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To cite this article: Gregory Trencher *et al* 2022 *Environ. Res. Lett.* **17** 123002

ENVIRONMENTAL RESEARCH
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OPEN ACCESS

RECEIVED
29 May 2022

REVISED
23 October 2022

ACCEPTED FOR PUBLICATION
3 November 2022

PUBLISHED
25 November 2022

TOPICAL REVIEW

The rise of phase-out as a critical decarbonisation approach: a systematic review

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Keywords: phase-out, climate change, decarbonisation, climate policies, governance, decline, socio-technical transitions

Supplementary material for this article is available online

Abstract

'Phase-out' is increasingly mobilised in research and policymaking as an approach to catalyse the gradual decline of technologies, substances and practices that compromise environmental sustainability objectives. This trend is particularly pronounced in the context of climate change, demonstrated by the accumulation of a vast body of scholarship over multiple decades. Our work provides the first systematic review of the state of this knowledge, mapping out how phase-out is studied and employed as a policy tool for mitigating climate change. We systematically review over 400 publications, spanning three decades (1990–2021) and diverse scientific fields. Our review asks: how has scholarly work discussed phase-out as an approach to mitigate climate change, and how has this changed over time? We tackle this question from five perspectives: (a) elements targeted by phase-outs, (b) policy instruments, (c) affected industries, (d) geographic context, and (e) benefits besides climate change mitigation. Results reveal that phase-out has widely proliferated as a decarbonisation approach, developing into a bridging concept that links diverse communities of contemporary science and practice. This is reflected by engagement with manifold phase-out targets—stretching well beyond the usual suspects related to fossil fuels and end-use technologies—as well as discussion of a growing diversity of industries, policy instruments and geographies in the literature. This global proliferation of phase-outs is propelled by expectations of diverse co-benefits. Aside from gains for the environment, economy, society and health, we find widespread acknowledgment that phase-out can drive innovation and systemic change beyond the mere substitution of problematic technologies and materials. Our study also identifies several underdeveloped and underrepresented directions meriting further study. These notably include phase-out activity beyond Europe, North America and China, hard-to-abate industry sectors and non-fossil fuel targets. We conclude by carving out broader implications for scholars and practitioners to inform future research directions and climate mitigation efforts.

1. Introduction

Supporting the development and diffusion of low-carbon technologies and industries has historically occupied a central place in policy responses to the climate crisis (Markard 2018). But fostering innovation can only accomplish so much in terms of mitigating climate change. The problem is that while new technologies such as renewable energy and electric mobility can reduce greenhouse gas (GHG) emissions, these gains are undermined if existing carbon-intensive industries, technologies and activities continue to operate or proliferate (Tollefson 2018). Accordingly, scholars are increasingly taking interest in various policy approaches to deliberately accelerate the decline of technologies, substances and processes that contribute to climate change (Rosenbloom *et al* 2020, Rosenbloom and Rinscheid 2020, McDowall 2022, Koretsky *et al* 2023a).

Amongst numerous attempts to conceptually frame this process of deliberate decline, *phase-out* is particularly prominent (Koretsky 2021, Rinscheid *et al* 2023, Turnheim 2023). Phase-out encompasses a variety of policy approaches that share the objective of sequentially downscaling one or more technologies, substances or processes that cause negative externalities (Rosenbloom and Rinscheid 2020). In contrast to abrupt policy interventions like a ban, which can take immediate effect, a phase-out typically involves a gradual downscaling during a specified timeframe, aiming for a complete abandonment at the endpoint. By granting time to develop alternatives and adjust business practices, phase-outs seek to minimise economic and societal disturbances that tend to occur when technologies and industries are deliberately dismantled (David and Schulte-Römer 2021, Rinscheid *et al* 2021).

The application of phase-out policies in the environmental domain extends back to at least the 1970s, demonstrated by manifold efforts across the globe to curb the production and use of substances, technologies and industrial processes with negative ecological effects. These include substances that deplete the ozone layer (Powell 2002), chemicals like mercury, lead and cadmium that endanger human health and ecosystems (You 2015) and nuclear power stations that pose toxicity risks and intergenerational challenges for waste management (Rogge and Johnstone 2017). Many of these experiences are documented in literature, particularly from the environmental sciences and engineering, where scientists have actively discussed policy developments and technological substitutes or measured the environmental outcomes of phase-out programmes (Rinscheid *et al* 2023).

In recent years, however, the study and application of phase-out has increased markedly in the context of climate change mitigation. Frequently discussed targets of phase-out include fossil fuel extraction (Piggot *et al* 2018), internal combustion engines (ICEs) (Meckling and Nahm 2019) and supporting institutions like fossil-fuel subsidies (van Asselt and Skovgaard 2021). Furthermore, such phase-outs are increasingly advocated in science and policy. Consider the heated debate at the United Nations climate change meeting (COP26) in Glasgow in late 2021 around efforts to formalise the objective to 'phase out' unabated coal power and fossil-fuel subsidies (Harvey *et al* 2021). Likewise, the IPCC mentioned within its Sixth Assessment Report that meeting the Paris Agreement's temperature targets requires 'a timely phasing out of fossil fuels, especially coal, from the global energy system' (2022, p 23).

