction, foremost in Asia (Global Energy Monitor 2020). The successful construction (and utilization) of these capacities in China, India, and other Asian countries would counterbalance current and prospective reductions of coal use in the United States and Europe and fail climate targets.

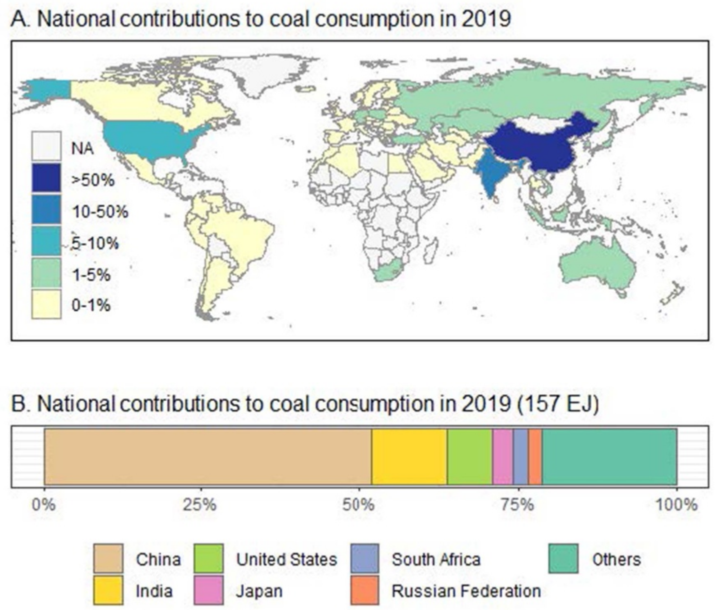

Figure 4. Coal consumption worldwide. Panel (A) shows country coverage and national contributions to global coal consumption (%). Panel (B) lists the countries that account for more than 80% of global coal consumption. Source of data: BP (2020). Consumption refers to commercial solid fuels only, i.e. bituminous coal and anthracite (hard coal), and lignite and brown (sub-bituminous) coal, and other commercial solid fuels. NA values in panel A do not necessarily indicate 0 coal consumption, but missing data where BP has aggregated smaller consumers into an 'other' category where individual national values cannot be distinguished.

Further uncertainty has followed the Covid-19 pandemic, which reduced coal demand (−5%) and production (−6.5%) in 2020 (IEA 2020b). The medium and long term trend, however, depends in large part on the nature of economic stimulus packages in different countries, which include 'green' recovery schemes that facilitate a transition away from coal (Yanguas Parra *et al* 2020), as well as 'brown' subsidies that prolong dependence on it (Jakob *et al* 2020a). Existing global downward trends, however, are in any case not steep enough to meet needed trajectories to comply with the international climate targets (Yanguas Parra *et al* 2020).

The global uptake of coal over time might be counterintuitive, as many countries decreased their coal consumption and production substantially over time. To identify countries whic experienced a transition away from coal over time and to have a benchmark against which to compare the results of our map, we adopt the following definition of transition: a period of *steady* decline in coal production and consumption since a *peak year* (i.e. the year in which a country reached its maximum level of coal production or consumption). For each country we identify a peak year both for coal production and consumption. We rely on BP (2020) because it provides data for specific fossil fuels instead of aggregated emissions data. Nevertheless, the time series starts from 1965 for coal consumption and 1981 for coal production. This time span is sufficiently long to include the peak years of many countries, with some exceptions for which we know that the transition started well before (as shown in section 4).

The *peak criterion* adopted here serves as a first indication to identify ongoing transitions. After finding a peak year for every country, we calculate the relative and absolute declines between that peak year and 2019. Figures 5 and 6 show the ten countries with the largest absolute reductions and the duration of the ongoing transitions since the country-peak year. This strategy omits reductions due to fluctuations in the business cycle allowing us to (a) identify ongoing transitions, (b) observe when they started, and (c) compare them with historical transition periods reported in our map. In section 4 we confront the country and time coverage of our studies with historical transitions identified through this criterion.

Focusing on coal production, we observe that countries experiencing significant reductions are in Europe or North America. It is worth noticing that the United States is the country with the largest absolute reduction (9.8 EJ) since peak, followed by Germany, Poland, and Ukraine. BP data, however, cumulates coal production across subnational regions and coal types. More detailed case study analysis shows that, e.g. in Germany, hard coal production started its decline already in the early 60s (Oei *et al* 2020) but was overcompensated by rising lignite production until overall coal production peaked in 1982 (Stognief *et al* 2019). Also in the case of the United Kingdom, our collection of case studies clearly shows that the country started reducing coal production already in

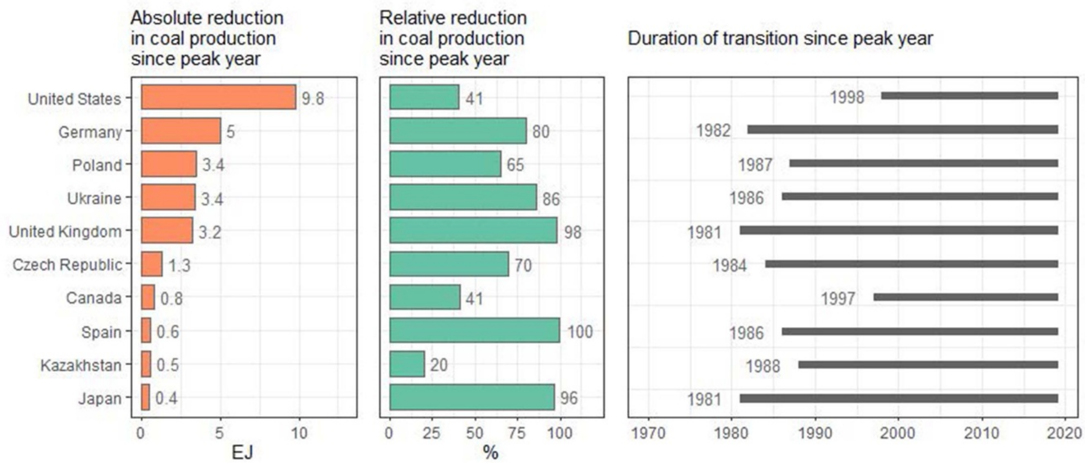

Figure 5. First ten countries in terms of absolute declines since peak year. The first two columns show the absolute and relative declines in coal production between peak year and 2019. The last panel depicts the year of peak for each country and the duration of the transition. Source of data: BP (2020). Production refers to commercial solid fuels only, i.e. bituminous coal and anthracite (hard coal), and lignite and brown (sub-bituminous) coal, and other commercial solid fuels. It includes coal produced for coal-to-liquids and coal-to-gas transformations.

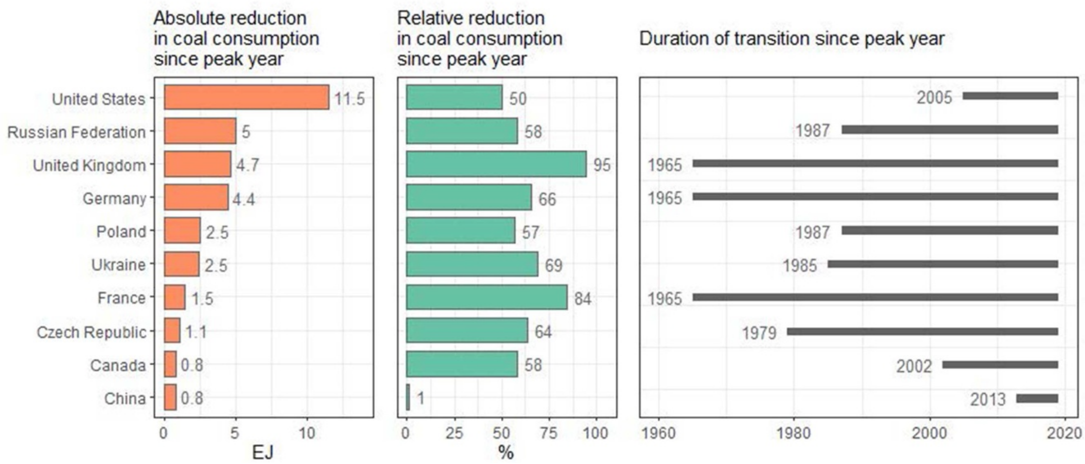

Figure 6. First ten countries in terms of absolute declines since peak year. The first two columns show the absolute and relative declines in coal consumption between peak year and 2019. The last panel depicts the year of peak for each country and the duration of the transition. Source of data: BP (2020). Consumption refers to commercial solid fuels only, i.e. bituminous coal and anthracite (hard coal), and lignite and brown (sub-bituminous) coal, and other commercial solid fuels.

the beginning of the 20th century. Several countries in Eastern Europe share a common trend in reducing both production and consumption since the late 80s. Beyond Poland, Ukraine and Czech Republic, included among the first ten countries for absolute reductions, we observe substantial coal production declines also in Romania and Hungary. In some countries, however, coal production is still increasing and a peak has not yet been reached. Among these countries we find Australia, China, Indonesia, Mongolia, and Pakistan. India and Russia show a peak in 2018 and a slight decrease in 2019, while Colombia reached a peak in 2017. For these countries the peak year is too recent to provide any assessment.

The list of the ten countries with the largest reduction in absolute coal consumption only slightly differs from the list for production: we find the same countries with the exception of Spain, Kazakhstan, and Japan which are replaced by Russian Federation, France, and China. As for the reduction of production, the United States comes first for absolute decline of consumption (11.5 EJ), followed by Russian Federation (5 EJ) and the United Kingdom (4.7 EJ). It is worth mentioning that in 2019 the United States experienced the largest annual coal generation percentage decline in its history (16%) (EIA 2020). Among the countries covered by BP data, Bangladesh, Colombia, India, Indonesia, Morocco, Oman, Pakistan, Philippines, Sri Lanka, United Arab Emirates, and Vietnam have not yet reached a consumption peak, while other countries have peaked very recently (2017 or 2018), so it is not possible to assess, based on the data coverage we have, if they are experiencing a cyclical downturn

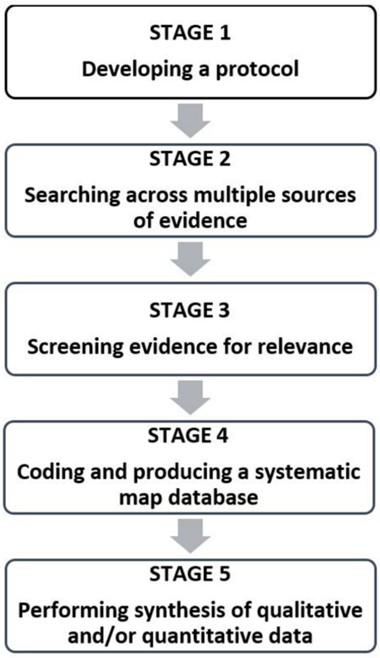

Figure 7. Stages of the coal transitions systematic map.

in coal consumption or starting a proper transition. Among these countries, in order of absolute consumption reductions, we find the Republic of Korea, Japan, Mexico, Thailand, Chile, Malaysia, Iran, Turkey, Uzbekistan, Singapore, Egypt.

3. Research design

Systematic mapping is an established systematic evidence synthesis methodology used to collate, describe and catalogue existing research evidence. Systematic maps are conducted through transparent and repeatable processes, to maximize objectivity and comprehensiveness in the review process and minimize biases affecting traditional literature reviews. It is usually possible to identify sequential stages in the conduct of systematic maps (James *et al* 2016, Haddaway *et al* 2018). Figure 7 summarizes the procedure adopted in this work.

Stage 1: Developing a protocol

We set up a review team comprising eleven people belonging to three international research networks. We then identified the scope and research question of our map and established a set of inclusion/exclusion criteria. Our aim is to understand what evidence exists in terms of policies, drivers, barriers, and outcomes of market-driven and regulated regional, national and sub-national coal transitions. To this end, we developed a conceptual framework based on the PICO format (population, intervention, comparator and outcome) (O'Connor *et al* 2008) and applied it in the following way: population (= all coal countries/regions), intervention (= coal transitions)

Table 1. Inclusion/exclusion criteria.

Inclusion	Exclusion
Publication is in English	Publication is not in English
Studies on historical coal phase-outs	Studies on future coal phase-outs (models, scenarios, policies and regulations to achieve the phase-out, discourses on coal phase-out, planned transitions, ...)
A relative or absolute coal decline is mentioned in the study	
More than one coal mine or plant is covered	
Date and place are reported	

and outcome (= environmental, social, and economic outcomes)[4].

We built our map around the concept of 'historical coal transitions' (i.e. reduction of coal consumption and/or production). To be included in our dataset, the study had to mention location, time, and coal decline and cover more than one coal plant/coal mine. We decided to include publications even when the transition was not the core of the study. This allows the inclusion, for instance, of all the studies focusing on transition outcomes or transition management, instead of transition per se. Furthermore, we included historical transitions regardless of the coal substitute (oil, gas, RE, nuclear). We decided to also include studies addressing 'relative transitions', where only the relative share of coal production and/or consumption was reduced, and supply side transitions during which local production of coal was substituted by coal imports. We did not constrain our map to reductions happening in specific sectors, periods of time or locations and we included all types of publications (e.g. journal articles, book chapters, reports). Studies were excluded if focusing on models, scenarios, or policy recommendations for future coal transitions. During the searching and screening stages we also excluded publications for which the full text was unavailable and/or it was not in English. Table 1 summarizes our inclusion/exclusion criteria.