Phase-out is rapidly gaining traction around the world as a decarbonisation approach for at least three reasons. First, operational lifetimes of carbon-intensive technologies and infrastructures typically extend over several decades (Erickson *et al* 2015). If achieved, such multi-decade lifetimes would counteract global efforts to reduce GHG emissions to zero by mid-century as aimed for under the Paris Agreement (Edenhofer *et al* 2018, Trout *et al* 2022). Since carbon-intensive assets are frequently entangled with sunk investments and the motivation for self-preservation, efforts by industry to accelerate their downscaling are unlikely to proceed without policy intervention (Hoffmann *et al* 2017). Second, curbing the production and use of carbon-intensive technologies and arrangements can promote innovation, opening market shares for cleaner alternatives (Goulet *et al* 2012). Phase-out interventions are thus a powerful policy instrument for redirecting investments towards the production and diffusion of sustainable replacements (Kivimaa and Kern 2016, Rogge and Johnstone 2017, Davidson 2019). Third, targeted phase-out interventions contrast to other wide-reaching and often politically or technically complex policy options available to support climate change mitigation, such as carbon pricing, cross-border carbon adjustment schemes, etc. Thus, singling out and deliberately terminating specific technologies and substances has an attractive simplicity that resonates with some societal actors (Rosenbloom 2018).

Although phase-out has entered a prominent place in debates about climate change mitigation, little systematic knowledge has accrued about its contribution to achieve decarbonisation. Knowledge gaps remain due to the tendency to study single or small sets of cases. Recognising this limitation, recent work has sought to broaden understanding by systematically examining large numbers of historical phase-out cases. Yet, these studies have bounded their analyses to specific targets like coal (Diluiso *et al* 2021). Another issue is that although phase-out and the broader topic of socio-technical change have gained traction as a research topic in the transitions and innovation management literature (Rinscheid *et al* 2021, Koretsky *et al* 2023a), these discussions tend to be disconnected from the rich body of phase-out experiences documented in other fields. For instance, the study of phase-out in environmental science, engineering, medicine and economics predates by several decades the recent interest by transitions and innovation scholars (Rinscheid *et al* 2023). Consequently, there is a need to collate this dispersed scientific knowledge to generate a comprehensive global picture of the core features of phase-out, including the targets of interventions, underlying policies and surrounding scientific debates.

To address these gaps, this study comprehensively reviews over three decades of peer-reviewed publications that discuss phase-out initiatives linked to decarbonisation objectives. Our research proceeds from the following question: how has scholarly work discussed the notion of phase-out as an approach to mitigate climate change and how has this changed over time? Breaking down our overarching motivation into precise research questions, five core areas of interest guide our review: (a) what is the nature of phase-out targets discussed in scholarship? (b) What policy instruments are associated with these? (c) What industries are commonly affected? (d) Which geographic contexts have been under scrutiny? (e) What kinds of benefits accompany phase-outs besides climate change mitigation? Methodologically, we rely on a systematic mapping method (James *et al* 2016) to trace the emergence and evolution of phase-out as a climate change mitigation tool. We do so by coding and analysing over 400 publications.

This study's novelty and contribution to the literature can be summarised as follows.

First, by capturing over 30 years of scientific debates and policy experiences, we provide the most comprehensive picture to date on phase-out research and practice, synthesising knowledge that was until now scattered across different academic fields. Second, by charting the development of phase-out as a critical approach for decarbonisation while accentuating its defining features, we contribute to the rapidly mounting interest in processes of socio-technical decline within the energy transitions, sustainability and climate literature (Markard 2018, Davidson 2019, Rosenbloom and Rinscheid 2020, Koretsky *et al* 2023a). Although we take an explicitly descriptive approach, our work also contributes to addressing a conceptual gap whereby the literature has predominantly examined processes of creation and innovation while tending to neglect the 'flipside' of innovation (Turnheim and Geels 2012, Kivimaa and Kern 2016, Koretsky and van Lente 2020). Third, by identifying macro-level trends derived from over 400 peer-reviewed publications and 60 descriptions of phase-out targets, we move beyond tendencies in the emerging literature on socio-technical decline to study small sets of case studies. Finally, we anticipate that our findings will contribute to the formation of an inter- and even transdisciplinary scientific agenda aimed at stimulating the exchange of knowledge and experiences related to phase-out between researchers and practitioners.

2. Background: conceptualising phase-out

'Phase-out' is defined by a gradual or stepwise approach to scaling down the production or use of a technology, practice, or other component of a socio-technical system, which may concern transport, electricity, or agri-food (Koretsky and van Lente 2020, Rosenbloom and Rinscheid 2020, Stegmaier *et al* 2021). Unlike abrupt policy interventions such as bans, the incremental nature of a phase-out provides time for industry and societal actors to adapt by developing alternatives or adjusting business models and consumption patterns. Moreover, the process of gradual downscaling allows policymakers to monitor outcomes and address negative consequences in sequence (Plötz *et al* 2019). The emerging body of scholarship on phase-out suggests several lines of enquiry that are particularly relevant for understanding the dynamics of this policy approach. These concern the basic temporal dynamics of phase-outs, the nature of socio-technical elements commonly targeted, policy instruments that contribute to phase-outs as well as functions performed by these—particularly from an innovation perspective. We summarise existing understanding on these issues below.

First, with respect to temporal dynamics, in policy practice a phase-out is often operationalized by fixing a specific period during which the downscaling must occur. This may involve intermediate steps or milestones along with an end date by which the complete abandonment of the targeted element must be achieved. In the case of the Montreal Protocol on Substances that Deplete the Ozone Layer (henceforth Montreal Protocol), for instance, steps are explicitly defined (Powell 2002). To illustrate, the production of chlorofluorocarbons (CFCs) was mandated to decline 20% by 1993 from 1989 levels, 75% by 1994, then culminating with a complete termination by 1996 (Powell 2002). The phase-out of incandescent light bulbs in Europe was also pursued incrementally, with energy efficiency regulations progressively tightened in accord with an explicitly defined timetable (Stegmaier *et al* 2021).

However, the temporal dimensions of a phase-out may also be defined in a less explicit manner. For instance, policymakers may aim to trigger a process of incremental downscaling by simply announcing the intention to cease the production, sale or operation of a certain technology by a specific year or period in the future (Rinscheid *et al* 2021). This is exemplified by current strategies to replace ICEs (Meckling and Nahm 2019, Plötz *et al* 2019). With few governments explicitly prescribing step-by-step targets to guide the cessation of ICE sales by a specific point in time, the pace of interim change is left to societal stakeholders. Likewise, although the Powering Past Coal Alliance fixes the year 2035 as a target for the complete removal of coal from a jurisdiction's electricity mix (Blondeel *et al* 2020), the alliance itself along with its many members does not stipulate an incremental schedule to achieve this. Summarising the above, figure 1 depicts two stylised ways phase-out targets may be defined.

Second, beyond their temporal dynamics, phase-outs are also characterised by the specific components in a socio-technical system that they target

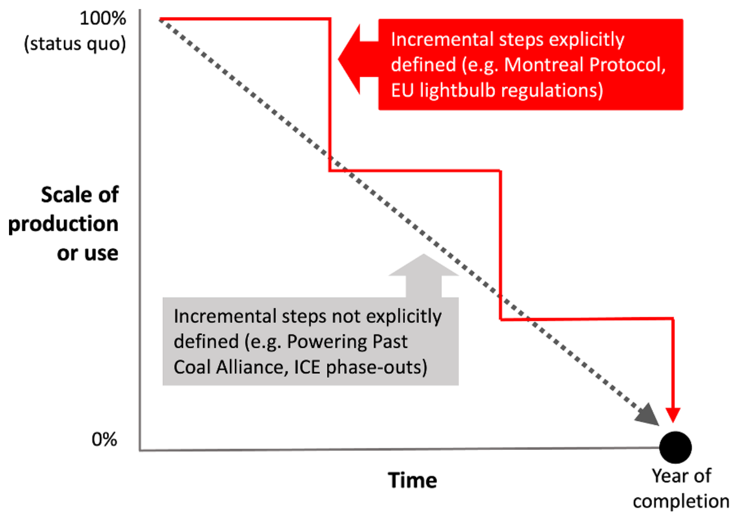

Figure 1. Two stylised phase-out pathways.

(McDowall 2022). Previous research indicates that common targets include *technologies* (e.g. power plants), *substances* (e.g. lead or pesticides) and commercial or industrial *processes* (e.g. logging or fishing) (Rosenbloom and Rinscheid 2020). Other works point to further phase-out targets, such as formal institutions like fossil fuel subsidies (van Asselt and Skovgaard 2021) and other policies that hamper innovation and decarbonisation (Bednar-Friedl *et al* 2012). Recently, phase-out has even been discussed in the context of progressively abolishing fossil-fuel infrastructure (Furnaro 2021) or transforming entire industries, such as heavy manufacturing (Qian *et al* 2021). Taken together, the literature suggests that phase-out targets range from more narrow and well-defined components of socio-technical systems (coal-fired power plants in the electricity system) to broader and less easily defined elements (e.g. GHG emissions or fossil fuel substances in general) (Koretsky *et al* 2023b). This said, the literature is yet to comprehensively engage with the full spectrum of elements targeted by phase-outs in the context of climate change mitigation, especially in terms of changes over time and the emergence of novel targets.

Third, another perspective that can help distinguish different phase-out approaches relates to the number and type of policy instruments used. Previous research suggests that one or more policy instruments may be used (Rinscheid *et al* 2023) and that command-and-control policies are particularly prominent. Exemplary instruments include environmental standards backed by regulations that involve targeted restrictions, often rising in stringency over time to culminate in an outright ban. The case of Europe's approach to phasing out the incandescent light bulb provides a case in point (Stegmaier *et al* 2021). While command-and-control instruments may be connected to international frameworks (e.g. the Minamata Convention on Mercury), the national or sub-national level is where policies are developed and implemented. However, other approaches are also discussed, such as management and planning instruments. These can situate phase-outs within overarching policy frameworks. For instance, both Hong Kong and Greece have formalised the commitment to phasing out coal power within climate plans (Environment Bureau of Hong Kong 2017, Marinakis *et al* 2020). Management and planning instruments may also fix phase-out schedules with numerical targets, such as through decreasing yearly quotas for problematic technologies, as illustrated by the case with ICEs in California and China (Trencher *et al* 2021). Some management plans combine phase-outs with complementary measures like public funds and strategies to help compensate and restructure affected industries and regions (Keles and Yilmaz 2020). Scholars also describe how economic approaches can play an important role in inducing phase-outs. These include reducing subsidies to polluting industries (Kivimaa and Kern 2016), incentivising technological change through carbon taxes and emissions trading schemes (Yan 2021) and providing financial support for clean technology (Hast *et al* 2016, Thoday *et al* 2018). Finally, capacity building, education and information instruments can also support the implementation of phase-outs (Goldberger *et al* 2011, Carrión *et al* 2018). Despite the rich descriptions of policy instruments provided in the literature, most have been made in relation to small sets of phase-out targets. Conversely, there is still a need to ascertain the relevance of particular policy instruments to a large body of phase-out targets, taking into account changes over time.