Stage 2: Searching across multiple sources of evidence

To identify the relevant literature, we conducted a search in Scopus, Web of Science, JSTOR, MEDLINE and Publish or Perish databases on titles, abstracts and article keywords. Our search string links synonyms for coal with synonyms for transition:

TS = ((coal OR anthracite OR lignite) NEAR/10 ('phas* out' OR exit* OR transition* OR transform* OR clos* OR shift* OR decommission* OR 'shut*

[4] Due to the exploratory nature of mixed and qualitative systematic maps 'Comparison' groups are frequently excluded, as they are not typically part of a qualitative research question.

down' OR moratori* OR end* OR stop* OR declin* OR reduc* OR ban* OR displac*)).

We chose wild cards (*) to ensure that synonyms for coal and transition were found independently from word endings. The Boolean Operator 'NEAR/10' was included to ensure that the two words coal and transition, or their synonyms, appeared within ten words.

This search resulted in 42 713 potentially relevant publications, to which we added further references identified while reading documents in the later stages of our review.

Stage 3: Screening evidence for relevance

To screen all the potentially relevant documents yielded by our search, we adopted a machine-learning algorithm to predict the relevance of publications. We initially screened a random sample of 259 potentially relevant abstracts and decided which abstracts to include or exclude based on our inclusion/exclusion criteria. To ensure consistency, the team discussed the sampled abstracts to reach a consensus on the application of the inclusion/exclusion criteria. We used this screened set of articles to train a supervised machine-learning algorithm. We train a support-vector machine using 1–2 word ngrams[5] from the document abstracts and predict the relevance of the remaining articles. We ranked the articles from highest to lowest predicted relevance. The abstracts with the highest likelihood of inclusion were screened by the team and the results were used to further train the algorithm. This iterative process was repeated several times and produced a final set of 761 potentially relevant documents[6]. We then read the full-text versions of all 761 documents and further excluded articles that turned out not to be relevant, because they do not fulfill our inclusion criteria (see table 1) upon closer inspection. This further round of exclusion corrects potential erroneous relevance predictions from the previous steps. This left us with a final sample of 194 included publications (figure 8).

Stage 4: Coding and producing a systematic map database

The review team read full-text publications and conducted the meta-data extraction and coding[7]. For each publication, we reported generic information: title, author, year and type of publication, journal focus and publication focus[8]. We added information on the method adopted by the study (qualitative, quantitative, literature review) and we developed our codebook based on the dimensions shown in table 2.

We developed a dropdown menu for each subdimension and gave the coders the possibility to add additional elements to the list where needed. When a single publication reported different transitions, information on all the transitions was collected. Multiple case studies from a single publication have been included in the sample under two circumstances: (a) the publication covers more than one location, or (b) the publication covers transitions that happened in the same place but in different periods. Our final dataset comprises 278 cases of coal phase-out extracted from 194 publications, including 143 journal articles (73% of the sample), 29 reports, 10 conference papers, 9 book chapters, and 3 news articles. 32 publications include more than one case study.

Stage 5: Performing synthesis of qualitative and/or quantitative data

In the final stage, we mapped and interpreted available evidence, first providing an overview of our dataset and then focusing on national coal transitions and political economy aspects.

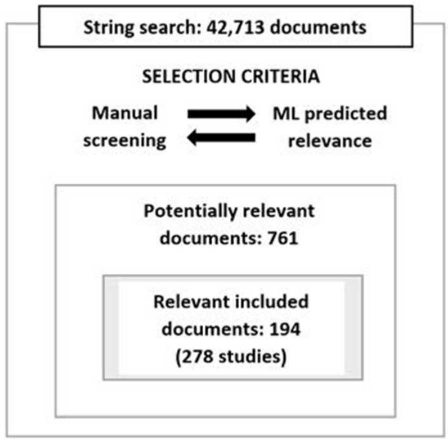

Figure 8. Overview of the document selection procedure.

4. Historical coal transitions

In this section we describe the historical coal transitions covered by our map. The aim is to (a) provide an overview of the main patterns in the literature and detect the main knowledge clusters and knowledge gaps and (b) identify major transition events

[5] n-gram is a contiguous sequence of n items for a given sample of text or speech. We use words as items.

[6] To check the robustness of our ML selection procedure, and thus the comprehensiveness of our dataset, we also asked researchers in the field for references and used snowballing (i.e. using the reference list of a paper to identify additional potentially relevant papers) as an additional search approach.

[7] We organized specific training sessions to ensure consistency in the screening and coding processes and we double coded a sample of articles before conducting the full review.

[8] We reported the publication focus also for the 567 publications we did not include, to detect potential patterns in terms of topics covered. The sample was heterogeneous and no clear research clusters were identified for the excluded publications.

Table 2. Coding scheme.

Dimension	Sub dimension I	Sub dimension II
Type of coal transition	Supply Demand	Intervention Magnitude of coal reduction Date Substitute for coal Implications for demand/supply
Political economy of coal transition	Actors involved Policy instruments Management policies Drivers Barriers	
Outcomes of coal transition	Social Economic Environmental	Quantitative information Date

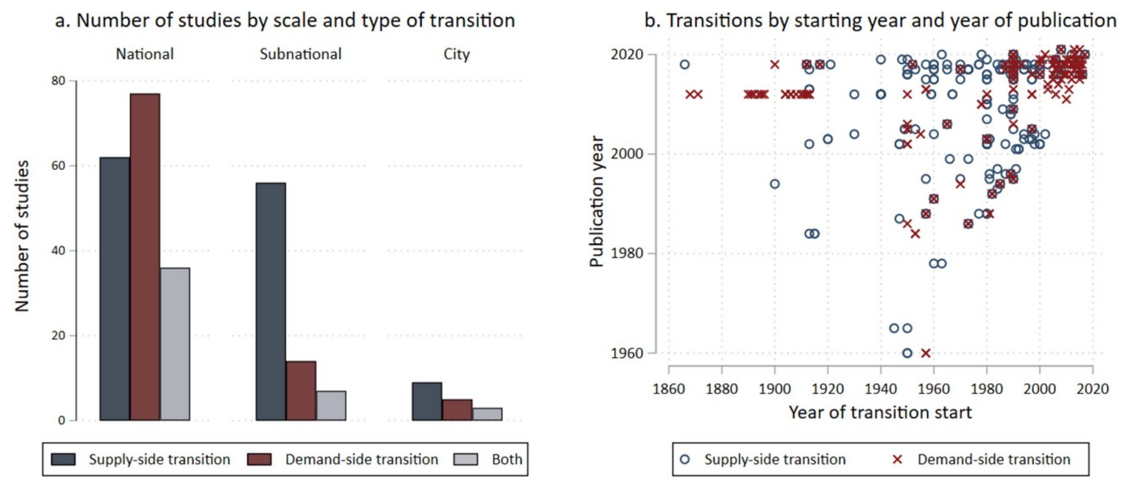

Figure 9. Panel a: number of studies in the systematic map grouped according to the type of transition covered. Panel b: transition events covered in our sample with the starting year of the event and the year of publication of the study. Transition events are grouped according to the type of transition.

and potential similarities across countries and time periods.

4.1. Literature landscape: main trends, knowledge clusters, and knowledge gaps

Our sample is composed of regional, national, subnational and city-level studies. We included, among the subnational studies, all studies focusing on a specific region inside a country and, among regional studies, all studies adopting a supra-national perspective[9]. Most of the studies in the sample (63%) have a national focus, followed by subnational studies (28%). Each study can report only supply-side transitions (decline in production), only demand-side transitions (decline in consumption) or both. The documents included in the map have been published between 1960 and 2021, even if only 11% of the studies appeared before the year 2000. Figure 9 shows that the literature on coal transitions is expanding and that older transitions are also covered by relatively recent studies. We can see that studies at national scale have a good balance in terms of demand-side transitions and supply-side transitions, while subnational and city-scale studies focus mainly on supply-side transitions. These latter studies' focus on decline in production could be explained by the great impact mining activities have on local economies and territories. Subnational studies tend to focus more on economic impacts and structural change policies required by supply-side transitions.

To look at coal substitutes in history, we divided our sample between studies analyzing transitions which have occurred before and after the oil crisis in 1973. We can notice that, before 1973, coal has been primarily replaced by oil and gas (figure 10). Some studies at the national level also report that other coal sources have been used as substitutes. The category *Coal* includes coal imported from other locations, due to competitiveness or regulatory reasons, as well as other types of coal (e.g. hard coal replaced by lignite). Studies focusing on transitions that occurred after the

[9] We have only two regional studies, one focusing on Latin America and the other one on Europe.

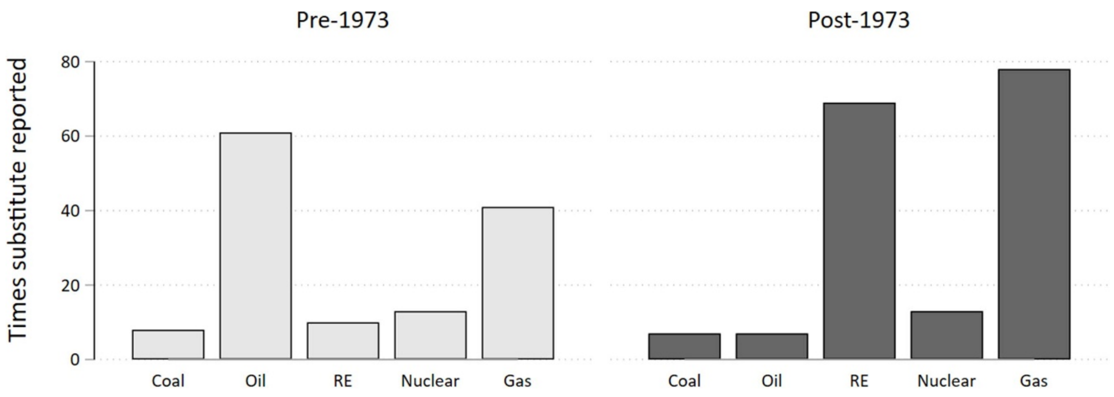

Figure 10. Coal substitutes mentioned in the studies and number of occurrences. Substitutes are grouped according to the time period of the transition. The cut-off is the oil crisis in 1973. The category 'Coal' includes imported coal and alternative types of coal.

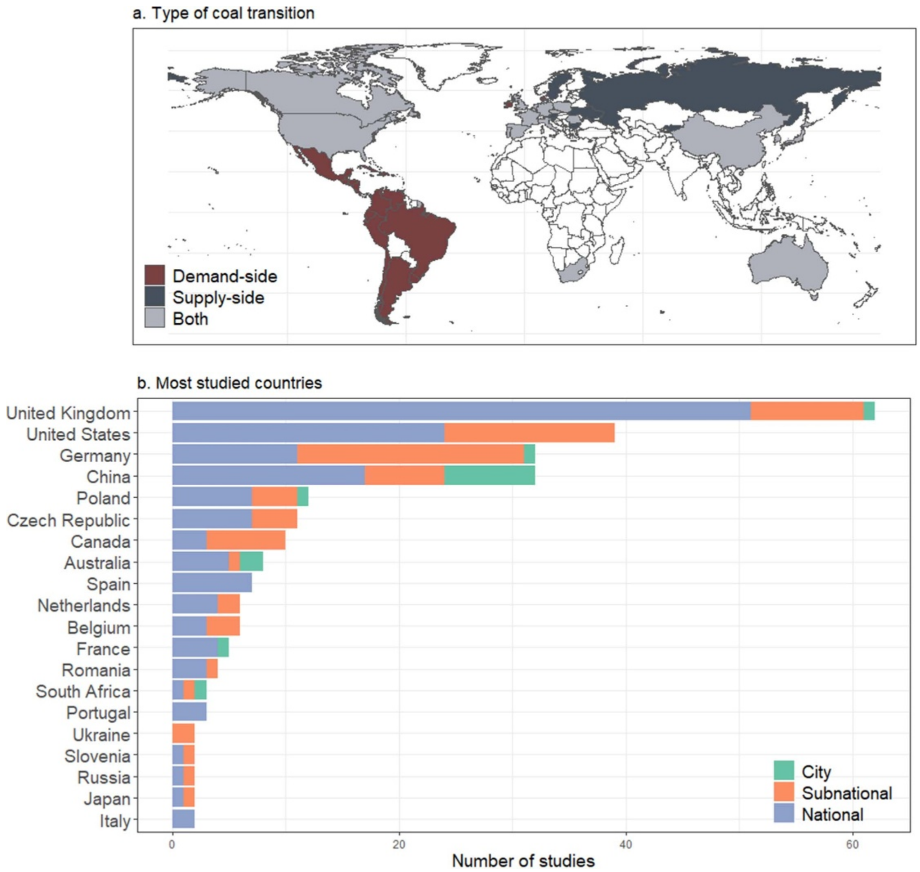

Figure 11. Country coverage based on transition type and number of studies grouped by study scale. Note: panel b shows only countries covered by more than one study.

oil crisis depict a very different story. We observe a drastic reduction of oil as a coal substitute, replaced by renewable energies and gas[10].

Our sample covers 44 countries, but almost half (48%) of the studies refer to the United Kingdom, the United States, and Germany (figure 11). This effect might be amplified by focusing only on publications in English (and origin of most authors in any of the three countries). Even if the evidence on coal transitions covers a large set of countries across the globe, we can clearly identify some clusters. The high number of studies focusing on the United Kingdom, the United States, and Germany is in line with the large relative and absolute coal declines these countries experienced. The fourth most studied country in our dataset is China but the results in this case should be

[10] The results hold also considering the 1979 oil crisis as cut-off year.

interpreted carefully. The type of evidence we have for this country differs quite substantially from the evidence we have for the United Kingdom, the United States, and Germany. For these three countries we have a predominance of studies, fairly distributed over time, describing transitions occurred at national or subnational level that match quite well historical data on declines in coal production and consumption. In the case of China, instead, we observe a significant number of case studies at city level, mostly published in the last few years, that do not necessarily reflect national trends. Moreover, the peculiar situation of the coal industry in China compared to other countries should be considered when interpreting the results (see section 4.2.3). The increasing number of studies for this country reflects the role of China as a major player in the global coal market as well as specific wide debates related, for example, to severe air pollution problems or the restructuring of the Chinese coal industry. The great number of studies we have regarding some countries requires a first caveat. The objective of a systematic map is to reproduce the state of the art of the literature and identify clusters of knowledge and gaps. Our work highlights that most of the evidence available is built around a cluster of few countries. This should be kept in mind when interpreting our results and assessing their external validity.

By looking at both country and time coverage of the studies we can compare them with sustained historical declines in production and consumption shown in figures 5 and 6. Even if the definition of decline adopted in the map is broader, we still think figures 5 and 6 serve the purpose of providing a first indication of the main literature gaps.

The large amount of studies focusing on the United Kingdom well reflects the long and steady transition away from coal that the country has undertaken. Nevertheless, it should be noted that for the United Kingdom, the United States and Germany, as well as for other countries, we have studies documenting absolute and relative declines in production and consumption preceding the peak year we recovered from the BP (2020) data (see section 2). This is in line with the fact that (a) figures 5 and 6 show only absolute declines, (b) aggregate all types of coal, and (c) exclude all cyclical and temporary declines, and (d) cover a shorter time span compared to the time span covered by the literature.

Besides the United Kingdom, the United States, and Germany, among the ten countries that constantly have been reducing both production and consumption since peak year there are Canada, Czechia, Poland, and Ukraine. For the first three countries we have 10, 11 and 12 studies respectively which cover both demand-side and supply-side transitions. For Ukraine, instead, we have only 2 studies at subnational level (Babaev *et al* 2000, Haney and Shkaratan 2003) even if the country experienced a national decline in coal consumption and production of 69% and 86% over the period 1985–2019. Looking at the significant coal reductions that countries in the Eastern Europe have undertaken we have relatively few studies. This is clearly a first lack of evidence we can identify in the literature, which might be intensified by our limitation of including only publications in English.

Regarding the top ten countries that significantly reduced coal production (figure 5), we find no evidence on Kazakhstan and only 2 studies on Japan. Relatively few studies focus on Spain (7), despite a substantial decrease also of coal consumption (77%), taking place from 2002. Other countries that significantly reduced their coal production for which we can detect a lack of evidence are Romania, for which we have only 3 studies at national level (Sheldon *et al* 2002, Cobârzan 2008, Zlateva *et al* 2020), and the Republic of Korea for which we have only one study (Park and Kwon 2011).

Regarding countries that reduced coal consumption (figure 6) we can say that China is well represented in the dataset, while for France we only have 5 studies and for Russia we have 2 studies, one on the national scale (Crowley 2018) and one on the subnational scale (Haney and Shkaratan 2003).

Finally, regardless of the peak criterion, we can see, with few exceptions, a general lack of evidence for countries in the Global South. We will come back to this in the discussion section.

4.2. National focus: supply-side and demand-side transitions

Focusing on studies at country level, we find evidence of *national* coal transitions for 40 countries (out of 44 covered by our dataset)[11]. By grouping countries according to the type of transition that they have experienced it is possible to identify some main 'transition waves'.

Supply-side transitions are distributed over a time period extending from 1900 (mine closures in the United Kingdom) (Robb 1994) to 2019 (coal production decline in Bulgaria, Zlateva *et al* 2020), even if many countries experienced coal production declines in the 80s and the 90s (figures 12 and 14). This could be due, on the one hand, to the fall of the Soviet Union (which had a direct impact on the regional coal markets of Eastern Europe, especially Poland) and, on the other hand, to the globalization of economic markets in general and coal market in particular (which affected domestic consumption primarily in Asia, the

[11] The only exceptions are Austria, Ireland, Kyrgyzstan, and Ukraine.

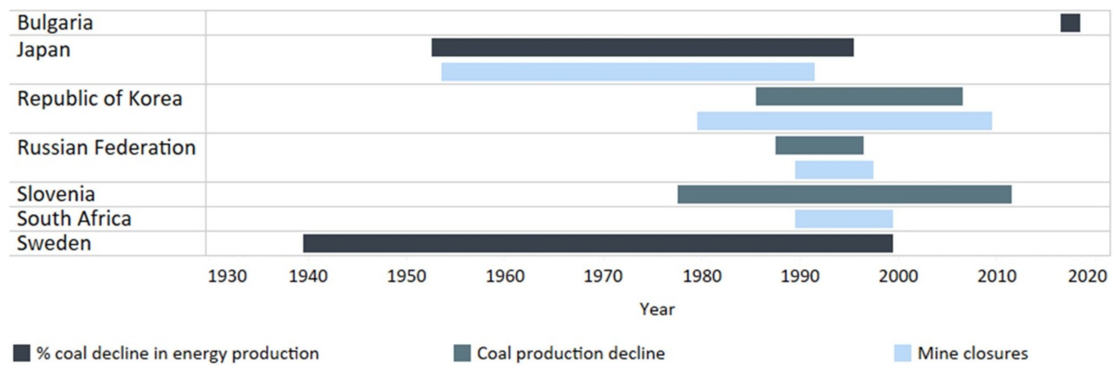

Figure 12. Country, time period, and description of national historical supply-side transitions included in the map. Note: the figure is based on the transitions covered by our studies. It does not necessarily represent all coal declines in production and consumption that occurred in the history of the country.

Pacific, and North America). Privatizations and liberalizations in some countries increased the degree of competition and market-free entry for alternative sources, like imported coal or gas that provided cheaper alternatives to domestic coal (Fothergill 2017, Littlecott *et al* 2018). In addition to economic considerations, environmental regulation directed at coal mining operations played a strong role in reducing mining profitability, fostering the closure of mines in some regions. With public health risks on residential communities and environmental harms linked to coal mining and processing becoming apparent, governments increasingly enforced specific legislations to ensure the safe conduct of mining activities (ILO 1986, Weeks 1991).

Regarding demand-side transitions, the first evidence dates 1642 and is provided by a study focusing on coal consumption decline during the English civil war (1642–1651) (Fouquet 2012)[12]. It is the oldest transition documented in the dataset. The remaining demand-side transitions are distributed between 1850 (coal decline in primary energy consumption in the United Kingdom) (Fouquet 2012), and 2020 (coal consumption decline in China) (Yang *et al* 2021). We observe (figures 13 and 14) two main demand transition periods, common to many countries. The first transition wave occurred in the first half of the 20th century, probably due to market dynamics and the disruptions caused by the First and Second World War. The second wave started around 1990 and was based on different events: decline in the share of coal in electricity generation and plant closures. This transition thus seems to be driven by structural shifts in the electricity sector as well as regulation. The recent increased awareness of the harmful effects of coal burning on human health and the contributions of coal combustion pollutants to climate change have led to international efforts to reduce coal dependency and coal-combustion emissions. Most countries around the world have implemented air pollution regulations and set up emission standards for coal power plants (Directive 2010/75/EU, Thomson *et al* 2018). Even if the modernization of some of the oldest plants would have reduced emissions, in many cases retrofitting them was too expensive, which led to their closure. In Europe large reductions of sulphur dioxide (SO_2) have been caused by a decrease of coal consumption and by the implementation of directives introducing stricter limits for most classes of pollutants.

In the following we provide a timeline of the main national transition events we have been able to retrieve from our case-studies (figures 12–14)[13]. A more disaggregated overview of transition events is provided in appendix. In the same period, different interventions or dynamics can be in place and each study can report more than one 'event', while describing the same transition (e.g. closure of plants and decline of coal share in energy consumption). We have included, among the transition events, both absolute and relative coal reductions, in line with the heterogeneous information reported by the original studies. For some countries we have evidence of both relative and absolute declines, while in other cases the original studies report only relative reductions (that do not necessarily imply absolute declines). Relative reductions in all the studies mostly refer to reductions occurring in the power sector, while studies reporting absolute declines do not disentangle between coal used for power generation and coal used for industrial processes, thus we cannot provide any detail on this aspect[14].

[12] See table A2. We excluded this study from figure 14 for the sake of readability.

[13] The appendix reports specific tables also for regional (table A1), subnational (table A3), and city-scale (table A4) transitions covered by the studies. Most studies at the subnational level focus on mine closures in specific coal mining areas, while the evidence on national-scale transitions presents a more diverse set of evidence.

[14] Please note that the transition episodes we report and discuss in this subsection are extracted by the studies in the datasets and are thus subject to the reliability of information reported in the original publications and the number of evidence per country we have.

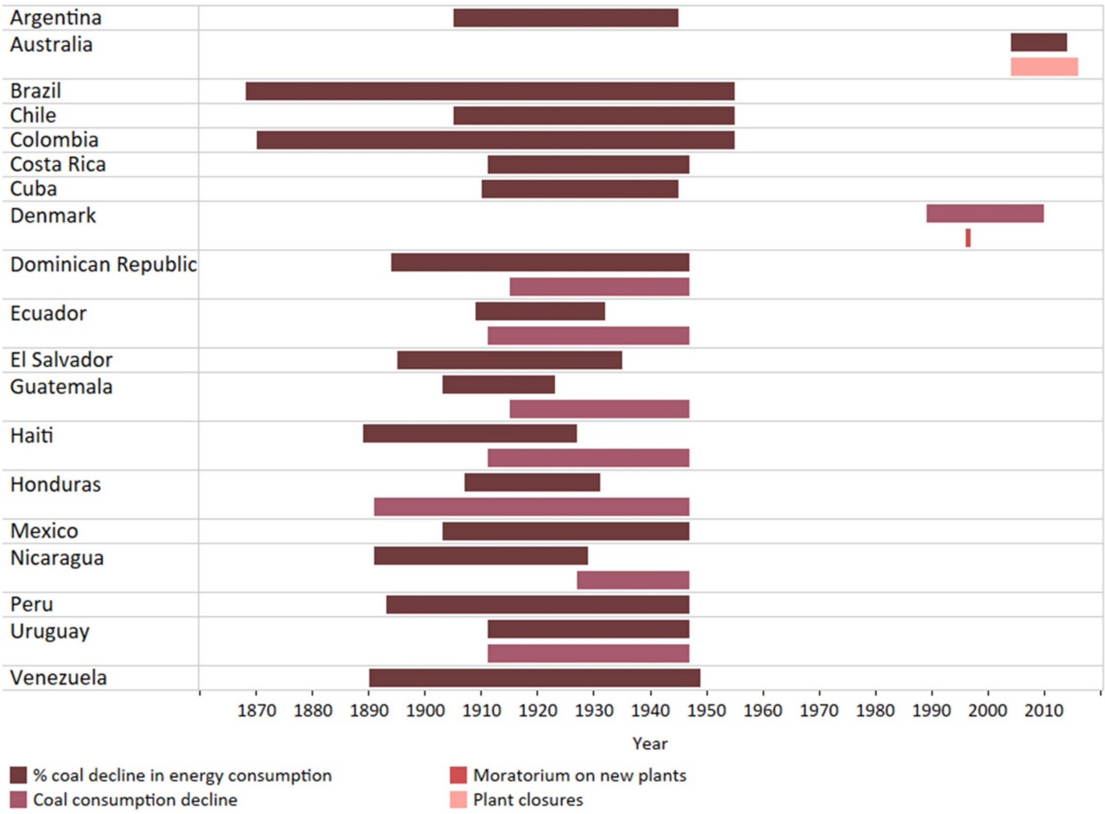

Figure 13. Country, time period, and description of national historical demand-side transitions included in the map. Note: the figure is based on the transitions covered by our studies. It does not necessarily represent all coal declines in production and consumption that occurred in the history of the country.

4.2.1. Supply-driven transitions

Figure 12 shows the countries for which we have only evidence of supply side transitions, namely Bulgaria, Japan, Republic of Korea, Russian Federation, Slovenia, South Africa, and Sweden. The figure shows transition events and transition periods covered by our case-studies. For these seven countries it is possible to group the transitions along three major transition events: absolute declines of coal production, mine closures, and relative decline of coal in energy production.

While for Bulgaria and Sweden we have only one study each reporting a relative decline of coal in energy supply (Grubler 2012, Zlateva *et al* 2020 respectively), for the other countries the transition away from coal has been driven by absolute reductions. In Japan and in the Republic of Korea the studies document massive declines, which are confirmed by our data analysis[15]. In Japan, the share of coal in energy production declined from 48% to 16% in the second half of the 20th century and all the mines were almost completely shut down by 1992 (Garside 2005). In the Republic of Korea, the coal industry went through a rapid adjustment, with the closure of almost 90% of mines over the period 1980–2010, with a drastic reduction in coal production (from 27 million tons to approximately 3 million tons) (Park and Kwon 2011). National coal production has progressively been replaced in these two countries by an increasing reliance on coal imports.