While phase-outs are most prominently implemented through state intervention, in some cases they are carried out voluntarily by societal actors.

Take for example the case of electronics makers Sony, Apple and Samsung that adopted phase-out programmes to eliminate the use of toxic chemicals (Paska 2010). Consider also the case of the 'Clean Heat' policies in New York City, which have moved to progressively eliminate the use of heavy oil in citywide heating systems by 2030 (Hernández 2016). Backed by laws and mandatory actions, the phase-out programme involves a partnership with non-profit Environmental Defense Fund to provide subsidies for new heating systems and diffuse information about best practices (Carrión *et al* 2018).

Fourth, as discussed above, although the factors marking phase-out are well established—albeit disparately—across scholarship, conceptual understanding of the functions performed by this policy approach is limited. Here, we turn to sustainability transitions research, since this field has made particularly important advances in conceptualising phase-out both as a process and a governance approach.

Transition studies tend to situate phase-out as part of the destabilisation and decline of established socio-technical systems (Turnheim and Geels 2012, Normann 2019, Koretsky *et al* 2023a). That is, a phase-out can be alternatively understood as a core contributor and potential outcome of the delegitimisation and eventual erosion of a system, which opens it to transformative change (Turnheim 2023). Thus, it is part of the 'flipside' of the innovation dynamics that form the basis for a transition, helping tear down the old and make way for novelty. Reflecting this, researchers have highlighted the role of phase-out in driving 'exnovation' (Davidson 2019) or the destructive part of 'creative destruction' processes (Kivimaa and Kern 2016).

Recent transition research has helped elaborate the multiple functions phase-out can play in processes of destabilisation and decline. First, it can involve *delegitimising* functions (Rosenbloom 2018, Bento *et al* 2021), such as by supporting storylines that undermine the social legitimacy upholding the continued (re)production of a technology, substance or practice (Leipprand and Flachsland 2018, Koretsky and van Lente 2020, Markard *et al* 2021). Second, phase-out can play a *signalling* function by identifying the desired outcome of a particular transition process. This can act as a powerful deterrent for new investments while at the same time propelling market exits (Bento *et al* 2021, Rinscheid *et al* 2023). Third, by signalling the desired long-term direction of socio-technical change (Meckling and Nahm 2019), a phase-out can promote *creation*, catalysing and focusing the search for and the diffusion of alternative technologies, materials and practices (Rogge and Johnstone 2017). Finally, phase-outs can also function to drive varying degrees of transformation, ranging from *substitution* to *transformation* (Rinscheid *et al* 2023). The former involves the narrower goal of replacing one socio-technical system component with another (e.g. an ozone-depleting refrigerant with an alternative chemical). Conversely, a phase-out may directly encourage a broader process of transformation that recognises the embeddedness of socio-technical system elements (Rinscheid *et al* 2023). A phase-out targeting coal-based blast furnaces in steel production, for instance, can reside within the broader ambition of transitioning to a hydrogen-based or post-carbon economy (Karakaya *et al* 2018). In aggregate, this highlights the important role of phase-out in transition processes, with both destructive and creative functions (Rosenbloom *et al* 2020, Rinscheid *et al* 2021). Despite the utility of these conceptual discussions, the existent literature has not yet exhaustively investigated to which extent these functions are recognised by stakeholders or observed in actual phase-out programmes. We thus see a parallel need for scholars to empirically examine a large number of cases from around the world to deepen understanding into how phase-outs function and what instruments enable this.

This more comprehensive view of phase-out cast by transition studies helps elucidate the structural challenges and interactions that accompany such interventions, revealing how the targets of policies are embedded within broader socio-technical systems and transformative processes (Markard 2018, Andersen and Gulbrandsen 2020, David and Schulte-Römer 2021). For instance, Koretsky and van Lente (2020, p 304) understand phase-out as 'the unravelling of materials, competencies and meanings in socio-technical configurations', highlighting the interdependencies of system elements and human practices. This further underscores the potentially disruptive consequences of this policy approach. Take for example how the phase-out of ICEs is expected to generate disruptive impacts to established business models across broader value chains in the automobile industry and society. Not just limited to vehicle assembly lines, the transition to electric drivetrains is expected to provoke a contraction of associated industries from upstream part suppliers, to gasoline stations, mechanic workshops and oil producers (Nikkei Asia 2020, Pichler *et al* 2021). Anticipating and minimising such side-effects through compensation packages, retraining programs and long-term planning has therefore emerged as a central concern for the phase-out process (Normann 2019, UNFCCC 2020).