It is worth noticing that Japan, the Republic of Korea, the Russian Federation and South Africa are today among the major coal consumers worldwide. This is in line with the fact that we do not find any evidence about demand-side transitions for these countries. Supply-side transitions, without a concurrent decline in the demand for coal, do not necessarily translate in a reduced coal dependency.

4.2.2. Demand-driven transitions

For 19 countries we have studies covering only demand-side transitions. This group is composed of Latin American countries, Australia, and Denmark. Transition periods, dynamics and key messages here should be interpreted taking into account the heterogeneous history and energy structure of these countries.

We can observe a common pattern in Latin American countries: all of them experienced a decline of coal share in energy consumption during the first half of the 20th century, in some cases associated with an

[15] Note that Japan is among the ten countries which have reduced coal production the most according to our peak criterion (see figure 5). The Republic of Korea is 12th in our ranking.

Figure 14. Country, time period, and description of national historical supply-side and demand-side transitions included in the map. Note: the figure is based on the transitions covered by our studies. It does not necessarily represent all coal declines in production and consumption that occurred in the history of the country.

absolute coal consumption decline. Mostly following the disruptions created by the First World War, Latin American countries replaced coal with oil as their main energy source. The transition from coal to oil in Latin America was extremely rapid and occurred 40 years in advance in comparison with the industrialized nations, due to a combination of technical, geographical, and historical contingencies, not least the shortage in coal imports due to the First World War (Rubio-Varas 2019).

Australia recently (2000–2017) experienced a demand-side transition based on coal plant closures due to multiple reasons (including plants reaching the end of their operative lives) and investments in new industries (Burke *et al* 2019). Regarding the energy infrastructure, coal plants were substituted by new natural gas and renewable energy plants (Simshauser 2018). It is worth mentioning that Australia is today one of the biggest coal producers and exporters worldwide. Even if the domestic demand for coal is decreasing, the country strongly relies on coal exports.

Denmark experienced a decline of coal consumption as fuel for combined heat and power plants (CHP) from 40% to 8% in 20 years, accompanied by a moratorium on the construction of new coal plants in 1997. Cogeneration units were required to replace district heating units, and the use of oil, diesel, and coal was prohibited. Coal was replaced in large part by renewable energy and biomass and, to a lesser extent, by gas. It is worth mentioning that this sectoral transition is part of a larger effort put in place by Denmark to fully reorganize its energy system and become self-sufficient in its own energy production and use (Sovacool 2013).

4.2.3. Demand- and supply-driven transitions

For 14 countries the studies provide evidence of both demand- and supply-side transitions (figure 14). Most of the countries simultaneously experienced relative and/or absolute declines both in coal production and consumption. In this group we find mainly European countries. The only notable exceptions are Canada, China, and the United States.

The case of China is peculiar, and compared to other countries we can clearly see that the transition has mainly been relative, with absolute coal consumption declines starting recently and not complemented by a steady decline in production. Regarding the closure of mines in the country some caution is in order. In the late 1990s and early 2010s the country put in place efforts to reform its coal industry towards sustainability and greater efficiency and safety, with a series of initiatives to consolidate its coal resources and upgrade its mining sector (Bridle *et al* 2017, Cao 2017). In the 1990s and 2000s a lot of small mines closed. The studies in our dataset document two major phenomena: the closure of small township and village-owned or private mines, which proliferated after the launch of China's open-door policy in the early 1980s, and the bankruptcy of loss-making state-owned coal companies. For example, in 2000, 250 state-owned coal mines and 40 000 illegal small coal mines were closed (Sheldon *et al* 2002), followed by other closures in the rest of the 2000s. Over the period 1998–2002, 44 776 (around 62%) mining companies closed (Rui 2005). While some of these closures were driven by the attempts to rationalize the industry, most of the small and illegal mining operations shutdowns were motivated by safety reasons and in the attempt to address coal fires. These mines were mainly characterized by unauthorized operations, irrational locations, low recovery rates, poor safety and sustainability records. Coal fires were reported mainly in the coal belt running across the North of China, in Inner Mongolia, Xinjiang, Ningxia, Shanxi, and Heilongjiang, with mining activities being identified as the key factor triggering coal fires in China (Song and Kuenzer 2014). Beside economic losses, these fires heavily contribute to air pollution and greenhouse gas (GHG) emissions. The country, in the past decades, closed mines and spent several 100 million US dollars to extinguish coal fires. Nevertheless, the situation remains severe, with fires still on-going, new ones occurring, and extinguished ones re-igniting due to illegal mining activities. Our sample of studies also documents a decline in the share of coal in primary energy supply (1949–2002), substituted in large part by oil and natural gas. On the demand side, the studies reported an absolute coal consumption decline in the 2013–2016 period and a decline of coal share in primary energy consumption starting in 2000. In 2016, China started cancelling and suspending a large number of new plants to be built (Kimmel and Cleetus 2018). In most cities and regions the government has been under intense pressure to reduce coal use and relocate the coal industry due to high levels of pollution. A prominent example is Beijing, where all the coal power plants have been closed and the authorities have implemented a number of forceful energy policies and laws to adjust the energy mix and tightened emissions standards in response to more frequent and severe smog events and air pollution issues (Zhang *et al* 2018).

In Europe, the largest body of evidence pertains to the United Kingdom and Germany. Both countries have a long history in both coal production and consumption[16], being heavily dependent on coal for electricity generation. The United Kingdom's and Germany's coal industries faced similar conditions as hard coal mining has been uneconomic for decades, coal infrastructure has been old and import dependence has been rising. In both countries coal has been in decline but at different speeds (Brauers *et al* 2020). Coal production steadily declined in the United Kingdom from 1929 to 1999 in line with the corresponding coal decline in electricity generation. Especially due to government subsidies, hard coal mining in Germany experienced a continuous 60 year controlled decline, contrasting with a far more abrupt collapse of coal production in the United Kingdom. In the 1960s Germany produced around 500 million

[16] Please note that we have studies documenting % coal declines in energy consumption for the United Kingdom starting from 1850. This should be kept in mind in interpreting figure 14. We excluded the period 1850–1900 from the figure to make it more readable.

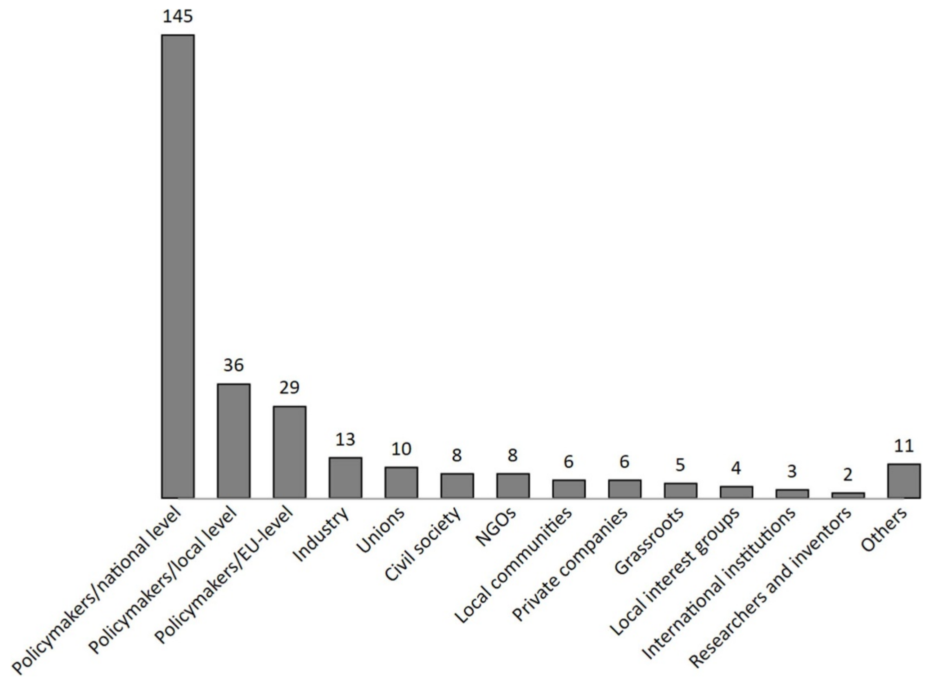

Figure 15. Actors facilitating coal transitions. Number of occurrences in the dataset.

tons of coal (hard coal + lignite). The last hard coal mine closed in December 2018. Nevertheless, in the period from 2000 to 2018 Germany still produced around 170 million tons of lignite every year (Brauers *et al* 2020) and coal still had a share of 26% in the electricity generation in 2018. The United Kingdom announced a coal phase-out by 2025 already in 2015 and founded the Powering Past Coal Alliance aiming to incentivize other countries to phase-out coal as well. In Germany the coal phase-out is planned to end much later, in 2038 (or 2035).

Regarding the United States we have studies reporting a decline in coal production at the beginning of the 19th century and a temporary coal production decline over the period 1950–1960, finally followed by a steady decline starting from 1985 with mine closures and an overall decline of the coal industry. On the consumption side, studies report relative and absolute declines starting from the 80s.

In conclusion, as figure 14 highlights, countries which experienced substantial declines in coal use underwent both supply- and demand-side transitions. The historical evidence we collected seems to support the hypothesis that, to effectively reduce the overall countries' dependency from coal, both supply and demand-side interventions are needed.

5. Political economy aspects

This section provides an overview of political economy aspects characterizing historical coal transitions with the aim of retrieving major patterns across all case studies we have collected. We present our results structured in: (a) drivers and barriers of coal transitions, (b) outcomes of the transitions, and (c) policy instruments that encouraged the transition or addressed the challenges induced by it.

5.1. Drivers and barriers

To understand the political economy of coal transitions, it is important to outline which stakeholders have historically played a role in facilitating transitions and to what extent the declines in coal demand and coal consumption have been the results of market dynamics. Figure 15 shows the weight of different actors in facilitating the transition. Policymakers at different levels are reported as the main driving force. The literature considered suggests that, even when market forces are in place, the transformative processes requested from energy transitions often require the intervention of policymakers at different stages of the transition process.

In the context of this analysis, a consideration about the intentionality of the decarbonization of the system is in order. Thirty-one percent of studies covered transitions that happened on the basis of considerations beyond decarbonizing the system, e.g. for economic reasoning. In 19% of cases the transition was driven only by decarbonization reasons, while in 17% of the studies the decarbonization goal was only one of the multiple drivers leading to the reduction of coal. The rest of our sample is lacking information regarding the reasons at the origin of the transition.

Almost all 19% of studies stating decarbonization as the only driver of the transition report specific information about climate policies adopted. Not surprisingly, due to the deleterious effects on health

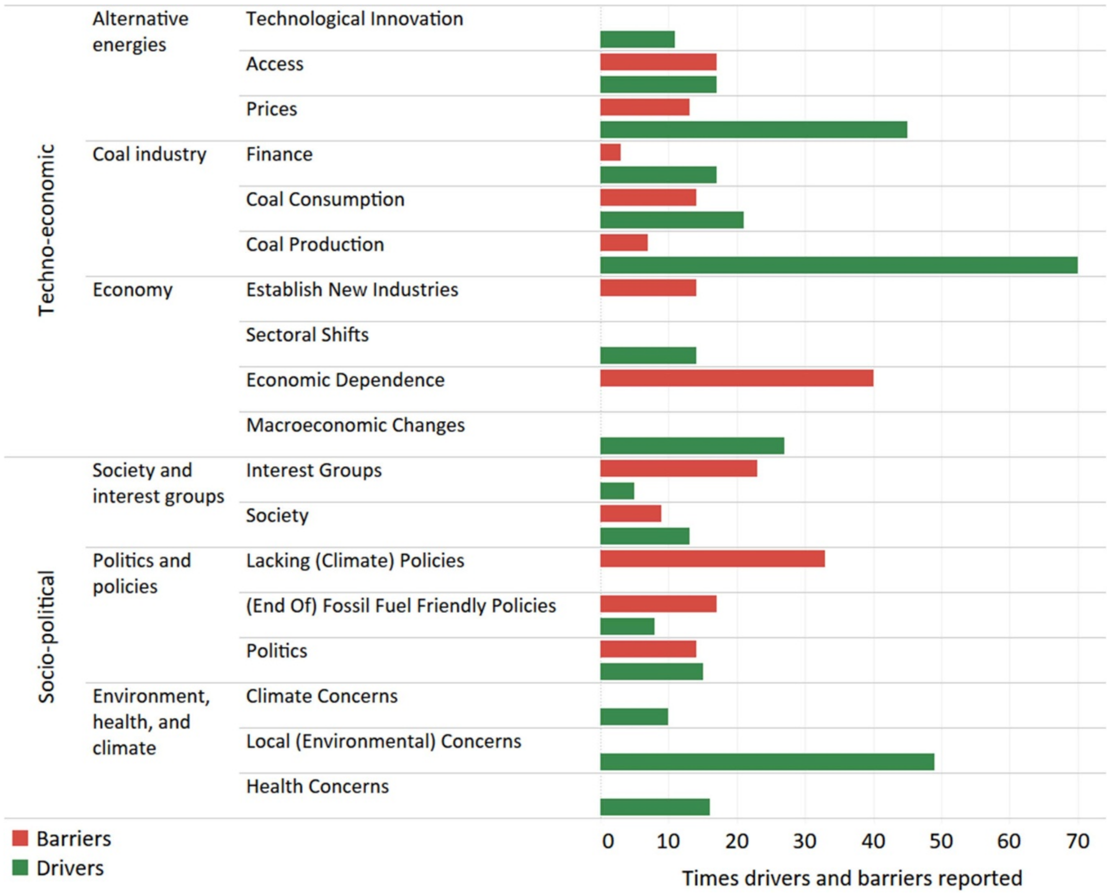

Figure 16. Drivers and barriers of historical coal transitions reported by the studies. Number of occurrences in the dataset.

associated with air pollution from coal mining and coal burning, several studies mention air quality regulation (see section 5.3 for a more detailed discussion) among the instruments used to decarbonize the system and encourage plants and mines closures or relocations (Goodman *et al* 2009, Song *et al* 2015, Culver and Hong 2016, Brinkman *et al*, 2017, Haggerty *et al* 2018, Zhang *et al* 2018).