In sum, the above discussion reveals that phase-out is of critical importance for the study and practice of decarbonisation. While it has garnered increasing attention within the scholarly literature (David 2017, Rosenbloom and Rinscheid 2020, Stegmaier *et al* 2021, Koretsky *et al* 2023a), the language of phase-out also pervades policy efforts to drive climate change mitigation and other sustainability challenges (Rinscheid *et al* 2021). Phase-out thus shows promise as a 'bridging concept' that links practical efforts and scholarly activities to drive more effective interventions to realise societal transformation toward a post-carbon future (Turnheim *et al* 2020). Systematically assessing the state-of-the-art of phase-out research therefore not only advances the scientific literature by identifying important trends and gaps at the intersection of various academic disciplines, but it also directly serves communities of practitioners seeking to advance the use of this approach.

3. Methods

3.1. Research design

This study adopts as its primary method a systematic literature review, and more specifically, an approach called 'systematic mapping' (James *et al* 2016). This approach allows researchers to deepen knowledge of a particular research topic by systematically exploring and synthesising the state-of-evidence in a corpus of scientific literature. Systematic mapping follows a process of: (a) identifying relevant publications, (b) sorting and coding the evidence in accord with pre-defined research questions, and (c) analysing trends and patterns. Coding is a core feature of this method. This essentially quantifies textual data, allowing the identification, visualisation and analysis of specific themes (Hsieh and Shannon 2005, McKinnon *et al* 2015, Scheelbeek *et al* 2021). A notable methodological trend in the application of systematic mapping approaches is the emergence of machine-learning techniques to identify, process and code large volumes of studies (Cheng *et al* 2018, Berrang-Ford *et al* 2021). While machine learning has strong advantages when it comes to large corpora of scientific literature, the number of publications dealing with phase-out as a tool to address decarbonisation is still relatively small. Moreover, since our work is of exploratory nature and we developed our research questions in an iterative and inductive way, no pre-existing algorithm could have been used to easily classify the relevant literature. We therefore manually identified, sorted and coded the corpus. In contrast to machine-learning methods, this helped deepen our knowledge of the body of literature investigated, which also enabled us to conduct qualitative analyses of the literature that extend beyond the confines of the coding scheme.

Compared with other and more qualitative review methods, the systematic mapping approach enjoys higher replicability. This can be attributed to the use of explicit inclusion and exclusion criteria when selecting literature as well as transparent protocols to guide the identification of thematic trends (Haddaway *et al* 2016, O'Leary *et al* 2017). Although originating from the social sciences, the systematic mapping approach has proliferated across diverse academic disciplines. These encompass environmental science and sustainability related fields (McKinnon *et al* 2015, 2016, O'Leary *et al* 2017) as well as topics related to climate change (Lamb *et al* 2019, Callaghan *et al* 2020, Berrang-Ford *et al* 2021, Scheelbeek *et al* 2021) and energy (Lu and Nemet 2020, Temper *et al* 2020, Fisch-Romito *et al* 2021). We draw on all these studies for methodological guidance and inspiration while respecting best practices for systematic reviews (Haddaway and Macura 2018).

3.2. Objective, scope, search query and relevance sorting

Our core research aim is to understand how phase-outs have been described by academic research and implemented in practice as a tool for mitigating climate change and to identify changing trends over time. The primary unit of analysis is scientific discussions about phase-outs. The studied literature includes empirical and theoretical discussions which describe both actually existing policies as well as phase-outs yet to be implemented in the real-world.

To identify relevant publications, we developed a search string shown in table 1. Modelled on our previous work (*citation removed for review*) this includes terms that capture: (a) our research topic (i.e. 'phase-out'); (b) descriptions of different mandatory and voluntary policies (e.g. 'regulation', 'initiative', 'incentive' and 'program'), and (c) the objective or context for pursuing phase-out (i.e. 'climate', 'warming' and 'decarbonisation').

We set the following conditions for the literature extraction:

- publication type: articles and reviews.
- Search field: Title, author keywords and abstract.
- Temporal scope: all publications published up to 1 January 2022.
- Academic field limitations: none.
- Language: English.

We used the Scopus database of scientific literature to identify relevant publications. We chose this over competing options like Web of Science and PubMed due to its superior coverage of journals, abstracts and keywords (Falagas *et al* 2008, Peñasco *et al* 2021). To verify the soundness of our decision to choose only Scopus, we ran a robustness check on Web of Science. This revealed a stronger coverage for Scopus in early years, yielding 35 publications up to the year 2000. Web of Science, in contrast, yielded only 12 hits for the same period. Due to our interest in identifying temporal trends, we opted for Scopus.

We extracted literature from the Scopus database on 18 February 2022. This returned 580 hits that were then sorted for relevance. After removing duplicates, this resulted in a dataset of 404 relevant publications retained for subsequent coding and analysis (see supplementary data 1).

Table 1. Search string used in this study.