Along the reason behind the transition, we also collected information on the specific drivers and barriers of coal phase-out reported in the studies. Ninety-two of the 278 evaluated case studies contain information on both drivers and barriers of the transition. Seventy-six studies contain information only on drivers, 16 only on barriers. Ninety-four of the 278 studies do not include any information on drivers and barriers. The reported drivers and barriers for coal transitions were clustered according to six domains. Three categories differentiate the *techno-economic aspects*: alternative energies, coal industry and economy. Additional *socio-political aspects* mentioned within past coal transitions are grouped in society and interest groups, politics and policies and environment, health and climate (figure 16).

The development and existence of alternative energies (other fossil fuels as well as renewables) is an important driver for coal transitions. Reduced prices for alternative energies (relative to coal) are mentioned in 45 studies, followed by access to new supplies (17) and technological innovation (11). The lack of access and too high prices consequently are also identified as barriers in some studies. Quite surprisingly, no study explicitly mentions energy efficiency among drivers and barriers.

Aspects related to the coal industry itself are more often reported as drivers than as barriers to coal transitions. Drivers concerning coal production, especially high production costs, are the most frequently mentioned driver occurring in 70 studies. Other drivers are coal consumption related aspects, such as aging coal power plants (21 times mentioned) and financial aspects (17). Barriers related to the coal industry are, for instance, cheap coal imports and capital investment towards modernization and mechanization at existing collieries. Regarding the economy, there are more barriers mentioned than drivers. Economic dependence on the coal industry in coal producing regions is the single most cited barrier to coal transitions, occurring in 40 studies. The territorial isolation of coal regions or the difficulty in adapting the professional capabilities of miners to new jobs hinders the establishment of new industries, which is mentioned in 14 studies as a barrier. Sectoral shifts are mentioned as economic drivers for the transition, such as the reduction of heavy industry or service sector growth.

Besides the presented *techno-economic aspects*, there are many *socio-political aspects* which deeply influence coal transitions. Regarding society and interest groups there are more barriers than drivers mentioned, such as the power of the fossil fuel industry and miners' unions (reported in 23 studies). Other societal aspects hindering a transition are, among others, identity related to coal or a missing public debate about coal phase-out.

Regarding politics and policies, several barriers are mentioned, such as lacking (climate) policies on the regional or national level (mentioned in 33 studies). Fossil fuel friendly policies, as for example subsidies or coal-oriented research money, are reported as barriers to a coal transition in 17 studies. The end of these policies is stated as a driver in eight studies. Other drivers related to politics are, for example, a change in government or geopolitical changes, such as the collapse of the Soviet Union. Specific policy instruments, which are of course drivers of coal transitions, too, are evaluated separately in section 5.3. Lastly, further drivers of coal transitions are environmental, health and climate concerns. Local environmental concerns, such as air pollution problems, are far more often identified as drivers than climate concerns (reported for 49 and 10 studies, respectively). In 16 studies health concerns, especially for local communities, are reported as drivers.

Summarizing, *techno-economic aspects* regarding the competitiveness of coal in relation to alternative energies are rather drivers of coal transitions. Falling prices for alternative energies and rising production costs in many coal-producing countries drive the transition. The main economic aspects hindering the transition are the economic dependence of many coal-producing regions on the coal industry. *Socio-political aspects* regarding politics and interest groups are more often mentioned as barriers to the transition than as drivers, such as the pro-coal lobbying of powerful incumbents and the lack of effective structural and climate policies. Still, local environmental concerns, especially regarding air pollution and growing public support for renewables, are *socio-political aspects* which drive coal transitions.

Overall, studies mentioning drivers cover 24 countries. Despite a large heterogeneity, some patterns can be identified. First, climate, environmental, and health concerns are mentioned as drivers of the transition consistently across countries and periods, in 16 over the 24 countries and for transitions happening across most time periods. Second, we observe that, while drivers for the United Kingdom and Germany are more diverse and spread along different categories, for the United States three quarters of the drivers are related to competition from alternative energies. For China, instead, most of the drivers (50%) are in the categories of health and environmental concerns. Third, the few studies covering Eastern European countries show, unsurprisingly, some similarities: they mostly mention, among the drivers, sectoral shifts, reduction of fossil fuels friendly policies, the collapse of the Soviet Union and the shift to market economy. In addition, studies on Poland and Czechia also mention several times the high coal production costs. Barriers are mentioned for 18 countries. The ones that are mentioned more consistently across countries are interest groups (nine countries), potential negative employment impacts (mentioned in eight countries), fossil fuel friendly policies (mentioned in seven countries and on the global level).

This analysis prompts further discussion on the distribution of these drivers and barriers over time, across countries, and on their correlations. Looking for example at the barrier 'establish new industries', which is mentioned in 14 studies, data for the United States (four studies) and the United Kingdom (four studies) show some differences. The studies on the United Kingdom tend to focus more on the long-term effects of the coal phase-out, which to a large extent already took place in the 1980s (at least with regard to mining). Even many decades after the closure of the mines, it is sometimes difficult to settle new industries in former coal regions, due to the poor design of the phase-out at that time (Fothergill 2017, Merrill and Kitson 2017). Studies on the United States are, in comparison, relatively recent and have a stronger regional focus (especially on Appalachia), as the phase-out process is still on-going (Culver and Hong 2016, Baker 2018, Sheldon *et al* 2018). Another example where a closer look into time frames and places might be interesting is the driver 'climate concerns'. In all ten studies where these concerns are mentioned as a driver, the observation period extends into the 2000s. As stated before, in these studies there is no clear country-specificity: Asian, European and American countries are represented. In three of the ten studies, local environmental concerns appear as drivers alongside climate concerns (Ohno *et al* 2011, Stala-Szlugaj 2016, Zhang *et al* 2018).

To conclude, the results presented here might be empirical material to test the arguments in the introduction on the difficulties to phase-out coal. The drop in profitability of coal power generation and production compared to its alternatives is reported much more frequently than its supposed affordability and the obstacles connected with its replacement (see coal production, coal consumption, and prices as drivers versus as barriers in figure 16). The second argument mentioned in figure 1—that coal infrastructure is often new and therefore coal is difficult to replace—is also rarely mentioned in the studies. However, regional economies' dependence on coal is frequently reported (see barrier economic

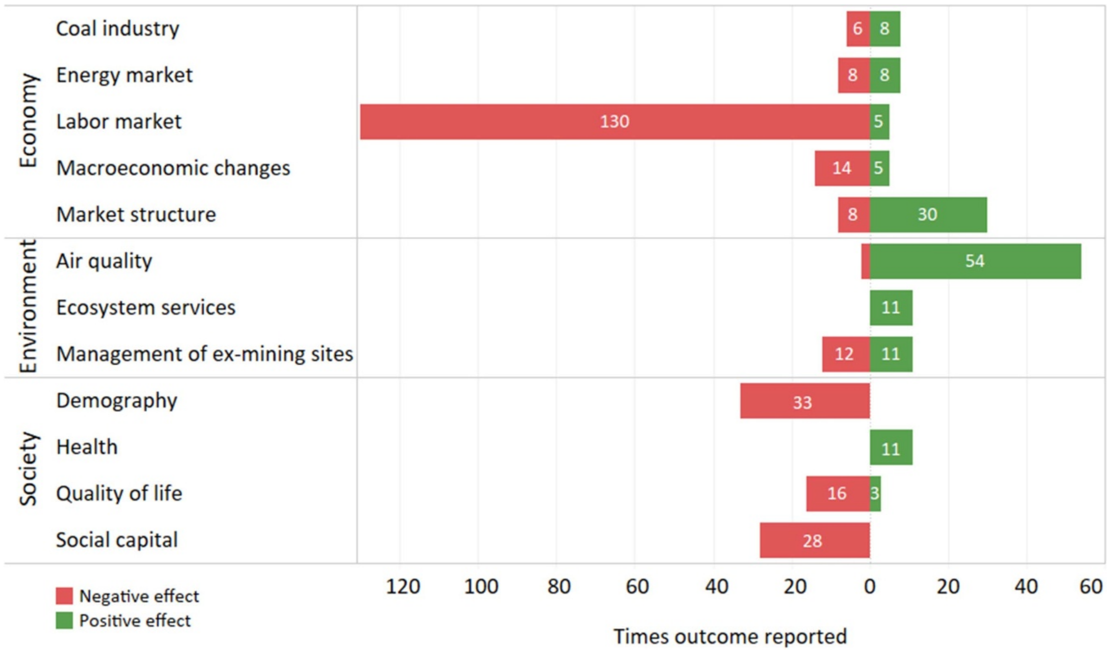

Figure 17. Outcomes of historical coal transitions reported by the studies. Numbers of occurrences in the dataset.

dependence mentioned in 40 studies), as well as the lobbying power of the coal industry. Interest groups in favor of coal are mentioned 23 times, whereas interest groups working against coal are only mentioned in five studies.

5.2. Social, economic, and environmental outcomes

One hundred and sixty-seven studies (60% of our sample) report at least one outcome—positive or negative—associated with the coal transition. We grouped the outcomes in three overarching areas: environment, society, and economy. We further classified outcomes in each of these areas in categories and distinguish between positive outcomes (i.e. beneficial effect) and negative outcomes (i.e. adverse effect).

Most of the reported outcomes fall in the economic category (figure 17). In this category, we observe a majority of negative effects mainly driven by the detrimental impact of the transition on the labor market in terms of job losses and increase in the unemployment rate, as reported in half of the studies. While some studies find an overall decline in employment in coal regions, others report only negative sectoral effects (reduced number of workers in coal plants, reduced employment in the coal mining sector or in the coal industry). Only four studies mention positive effects on employment for the United Kingdom (Pattison 2004), the United States (Haerer and Pratson 2015, Taber *et al* 2015), and Canada (Reitenbach 2013). Haerer and Pratson (2015) specifically mention an increase in the number of employees in the rest of the electricity sector. This is in line with recent evidence underlying the great potential of renewable energies in creating new job opportunities in the power sector, with large net gain in employment and greater socioeconomic benefits compared to conventional energy technologies (Ram *et al* 2020). Nevertheless, even if the negative effects of coal plant closures can be totally offset in the power sector, the impact on the overall employment in coal regions due to mine closures and outmigration remains a crucial aspect of coal transitions.

A final note on the impact of transitions on the labor market concerns the quota of female employment. Substitution effects in the sex composition of the labor force in coal regions have been in place. Even if we find evidence of labor relocation effects among genders only in two studies (Deasy 1965, Aragón *et al* 2018), we think it is important to disentangle the different dynamics at work and understand changes in the structure of the labor force when analyzing an increase or decrease in employment. In the case of coal transitions, we observe effects pointing in different directions. In some cases, we observe a reduction in the presence of women in the workforce composition of coal regions, mainly explained by the fact that male workers, previously employed in the coal sector, have replaced women in other sectors, in particular in manufacturing. In other cases, the portion of the female labor force in the coal region increased, as mine-based job opportunities for males declined.

On a related topic, we observe reports of outmigration of skilled and young labor or mining specialists. Closure of mines, in some cases, triggered a spiral of job losses and led to a significant demographic shrinkage in coal regions. We listed decline in population and outmigration of labor force among the social outcomes (demography category) but of course the two topics are deeply intertwined.

Beyond labor market effects, the economic outcomes of coal transitions include macroeconomic effects, market structure effects and specific effects on the energy market and on the coal industry. From a macroeconomic perspective, we find negative impacts on GDP (mainly at subnational level) due to industrial downturn, large decline in production, and economic stagnation. Some studies also report negative effects on public finances, due to a significant reduction of public revenues (Andrews-Speed *et al* 2005, Mayer 2018c) and mine closure costs (Sheldon *et al* 2002). Regarding market structure, it is worth noting the positive effects arising from the transition. We observe increases in the degree of diversification of the economy and the expansion of sectors like renewable energy, manufacturing, and tourism. The degree of initial dependence on mining has an inverse relation with the development of the service and trade sectors. Looking at the impact of the transition specifically on the coal industry, previous literature reports outcomes pointing in different directions. We find evidence of improvement in the degree of productivity of this industry (see e.g. Hudson 2002, Cao 2017), as well as bankruptcies (Rui 2005, Littlecott 2016a), increasing levels of debt (Suchacek 2005), or decreased profits for coal companies (Littlecott and Schwartzkopff 2015).

Focusing on the energy market, we can observe price effects, in particular increased coal prices and increased electricity prices. Among the other effects, studies report a decreased risk of supply shortage due to miners' strikes (Melsted and Pallua 2018), technological innovations (Union of Concerned Scientists 2017), and decrease and shift of R&D and capacity from the coal sector toward other energy sectors (Parker and Surrey 1995, Pouran 2018).

Looking at social outcomes, we mostly observe negative effects. Several studies mention an overall decline in the quality of life, due to worsening living conditions (Davies 1984, Winterton 1993, Hudson 2002, Tomaney 2003, Sun *et al* 2009, Rečková *et al* 2017, Merrill and Kitson 2017) growing poverty (Marley 2016, Ebke 2018), and a decrease of municipal and social services (Haney and Shkaratan 2003). Negative effects on social capital, with loss of individual and community identity and changes in social status, and loss of aggregation spaces due to the closure or dislocation of towns and municipalities, highlight the need to rebuild imagined futures. The only positive social outcomes are reported by studies looking at the health effects of the transition. Not surprisingly, we find evidence of reductions in mortality (Goodman *et al* 2009) and morbidity (Danek 1995, Parker and Surrey 1995, ILO 2015) with a decrease of deaths due to cardiovascular and respiratory diseases (Skorkovsky and Kotesovec 2006). Coal combustion releases SO_2 and nitrogen oxide (NO_x), which are major contributors to lake- and forest-damaging acid precipitation and leads to the development of tropospheric ozone and small particles that damage human health (Holdren *et al* 2000). At the high end of the range, the estimated health costs related to fossil fuel power plant pollution approach $700 billion each year (Katsouyanni and Pershagen 1997, Delucchi *et al* 2002, Romieu *et al* 2002).

Environmental outcomes are mostly positive. A large number of studies report air quality effects. Among them only two studies report a negative effect on air quality, due to the presence of mine water emissions (Brown *et al* 2002) and of increased methane emissions (Howart 2020). The rest of the studies highlight reductions in CO_2 emissions, SO_2 emissions (Parker and Surrey 1995, Zhang *et al* 2018) and black smoke (Goodman *et al* 2009) or mention overall emissions reduction in the electricity sector and/or a general improvement of air quality. Some of the studies consider relative measures, like the decrease in carbon intensity (Littlecott and Schwartzkopff 2015) or the decrease in CO_2 per capita (Sovacool 2013).

Looking at the environmental effects related to the management of ex-mining sites, we find negative geological effects related to the safety of the sites (mine gas leakage leading to explosion, large amount of underground spaces causing ecological and safety risk, instability of the groundwater system) and positive effects related to landscape interventions: utilization of natural capital, restructuration of residential areas, and higher degree of landscape diversity. Regarding restoration interventions we have mixed evidence. We have studies reporting good remediation intervention together with studies that testify slag heaps, decline of collieries, absence of rehabilitation interventions.

Outcomes are reported for 26 countries. Regarding their distribution, we find that for the United Kingdom there is a balance between the economic and social outcomes reported, which strongly outnumber environmental outcomes. Studies for the United States mostly report economic outcomes, while studies for China focus on environmental ones. Sixty-three percent of the studies reporting rising unemployment focus on the United Kingdom, United States, and Germany but the evidence is consistent across the sample (job losses are reported for 19 countries). The beneficial effects on air quality are also reported for several countries (12). Negative effects on social capital appear to be common as well in different transitions (17 countries). Finally, regarding temporal trends, it is worth mentioning evidence of protests, social tensions, and conflicts (11 countries), mostly from supply-side transitions starting in the 90s and earlier.

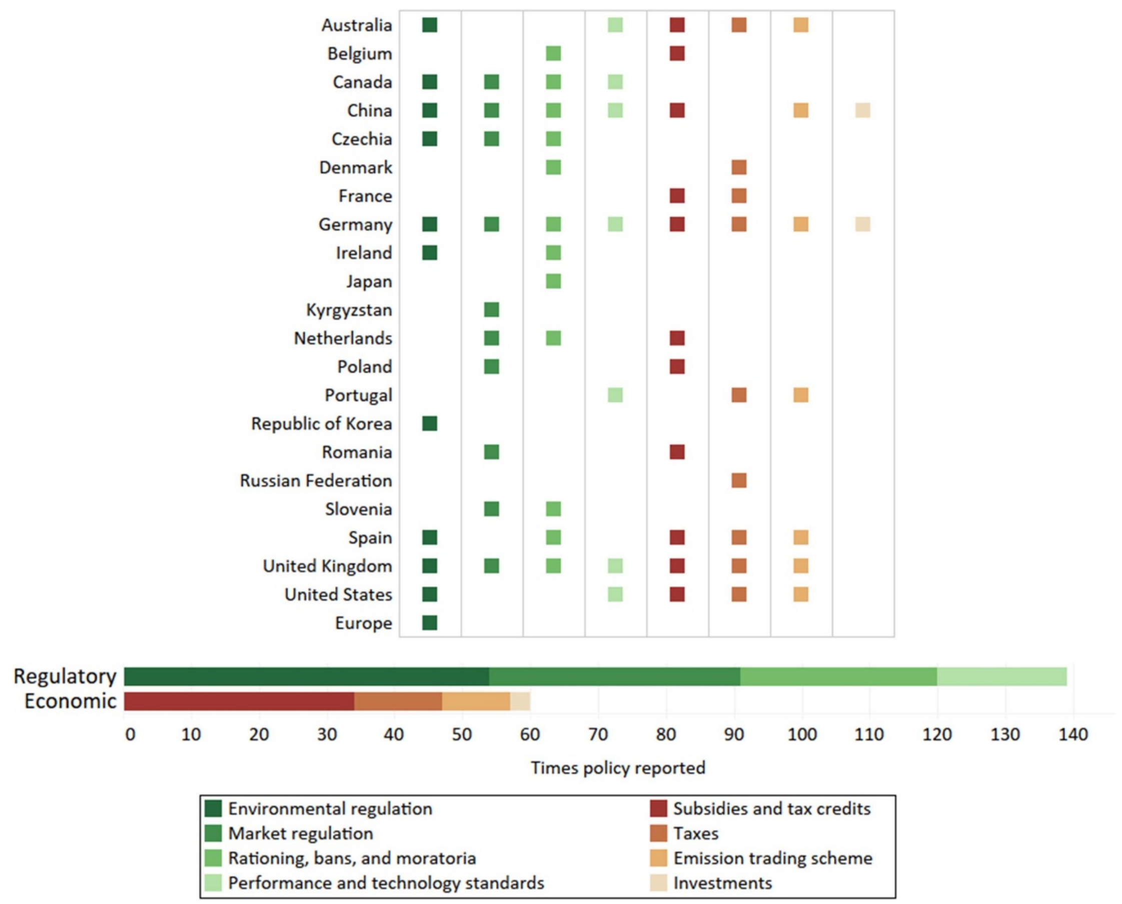

Figure 18. Transition policy categories: country coverage and number of occurrences in our dataset. Note: the categories include all policies that the original studies reported to be explicitly designed to drive the transition, or that unintentionally generated/accelerated the transition.

5.3. Policy instruments

We collected information on policies indicated by the original studies to be either at the origin of the coal transition (henceforth *transition policies*) or adopted to deal with the transformative processes induced by it (*management policies*).

5.3.1. Transition policies

One hundred and thirty-six studies in the dataset (49% of the sample) report at least one transition policy and, among these, 73 studies identify more than one policy. Studies mentioning transition instruments cover 21 countries, mostly located in the Global North. This could be explained by the lower number of studies focusing on the Global South, as well as by less experience and capacity of these countries in enabling coal transitions.

Looking at the range of policies listed in the studies, we find a predominance of regulatory instruments (70%) against economic instruments (30%). We can also observe that the only countries in our dataset for which only economic instruments are reported are France and Russian Federation (figure 18).

We group both regulatory and economic instruments in four different categories. *Environmental regulation*, in particular air quality regulation, plays a major role in the list of regulatory instruments. This category includes both policies set at the national level and some of the European Union policies on climate and energy. Several studies mention how the coal phase-out has been the result, or has been strongly accelerated, by broader strategies aimed at reducing air pollution. The Clean Air For Europe (CAFE) program is a notable example. It was launched in 2001 by the European Union, to assess the economic and environmental impacts of air pollution legislation and guide the development of future policy proposals and objectives to improve air quality in Europe. The goal of the program is the development of long-term, strategic and integrated policy advice to protect against significant negative effects of air pollution on human health and the environment (European Commission 2001). The broad perspective adopted in combining economic, environmental and public health considerations in a unified strategy had pushed European countries to consider and implement coal phase-out plans adopting a multi-objective approach. Moreover, the legal constraints introduced via air pollution regulation in many cases pushed older plants out of the market, as was the case in the United Kingdom where retrofitting these plants to comply with the regulation resulted uneconomic and led to the decision of closing them.

Market regulation is characterized by privatization and nationalization of the coal industry, industrial regulation, public and private partnership, and liberalization of the coal and electricity market. Privatizations seem to have played a major role in driving coal transitions, given their high occurrence (10% of the studies mentioning transition policies). All measures aimed at limiting production quotas, consumption quotas, ban on marketing and sale of coal, and moratoria on mines and on plants are summarized in the category *rationing, bans and moratoria*. Finally, among the *performance and technology standards* category, we find emission and renewable portfolio standards.

Among the economic instruments the category with the highest number of occurrences is the *subsidies and tax credits* category. It includes subsidies of different nature as well as investments and renewable energy tax credit. The *taxes* category includes, among others, carbon taxes, with an occurrence (4% of the studies) slightly lower than *emission trading schemes* (7%). Finally, the category *investment* includes both investment projects in natural gas and investments in R&D.

Summarizing, regulation has been the most adopted policy approach to directly and indirectly drive and foster coal transitions. Environmental regulation to reduce air pollution has played a dominant role in a large set of countries, suggesting an increasing awareness of the policymakers on this issue. This finding is consistent with the results in section 5.1, where local environmental concerns are listed among the major drivers of the transitions, and the results presented in section 5.2, which highlight the beneficial effects of the phase-out in reducing air pollution. The prominence of market regulation reflects the strong economic and political transformations most of the countries undertook around the 80s and 90s, period in which we observe the great wave of supply-side transitions (see section 4). The use of economic instruments of different types is instead more recent and mostly used to incentivize the switch from coal to renewable energies in support of the low-carbon transition. This is in line with the reduction in coal consumption observed in many countries in the last 20 years. These results suggest that the policy landscape has evolved along the different nature of coal transitions and the transformation of energy, economic, and socio-political systems.

5.3.2. Management policies

Ninety-two studies mention management policies, with 52 studies reporting more than one intervention. Evidence on management policies spreads over 17 countries. We group the strategies adopted as response to the impacts of coal transitions into two types: (a) strategies aimed at restoring the mining sites and reshaping the surrounding landscape and (b) strategies coping with the economic and social costs of the transition (figure 19).

The first type of interventions includes afforestation and re-naturalization plans, as well as actions to guarantee the safety of the area and the removal of waste and residuals from the extraction activity. Mining is extremely damaging to the environment not only in terms of exploitation of the site and loss of vegetation and of biodiversity, but also in terms of soil contamination, geological instability, and gas migration to the surface. Impacts on water are also severe. Mountaintop mining with valley fill operations (MTVF) in the Appalachian region of the United States has so far converted 1.1 million hectares of forest into surface mines and buried more than 2000 km of freshwater streams and rivers (Bernhardt and Palmer 2011).

Within our sample of literature, many studies emphasize how the management of former mining sites is one of the greatest challenges to be faced in relaunching the territory. The management of these sites should be carried out according to protocols able to guarantee the complete reclamation of the area based on safety and environmental standards. Restoration costs could be borne by coal companies, the State, or both.

If restoration is the first step in bringing environmental renewal to coal regions, spatial planning policies are likely the second. Among the policies mentioned by the studies we find urban sprawl control and village relocation (Wirth *et al* 2018), and resettlement of former mining villages (Pattison 2004). Clearly, the nature of these interventions is extremely context-specific and deeply connected with the infrastructure system and the economic development plans of the area.