1st segment		2nd segment		3rd segment
Phase out OR phase-out OR phasing out OR phasing-out OR phased-out OR phased out	AND	action OR agreement OR ban* commit* OR decision OR effort OR framework OR govern* OR incentive OR initiative OR instrument OR law OR legislat* OR management OR mandat* OR measure OR mechanism OR plan OR polic* OR program OR regulation OR rule OR scheme OR strateg* OR treaty	AND	climate OR warming OR decarbon*

Table 2. Criteria used to identify relevant papers.

Include ($n = 404$)	Exclude ($n = 175$)
(a) Papers that mention a phase-out policy that is explicitly associated with the objective of climate change mitigation or decarbonisation. (b) Papers that mention a phase-out in the context of discussing climate change or decarbonisation.	(c) Papers that mention a phase-out for reasons not related to climate change or decarbonisation (e.g. environmental contamination [lead, flame retardants etc], safety [weapons], the phase-out of financial incentives for home solar PV installations for fiscal reasons, etc). (d) Papers that discuss phase-out for the purpose of climate change adaptation.

Relevance decisions were made in accord with criteria in table 2 based on evidence contained in titles, keywords and abstracts. We included publications that explicitly discuss phase-out as an approach to mitigating climate change (criterion 1)[5]. Publications discussing phase-out targets without explicitly stating a decarbonisation objective were only included if clearly embedded in discussions of climate change mitigation (criterion 2). This includes, for example, papers that discuss targets like tetrafluoroethane, R404A or other ozone-depleting substances with high global warming potential in the context of climate change mitigation. Publications evoking the phase-out of a particular target in a context that does not relate to the objective of climate change mitigation were considered irrelevant (criteria 3–4). This strategy ensures that all publications engage in whole or in part with climate change mitigation.

3.3. Coding and analysis procedure

We created a coding book within which each relevant paper was assigned an identification number and coded (see supplementary data 1). To guide this process and ensure replicability, we developed research questions and coding frameworks shown in table 3. The coding frameworks consist of parent codes and specific sub-codes that were either taken from literature or created inductively. The parent codes generate an aggregated but coarse identification of general patterns while the sub-codes classify these at higher resolution. This coding and analytical approach advances our earlier work (*citation removed for review*) by distinguishing between mentions of existing phase-out initiatives (coded as 'actual') and hypothetical phase-outs not linked to any actually existing policy (coded as 'hypothetical).

The coding procedure examined evidence contained in the title, abstract and keywords of papers. We consulted full papers, however, in the case of ambiguous language (and also to build our understanding of the broader context for trends identified in the analysis). The coding frameworks and procedure were firstly tested in a pilot phase. In the case of inductively created frameworks, the pilot phase involved formulating brief textual descriptions of variables, converting these to codes, then iteratively refining these through several coding rounds. Multiple codes were assigned to papers as needed. Furthermore, care was taken to only code the portion of content connected to the discussion about a particular phase-out.

Three researchers collaborated to code all publications in sequence. The first researcher screened the bibliographic information by highlighting the relevant portions of text and suggesting parent codes. The second researcher worked as the lead coder to verify these decisions and independently code each publication. The third researcher reviewed all coding decisions and identified discrepancies. If found, these were discussed and resolved between the second and third researcher.

When analysing the coding results, we focused on mapping out trends identified at the parent-code

[5] We made this decision after verifying how many papers discuss phase-out as a measure for climate change adaption. Since we only found one, we decided to exclude such papers to retain a clear conceptual focus to the review.

Table 3. Summary of coding frameworks and guiding research questions.

Category	Research question	Code examples	Source of coding framework
Phase-out target	Which elements are targeted by the phase-out?	• Parent codes: substance, technology, process. • Sub-codes: coal-fired power plants, internal combustion engines.	Rosenbloom and Rinscheid (2020).
Type of discussion	Does the discussed phase-out refer to an existing policy initiative?	Actual or hypothetical.	Carley *et al* (2020).
Policy instruments	What policy instruments pursue or contributed to the phase-out?	• Parent codes: command and control, economic instruments, voluntary approaches. • Sub-codes: laws & legislation, environmental standards, reporting, monitoring & disclosure.	• Parent codes: OECD (2001). • Sub-codes: inductively developed based on descriptions in literature; e.g. (OECD 2001, 2007, Hood 2011, Kivimaa and Kern 2016, Peñasco *et al* 2021).
Affected industry	What industries are discussed or implied as producing, emitting or using the phase-out target?	• Parent codes: power generation, chemical manufacturing. • Sub-codes: rice farming, fishing, iron and steel mills and ferroalloy manufacturing.	• Parent codes: inductively developed. • Sub-codes: North American Industry Classification Scheme (NAICS)' from the United States Census Bureau (2017a).
Geographic region	What country or region is targeted by the phase-out policy?	• Parent codes: Europe, Africa. • Sub-codes: sub-Saharan Africa, West Europe, East Asia.	• Parent and sub-codes: standard country or area codes for statistical use (49 Standard) from the Statistics Division of the United Nations Secretariat (2021).
Co-benefits	What objectives and benefits are ascribed to the phase-out besides climate change mitigation?	• Parent codes: social, economic, technology and innovation. • Sub-codes: energy security, systemic change, substitution, response to public.	• Parent and sub-codes: inductively created.

level, using sub-codes to enrich understanding of these. To ensure a consistent conceptual focus, we built data visualisations and analytical explorations mainly from two dimensions. The first focuses on identifying trends in *temporal variation,* to illustrate how the practice and study of phase-out policies have evolved. The second dimension focused on identifying correlations across variables. To ensure a common thread is retained across the analysis, we mainly explore correlations between the 12 most discussed phase-out targets in the dataset and variables within other coding categories (policy instruments, co-benefits and geography).

4. Findings

4.1. State of the literature

First emerging in 1990, scientific work on phase-out as a tool for mitigating climate change has accumulated over some three decades (figure 2). The genesis of related scholarly discussions is tightly anchored to the evolution of the Montreal Protocol. Illustrating this, the first publication in the dataset appeared in the *International Journal of Climatology* (Bach and Jain 1990) and discusses the urgency of strengthening implementation of the Montreal Protocol in light of increasing scientific evidence that certain ozone-depleting gases, in this case CFCs, were contributing to climate change. After simulating how the volume of CFC phase-out commitments could mitigate further surface warming, the authors argue that evidence 'of a substantial CFC contribution to global warming' reinforce 'the urgency' of increasing the scope and volume of gases targeted under the Montreal Protocol'. This interest in mitigating climate change by curbing the production and use of ozone-depleting gases through phase-out regulations continued for at least two decades. It is only

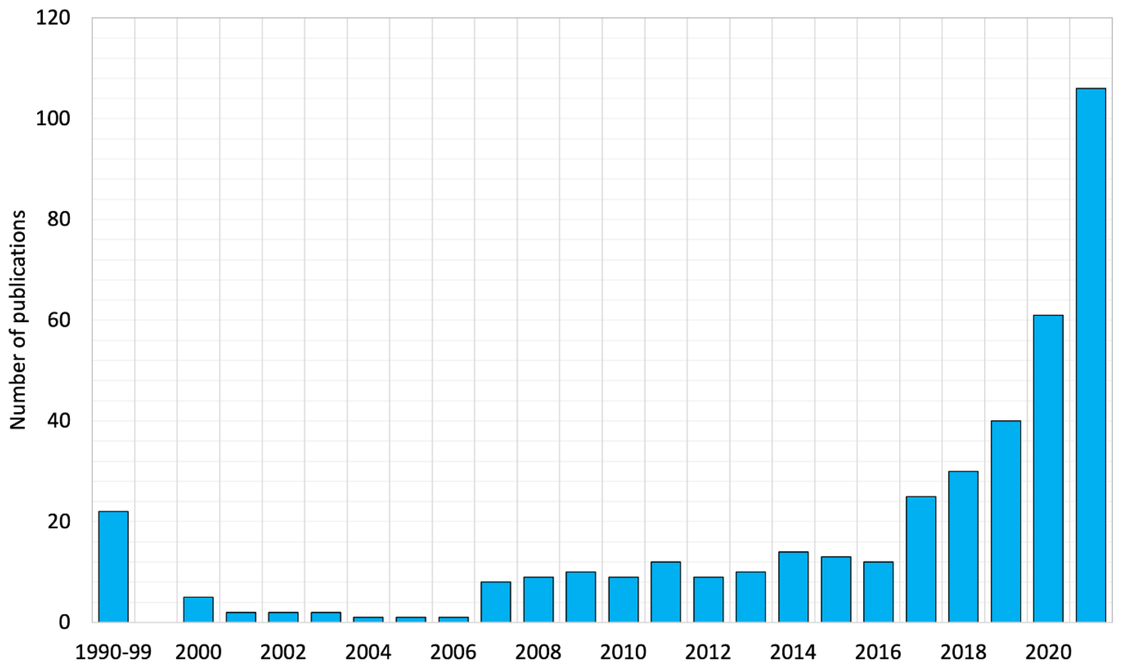

Figure 2. Publication year for studies in dataset.

after around 2000 that mentions of other phase-out targets—namely fossil fuels, GHG emissions, biofuels and the land application of sewerage sludge—begin to surface consistently in the literature.

For the periods 1990–1999 and 2000–2009, we found only 22 and 41 papers respectively that discuss phase-outs as a tool for mitigating climate change. However, interest in this topic builds rapidly after this period. In particular, publication activity surges after 2017, with almost two-thirds of publications appearing after this year. The growth trend continues to accelerate, with the last two years (2020–2021) alone seeing the addition of 167 new studies or 41% of the sample. The Paris Agreement, ratified in late December 2015, appears to have stimulated much of this momentum. Indeed, numerous studies (Bryngelsson *et al* 2017, Pan *et al* 2017) after this date begin to refer to the global objective of keeping planetary temperature rise to below 1.5 °C or 2 °C in justifying the need to phase-out an increasingly broad range of climate change drivers.

The wide range of journals (195 in total) publishing on this subject testifies to the highly interdisciplinary nature of the scientific work engaging with climate-related phase-outs (Rinscheid *et al* 2023). That said, some journals have more actively discussed phase-outs than others. These trends are presented in table 4, listing the most frequently occurring journals in the dataset. The top 17 journals have collectively produced 175 publications, making up around 43% of the dataset. Not surprisingly, the results indicate a strong presence of journals from energy and climate-related fields.