The second type of interventions comprises a broader set of socioeconomic policies. Investment strategies play a major role here. Studies in our sample mention different categories of investments: regeneration activities, investments in infrastructure, education, and technology and R&D (Greenpeace 2016, Sheldon *et al* 2018), as well as investments in nuclear programs (Turnheim and Geels 2012). Financial aids and compensation policies are also mentioned several times. We classified them according to the recipient: policies targeting coal regions overall (support for business projects, social cost grants, energy bill assistance programs), workers (retirement incentives, lump sum financial packages, subsidies, revenue replacement), and coal industry (government taking the main share of rehabilitation costs, subsidies for closing plants or mines, mine liquidation, redundancy payments, deficiency grants, grants for future concessionary coal provision). Financial compensations to workers are among the most reported policies

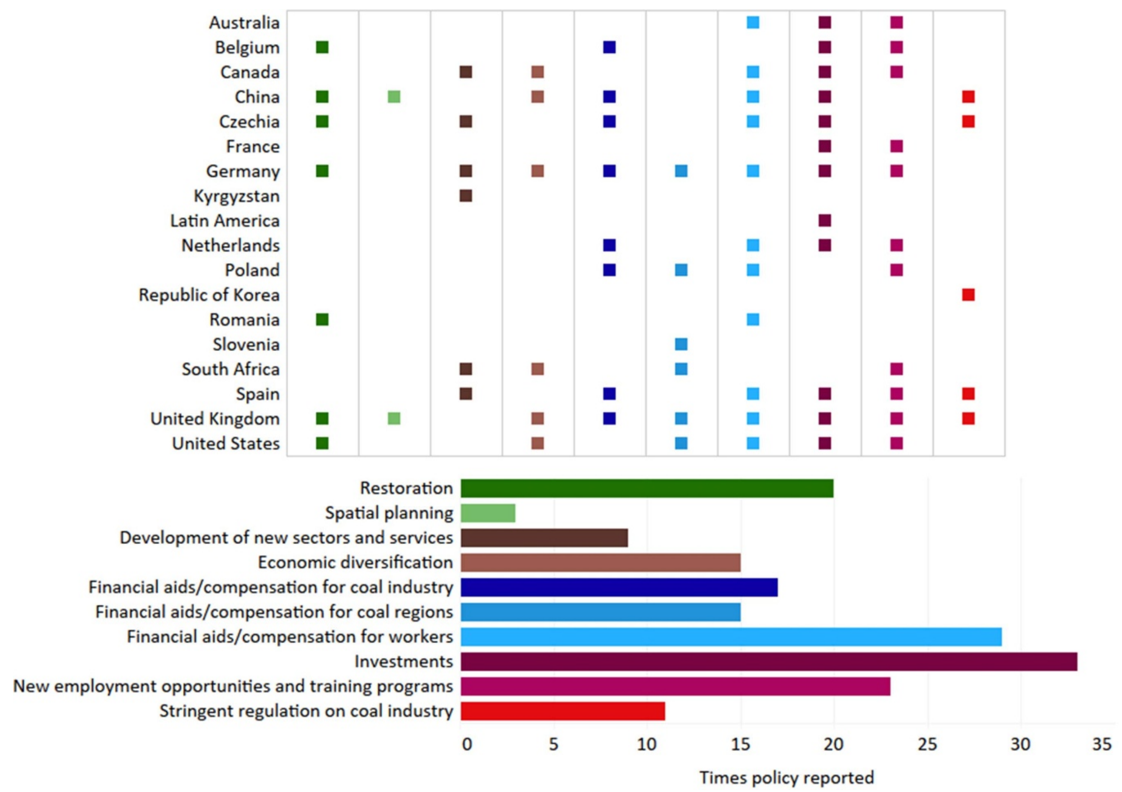

Figure 19. Management policy categories: country coverage and number of occurrences in our dataset. Note: management policies categories include all the policies that in the original studies are reported to be used to deal with the transformative processes induced by the coal transition.

(they are present in 32% of the studies mentioning management policies).

Employment seems to be a very sensitive issue as well for the successful management of the transition. This is confirmed by the fact that, beside financial aids, studies explicitly mention policies aimed at providing new employment opportunities and training programs (see e.g. Greenpeace 2016, Sheldon *et al* 2018). Finally, part of the literature emphasizes the role of economic diversification and policies aimed at reducing the dependency on the coal industry and helping the development of new sectors and services like tourism (Wirth *et al* 2018), for example through the reconversion of mining sites in museums or industrial cultural sites (Nel *et al* 2003).

From the analysis of management policies reported by our case-studies the following key messages arise. While transition policies are linked both to supply-side and demand-side transitions, management policies, in their wide spectrum, are mostly used to address the side effects of mine closures. This confirms that coal transitions are particularly challenging for coal regions, which rely on coal production and build a social, economic and spatial identity around mining activities. Management policies, in the past, have followed a double approach: compensating the losers while providing new economic opportunities via investment policies. Many interventions and programs focused on workers, confirming local unemployment as a source of major concerns for policy makers.

6. Discussion and conclusion

The paper provides a systematic map and review of coal transition literature based on a dataset of 278 case studies. Our dataset covers 44 countries and the majority of documented transition episodes range from the end of the 19th century until 2021.

Before discussing the results and implications of this study, it is important to acknowledge some limitations of our approach. First, all publications included in the dataset are written in English. The lack of evidence for some countries may be partially due to the language criterion adopted in this study. This might be especially true for national studies examining coal transitions in the Global South and post-socialist states. Limiting the analysis to English publications clearly excludes all grey literature and journal articles written in other languages. This also contributes to explaining the abundance of recent research outputs in the dataset, as English is increasingly becoming the *lingua franca* of scientific research. Second, we included all the studies mentioning a decline in production and consumption without any constraint on the duration, the speed, and the absolute or relative nature of the decline. The results should be interpreted with caution, in particular for countries with no reported evidence of absolute declines of coal production/consumption. Our target was to be as inclusive as possible, nevertheless, this heterogeneity in the scope and nature of the studies complicates comparison attempts, especially between countries. Third, our machine learning approach for identifying relevant literature from our broad query cannot guarantee a comprehensive coverage of all existing literature. However, screening of remaining documents suggested that we reached a fairly high recall of relevant studies.

Our first finding is that the literature on coal transitions is in large part relatively recent and it is increasingly expanding. Most of the studies covering transitions happening long ago have appeared in the last 20 years, while pre-1990 studies tend to focus on transitions closer to the publication date. We find that the majority of the studies documenting supply-side transitions focus on the 80s and 90s when increasing globalization increased trade and competition. Studies addressing demand-side transitions mostly focus on either very old (switching to oil) or very recent (switching to gas or renewables) transitions. Overall, the increase in the number of publications denotes a growing attention to the topic that could partially reflect the current debate on the need of a coal phase-out to reach the climate goals, a debate that clearly goes beyond studies based on scenarios analysis and policy forecasting provided by models alone.

The second finding of our study is that, while the literature on coal transitions covers a large set of countries around the world, it has mainly developed around a few countries. Almost half of the literature refers to transitions in the United Kingdom, the United States, and Germany. The strong focus on these countries is reflected in all the political economy dimensions of our analysis. In this sense, the results provided by our map could be considered fairly representative of the transition landscape of the aforementioned countries but could not necessarily prove to be robust for other (less researched) countries. The identified knowledge clusters (focusing on different time periods and subnational regions) map and represent quite well the main characteristics of the historical transitions in all three countries. Regarding the United Kingdom and Germany, the amount of studies also reflects the relevance of the coal phase-out topic in the political and public debate. We find, as well, a consistent number of studies covering China. However, as expected given the unique characteristics of the coal industry in this country, there are significant differences from the knowledge clusters above. The evidence mostly reports relative reductions in coal use and episodes of mine or plant closures due to coal industry restructuring, safety, and environmental reasons. These do not always translate to absolute declines, as was, instead, the case for Germany, the United Kingdom, the United States, and other countries in our dataset. Moreover, several studies describe city-scale transitions that do not reflect broader coal trends in the country. The large amount of studies focusing on China reflects its relevance in the worldwide energy market and the problems connected with coal management in the country.

The third result of our map points in the direction of literature gaps. By looking at countries that steadily reduced their coal dependency from a country-specific peak year, we identify a clear lack of evidence for Japan, Kazakhstan, Russia and for some Eastern European countries, like Romania and Ukraine that, from the end of the 1980s onward, experienced steady large coal declines. Our map includes, as well, little evidence for France and Spain. A reason for this might also be less (accessible) data in comparison to the United Kingdom, the United States, and Germany. Finally, there is a general lack of evidence for the Global South and developing economies. Little is known about the political economy of (potential) coal transitions in low- and middle-income countries and countries that are currently still investing in coal. A growing research body highlights that investments into coal serve other development goals, such as providing cheap and reliable electricity, and are fostered by powerful vested interests (Jakob *et al* 2020a). Finally, most research on coal transitions focuses on formal workers. The coal industry, and its potential decline, however, also has major (positive and negative) effects on informal workers, especially within the Global South. The lack of policy instruments documented for developing economies could be explained by the lower number of studies or by the lesser extent of impact or less capacities to enable and manage a transition.

A fourth evidence arising from our analysis is that there are studies reporting both supply and demand transitions for all countries that have been succeeding in significantly reducing their coal dependency compared to historical trends, as testified by data on coal production and consumption. Among these countries we find Canada, Czechia, Germany, Poland, the United Kingdom, and the United States. According to our sample, in these countries the transition away from coal relies on a combination of demand and supply interventions, often accompanied by a mix of transition and management policies. Examples in the opposite direction are provided by Australia, Japan, and the Republic of Korea. In the first case we have studies only on demand side transitions. Australia is reducing its dependence on coal in the electricity sector but remains one of the main coal producers and exporters worldwide. On the opposite side, Japan and the Republic of Korea closed their coal mines but this increased their reliance on coal imports to satisfy the domestic demand. Historical transitions and current trends suggest that interventions concurrently targeting supply and demand are more effective in achieving a proper phase-out.

From the analysis of different political economy dimensions carried on in the paper three main results arise. First, managing structural change and enabling a 'just transition' are at the very core of coal transitions and they should be a focal point for policy interventions. At the same time, as the examples of the United Kingdom and Germany in the 1980s and in the 1990s after the reunification show, examined policy interventions were not able to prevent structural breaks. Supply-side transitions (as these two) are particularly challenging for the territories, both from an economic and social point of view. The structural change required by the closure of mines is a key topic, as testified by negative effects on the labor market identified as the most common outcome reported by the studies for a large set of countries. Strictly connected with the problem of job losses are demographic shrinkage and outmigration that coal regions involved in previous transitions have experienced (Spencer *et al* 2018). Avoiding social and economic dislocation phenomena is strictly related to the capacity of policymakers of providing labor opportunities alternative to the coal industry to people in the affected jurisdictions. Several studies also mention the loss of identity, social capital, and social values as results of the transition. The main question for local and national policymakers is, thus, 'What new and different positive future are we proposing to coal regions?' The answer goes beyond providing financial aids and compensation schemes to regions, industry, and workers. Key challenges also include promoting a new identity for a region by investing in new sectors and activities, diversifying the economy, and offering sustainable long term alternatives. It also improves the social acceptability and legitimacy of coal phase-out operations.

Local job loss is very important, as it reduces income opportunities and compromises the local identity as (former) key actors in the energy system. However, it should not be interpreted as general economic decline or employment loss. Most case studies limit employment observations to the local setting and remain focused on the coal sectors and the coal region. Counterfactual investments into renewable energy, however, may easily overcompensate losses on a macro-economic national level (Ram *et al* 2020).

Additionally, among the most frequent positive outcomes of coal transitions are health benefits. Public health impacts of coal, across extraction, processing, use, and waste disposal, are largely documented in literature pertaining to several fields (Hendryx *et al* 2020). Consistently, our studies report significant reduction in mortality and morbidity, with health effects being the dominant co-benefit of coal phase-out policies. This is in line with recent scenario evidence. Recent model studies find that, if undertaken cost-effectively, health and environmental co-benefits outweigh the policy cost of a coal phase-out (Rauner *et al* 2020) and that informed decisions about power-plant dispatches and retirements should consider both air pollution and climate externalities (Strasert *et al* 2019). A final consideration must be made on the asymmetrical health effects of coal. Partly due to the fact that most of the coal consumption by domestic households takes place in developing countries, the harmful effects impact lower socioeconomic strata the most, strengthening the already existing health inequities (Grainger and Ruangmas 2018).

Previous literature shows that compensation schemes and various forms of investment and diversification policies have been extensively used to (in some cases less) successfully manage the transformative processes induced by the transition. It is also worth mentioning that soft location factors (e.g. care sector, health, education, culture, and leisure) can increase the attractiveness of former coal regions to avoid outmigration but also to attract new people. On these lines, observing the German experience in the near future might be able to tell us something more: a total of 40 billion dollars, proposed by the coal commission and decided upon by the parliament in the summer of 2020, will be invested in the German coal regions. To the best of our knowledge, a similar investment in (declining) coal regions is unprecedented. Looking at the United States, even if not yet officialized, the energy plan announced by the newly elected president Joe Biden includes large investments in clean energy and innovation and foresees specific interventions targeting communities and workers impacted by the changing energy market.

Second, even if different actors and categories can take an active role in facilitating the transition process, the main responsibility for fostering and managing the transitions lies with policymakers at different levels. The involvement of policymakers—and in particular of national-level policymakers—in facilitating the transition process has been mentioned in almost half of the studies. The main take-away message is that, even if coal transitions mainly impact subnational areas, a multi-level governance approach considering both national transition outlooks and local contextual factors is often necessary as subnational levels often lack sufficient financial means and expertise. Negative past experiences of insufficient support, causing structural breaks in the end of the 20th century in many Easter European countries, can increase fear, mistrust, and opposition against upcoming coal transitions (Stognief *et al* 2019, Brauers and Oei 2020).

Third, we find that past transition policies were mainly driven by regulatory instruments. These instruments present several advantages, not least the more limited political opposition they generally encounter compared to price instruments. In addition, the effect of regulatory instruments on specific industries (e.g. mining sites or power plants) is easier to predict and therefore eases softening the social and economic consequences.

However, phasing out coal must not result in locking in new fossil fuel dependencies. While the energy landscape in the past looked substantially different compared to the current one, where the alternatives provided by renewable energies are competitive and accessible, this is not necessarily true for all the countries. Using a combination of regulatory (emission performance standards, moratorium on new mines and plants) and market based instruments (carbon pricing) can avoid a shift toward other fossil fuels as a consequence of coal phase-out.

In addition to national and local instruments, it is worth thinking about the role of international climate policy, which should focus on both supply and demand channels for phasing out coal. On the supply channel, it will be key to incentivize countries and regions to reduce coal production (Harstad 2012, Asheim *et al* 2019). This could be done by using targeted financial transfers or subsidized loans that help to implement a long-term phase-out strategy with economic diversification. On the demand side, additional support for renewables, reducing subsidies for fossil fuels, and carbon prices can induce comprehensive fuel switching away from coal in the electricity sector. International climate policy can foster a rapid global coal phase-out when combining supply and demand side policies for major coal producers and consumers and at the same time preventing other countries from establishing new coal dependencies.

We conclude with some considerations on the feasibility of a future coal phase-out. In contrast to mitigation scenario results, the actual deployment of coal with CCS (Carbon Capture and Storage) has remained sluggish over the past decades. Only two projects have been realized so far, one of which has been stopped while the other is operating at a lower capacity than it was originally designed for (Global CCS Institute 2020). Without CCS, the future of coal-fired electricity generation is at best highly uncertain. This is evidenced by the 653 GW of coal power plant projects that have been scrapped between 2016 and 2020 (Global Energy Monitor 2020). Nevertheless, investments in coal infrastructure still abound in Asia and are growing in Sub Saharan Africa (Steckel *et al* 2020).

While scenario literature, synthetized in part 2 of this review (Minx *et al* 2022) suggests that an early coal phase-out is cost-effective and therefore needed in Paris-consistent mitigation scenarios, evidence based on existing literature suggests that there is a complex political economy at play, in particular when considering supply-side transitions. The good news is that coal has become less competitive in recent years, even faster than anticipated by nearly all models. The analyzed literature in this paper, however, shows that especially coal supply transitions can last several decades despite being uneconomic. Enabling a just transition for affected communities and people (through financial support schemes) and reducing the power of incumbents (through governance and regulation structures) is therefore needed to help speeding up the process (Spencer *et al* 2018). A prolonged global coal phase-out (compared to anticipated model runs) also implies that there is no time and CO_2-budget left for a potential low carbon bridge for natural gas—but instead a need to directly switch from coal to renewable technologies.

Data availability statement

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

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Appendix

Table A1. Regional coal transitions included in the map.

Region	Period	Production	Period	Consumption
Europe	1990–2014	Hard coal decline	1990–2014	% Hard coal decline in primary energy consumption % Hard coal decline in residential sector
Latin America	1912–1922	% Coal decline in primary energy production Coal production decline	1912–1922	% Coal decline in primary energy consumption Coal consumption decline

Table A2. National coal transitions included in the map.

Country	Period	Production	Period	Consumption
Argentina			1906–1946	% Coal decline in primary energy consumption
Australia			2005–2017 2005–2015	Plant closures % Coal decline in electricity generation
Belgium	1973–2000	Coal production decline	1973–1983 2016	% Coal decline in primary energy consumption Plant closures
Bulgaria	2017–2019	% Coal decline in primary energy production		
Brazil			1869–1956	% Coal decline in primary energy consumption
Canada	1997–2003	Mine closures	1990–2015 2005–2015	% Coal decline in electricity generation Plant closures
Chile			1906–1956	% Coal decline in primary energy consumption
China	1949–2016 1990–2000 1998–2002 2005–2015 2016–2017	% Coal decline in primary energy production Mine closures Mining companies closure Mine closures Coal production decline	1950–2017 2006–2015 2006–2016 2013–2020 2016	% Coal decline in primary energy consumption Plant closures % Coal decline in electricity generation Coal consumption decline New plant constructions cancelled
Colombia			1871–1956	% Coal decline in primary energy consumption
Costa Rica			1912–1948	% Coal decline in primary energy consumption
Cuba			1911–1946	% Coal decline in primary energy consumption

(Continued.)

Table A2. (Continued.)

Country	Period	Production	Period	Consumption
Czechia	1973–2019	Coal production decline	1990–1995	% Coal decline in electricity generation
	1990–2016	Lignite decline		
		Bituminous coal decline	1990–2004	% Coal decline in primary energy consumption
	1991–2001	Mine closures		
	1994–2002	Hard coal decline	1990–2016	Decline of solid fuels consumption
Denmark			1990–2011	Coal decline in CHP
			1997	Moratorium on new plants
Dominican Republic			1895–1948	% Coal decline in primary energy consumption
			1916–1948	Coal consumption decline
Ecuador			1910–1933	% Coal decline in primary energy consumption
			1912–1948	Coal consumption decline
El Salvador			1896–1936	% Coal decline in primary energy consumption
France	1940–2000	% Coal decline in primary energy production		
	1960–1973	Coal production decline	1960–1970	% Coal decline in electricity consumption
	1980–2000	Coal production decline		
			2009–2015	% Coal decline in electricity generation
Germany	1940–2000	% Coal decline in primary energy production		
	1950–2015	Hard coal decline		
	1980–2000	Coal production decline		
	1989–1994	Lignite decline	1989–1994	% Coal decline in primary energy consumption
			1990–1999	Plant closures
			1990–2017	% Coal decline in electricity generation
			2008–2013	New plant constructions cancelled
			2014–2016	% Coal decline in electricity generation
Guatemala			1904–1924	% Coal decline in primary energy consumption
			1916–1948	Coal consumption decline
Haiti			1890–1928	% Coal decline in primary energy consumption
			1912–1948	Coal consumption decline
Honduras			1908–1932	% Coal decline in primary energy consumption
			1892–1948	Coal consumption decline

(Continued.)

Table A2. (Continued.)

Country	Period	Production	Period	Consumption
Italy	1940–2000	% Coal decline in primary energy production		
			2016	Plant closures
Japan	1953–1996	% Coal decline in primary energy production		
	1954–1992	Mines closure		
Republic of Korea	1980–2010	Mine closures		
	1986–2007	Coal production decline		
Mexico			1904–1948	% Coal decline in primary energy consumption
Netherland	1940–2000	% Coal decline in primary energy production		
	1948–1973	Coal production decline		
	1965–1973	Mine closures		
			2015	Plant closures
Nicaragua			1892–1930	% Coal decline in primary energy consumption
			1928–1948	Coal consumption decline
Peru			1894–1948	% Coal decline in primary energy consumption
Poland	1977–2015	Hard coal decline	1970–1991	% Coal decline in primary energy consumption
		Hard coal mine closures		% Coal decline in final energy consumption
	1990–2002	Mine closures	1990–2005	% Coal decline in electricity generation
	1990-2006	Coal production decline	1990–2014	% Hard coal decline in primary energy consumption
			2016	Plant closures
Portugal	1940–1990	% Coal decline in primary energy production	2003–2019	% Coal decline in electricity generation
Romania	1989–2005	Mine closures	1989–2005	Plant closures
	2017-2019	% coal decline in primary energy production		
Russian Federation	1988–1997	Coal production decline		
	1990-1998	Mine closures		
Slovenia	1978–2012	Coal production decline		
South Africa	1990–2000	Mine closures		
Spain	1940–2014	% Coal decline in primary energy production	2014–2019	% Coal decline in electricity generation
	11980–2014	Coal production decline		
	1986–2009	Mining companies closure		
Sweden	1940–2000	% Coal decline in primary energy production		

(Continued.)

Table A2. (Continued.)

Country	Period	Production	Period	Consumption
United Kingdom	1900–2015	Mine closures	1642–1646	Disrupted coal trade
	1913–2017	Coal production decline	1850–2000	% Coal decline in primary energy consumption
	1930–2000	% Coal decline in primary energy production	1950–2016	% Coal decline in electricity generation
	1959–1965	Decline of coal industry		
	1960–2016	Mining companies closure	1955–1959	Coal gas demand decline
	1970–2003	Decline of coal industry	1957–1973	Coal consumption decline
	1980–2005	Hard coal mine closures	1960–1967	Improvement in coal burning efficiency
			1970–1990	Plant closures
			1981–1985	Coal consumption decline
			1990–2014	% hard coal decline in primary energy consumption
				% hard coal decline in residential sector
			1990–2016	Coal consumption decline
			2012–2016	Plant closures
United States	1917–1939	Hard coal decline	1957–1960	Coal consumption decline
	1950–1960	Coal production decline	1985–1992	Coal consumption decline
		% Coal decline in primary energy production	1987–2018	% Coal decline in electricity generation
	1985–2019	Coal production decline	2003–2018	Plant closures
	1985–2014	Mine closures	2007–2012	New plant constructions cancelled
	2000–2010	Decline of coal industry	2005–2016	% Coal decline in electricity generation
			2001–2017	Coal consumption decline
Uruguay			1912–1948	% Coal decline in primary energy consumption
				Coal consumption decline
Venezuela			1891–1950	% Coal decline in primary energy consumption

Table A3. Subnational coal transitions included in the map.

	Period	Production	Period	Consumption
Eisenerz (AT)	1980–1990	Mine closures		
Hunter Valley (AU)	2015	Mine closures		
Campine (BE)	1990–1992	Mine closures		
Limburg (BE)	1966–1992	Mine closures		
Alberta (CA)	2015–2018	Mine closures	1987–2015	Plant closures
Cape Breton (CA)	1950–1990	Mine closures		
Ontario (CA)	2003–2011	% Coal decline in primary energy production	1997–2015 2003–2011	Plant closures % Coal decline in electricity generation
Shanxi (CN)	1997–2009 2006-2011	Mine closures Coal production decline	2006–2010	Plant closures
Bohemia (CZ)			1990–2016	% Coal demand for heating decline
Northwest Bohemia (CZ)	1990–2016	Hard coal mine closures		
Petrvald (CZ)	1963–1998	Coal production decline		
Central Germany (DE)	1991–2018	Coal production decline		
Eastern Germany (DE)	1990–2000	Lignite production decline	1990–2003	Plant closures
	1990–2009 1990–2016	Mine closures Decline of coal industry		
Lusatia (DE)	1900–2003 1989-2018 2000–2020	Mine closures Coal production decline New mines construction cancelled		
North Rhine-Westphalia (DE)	1960–2018 2007–2018	Coal production decline Hard coal mines closure		
Ruhr (DE)	1957–2005 1970–1993 1957–2018	Coal production decline Coal production decline Mine closures		
Saarland (DE)	2007–2018	Hard coal mine closures		
Western Germany (DE)			1952–1972 1957–1965	% Coal decline in primary energy consumption Coal consumption decline
Cornouailles (GB)	1985–1998	Mine closures		
North East England (GB)	1920–2003	Decline of coal industry	1980–1990	Decline in energy demand

(Continued.)

Table A3. (Continued.)

	Period	Production	Period	Consumption
North Yorkshire (GB)	1963–1977	Mine closures		
North West England (GB)	1960–1977	Coal production decline Mine closures		
Scotland (GB)	1986–1990	Mine closures		
South Wales (GB)	1913–1992 1953-1974	Mine closures Coal production decline		
Wales (GB)	1913–1943 1950–1964 1984–1994	Coal production decline Mine closures Mine closures		
Limburg (NL)	1965–1974	Coal production decline Mine closures		
Gdańsk-Gdynia-Sopot (PL)			2015–2017	% Coal demand for heating decline
Silesia (PL)	1989–2007 1990–1999 1990–2018 1995–2018	Mine closures Coal production decline Hard coal production decline Hard coal mine closures		
Zasavje (SI)	1990–2000	Mine closures		
Dombass (UA)	Pre 1998	Mine closures		
Colorado (US)			2000–2013	% Coal decline in electricity generation
Illinois (US)	2012–2017	Coal production decline		
New Mexico (US)			2013	% Coal decline in electricity generation
New York State (US)			1990–2015	Coal consumption decline
Pennsylvania (US)	1950–1960	Coal production decline		
Southern Virginia (US)	1990–2013	Coal production decline		
KwaZulu-Natal (ZA)	1981–2001	Mine closures	1980–1990	Plant closures Decline in coal demand for export

Table A4. City-levell coal transitions included in the map.

City	Period	Production	Period	Consumption
Leigh Creek (AU)	2006–2014 2016	Coal production decline Mine closures		
Port Augusta (AU)			2016	Plant closures
Baoding (CN)			2017	% Coal demand for heating decline
Beijing (CN)	1995–2012	% coal decline in primary energy production	1987–2015 2010–2015	% Coal decline in primary energy consumption Coal consumption decline
Chongquing (CN)	1997–2000	Mine closures	1997–1998	Coal consumption decline
Fuxin (CN)	1998–2000	Coal companies diversified into other industries % coal decline in primary energy production	1998–2005	New plant constructions cancelled
Urumqi (CN)			2012–2013	Coal consumption decline
Xuzhou (CN)	2000–2018	Mine closures		
Zaozhuang (CN)	1998–2000 1990–2010	% Coal decline in primary energy production Mine closures	1998–2015	New plant constructions cancelled
Arklow, Drogheda, Dundalk, Limerick, Wexford (IE)			1998	Ban of sale, marketing and distribution of coal
Celbridge, Galway, Leixlip, Naas, Waterford (IE)			2000	Ban of sale, marketing and distribution of coal
Cork (IE)			1995	Ban of sale, marketing and distribution of coal
Dublin (IE)			1990	Ban of sale, marketing and distribution of coal
Shakhta Jyrgalan (KG)	2000–2019	Mine closures		
Wałbrzych (PL)	1994–1998 2006	Mine closures Mine closures		
Anina (RO)	1997–1999	Mine closures		
Motru (RO)	1997–2000	Mine closures		
Uricani (RO)	1997–2000	Mine closures		
Anzhero-Sudzhensk (RU)	1996–2001	Mine closures		
Novoshakhtinsk (RU)	1996–2000	Mine closures		
Gorlovka (UA)	1995–2000	Mine closures		
Stakhanov (UA)	1995–2001	Mine closures		
Dundee (ZA)	1980–2001	Mine closures		

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