The contributions of various scientific fields to this enterprise have evolved over time (supplementary data 2 figure 1). On the one hand, some established journals like *Energy Policy, Applied Energy, Energy* and the *International Journal of Refrigeration* (launched between 1973 and 1978) have consistently contributed papers over the three decades. On the other hand, for other journals which also contribute a meaningful quantity of publications, interest in phase-outs is a comparatively recent phenomenon that is concentrated principally over the past 5–10 years. Among these feature newer journals like *Climate Policy, Energies, Environmental Research Letters* and *Energy Research and Social Science*.

As expected, the various journals exhibit contrasting disciplinary orientations and approaches to studying phase-outs. At one end of the spectrum, publications from journals like *Atmospheric Environment, International Journal of Refrigeration* and *Applied Energy* display a prominent interest in perspectives rooted in the natural sciences and engineering. For some publications in this group, phase-out policies pose an engineering challenge that necessitates the development of alternative energies and technologies while others engage with phase-out activities in the context of climate change by measuring or simulating environmental impacts that result from actual or hypothetical policies (Velders *et al* 2015, Klockner and Letmathe 2020). Conversely, publications from journals with a stronger orientation to the social sciences, e.g. *Energy Research and Social Science* and *Journal of Cleaner Production*, exhibit an interest in the formulation and implementation of

Table 4. Most frequent[a] publication outlets.

Journal (year of inaugural issue)	Count	Share (%)
Energy Policy (1973)	25	6.2
Climate Policy (2001)	19	4.7
Energies (2008)	16	3.9
Environmental Research Letters (2006)	13	3.2
Energy Research and Social Science (2014)	12	3.0
Applied Energy (1975)	10	2.5
Energy (1976)	9	2.2
International Journal of Refrigeration (1978)	9	2.2
Renewable and Sustainable Energy Reviews (1997)	9	2.2
Sustainability (Switzerland) (2009)	8	2.0
Atmospheric Environment (1967)	8	2.0
Journal of Cleaner Production (1993)	7	1.7
Energy Economics (1979)	7	1.7
Climatic Change (1977)	7	1.7
Environmental Science and Technology (1967)	6	1.5
Joule (2017)	5	1.2
Nature Climate Change (2007)	5	1.2
Total	**175**	**43.3**

[a] *Note:* all journals with at least five publications are shown.

phase-out policies or in the dynamics that drive or impede efforts to reconfigure socio-technical systems that contribute to climate change (David and Schulte-Römer 2021, Koretsky 2021). Yet, engagement with the policy and governance dimensions of phase-outs is not limited to social scientists. Indeed, the sampled literature contains numerous publications from engineering and natural science fields within which scholars exhibit a considerable degree of sensitivity towards the challenges associated with developing and implementing phase-out policies (Powell 2002, Horrocks and Wilson 2021).

In sum, the above analysis reveals a rapidly growing area of scientific enquiry. Informed by multiple disciplines and methodological approaches, the evidence indicates that the study and practice of phase-outs as a critical approach for decarbonisation is proliferating widely across science and society.

4.2. Targets of phase-outs

Results show that ozone-depleting substances and coal power are the most frequently studied phase-out targets followed by fossil fuel extraction and coal extraction (figure 3). Works on ozone-depleting substances are especially prominent, being consistently discussed over the entire study period. This sustained interest largely reflects the evolution of the Montreal Protocol. This governing apparatus has expanded from two perspectives: first, in terms of targeted gases, growing from an initial focus on CFCs to other classes of climate warming halons such as HCFCs and HFCs, and second, in terms of geographic reach, as phase-out obligations have widened to affect developing countries.

The intricacies of some targets are not self-evident and merit brief explanation. Institutions such as policies and policy features, for example, feature prominently in academic discussions about phase-outs. The case of fossil fuel subsidies is a clear example. Largely driven by international political commitments such as declarations by the G7 and G20, many papers advocate the reform of public financial schemes supporting fossil fuel production as a critical tool for mitigating climate change. Such advocacy rests on views that financial support suppresses the cost of production and extraction, and thereby drives GHG emissions, while perpetuating the existence of carbon-intensive energy systems (van Asselt and Skovgaard 2021). In addition, the literature also discusses the phase-out of other policies and features (coded as distinct from fossil fuel subsidies). These especially relate to free pollution allowances to industry in emissions trading schemes. Arguing that these impede decarbonisation by lowering the imperative to innovate to reduce emissions, several scholars have called for the abolishment of such policy features using a phase-out approach (Nachtigall 2019, Leining *et al* 2020, Mai 2021). Finally, the category of heavy industries reflects historical and ongoing discussions about the need to transform *entire industries*. This notably differs to narrower phase-out interventions that simply target specific carbon-intensive technologies, such as blast furnaces. These discussions have emerged in relation to energy extraction in South Africa (Winkler and Marquand 2009), iron and steel production in China (Li *et al* 2020) and petroleum production in Norway (Afewerki and Karlsen 2021).

The full dataset (appendix table A1) contains 60 descriptions of distinct targets. Though 95% of codes are represented by the aggregated categories in figure 3, our complete inventory comprises an

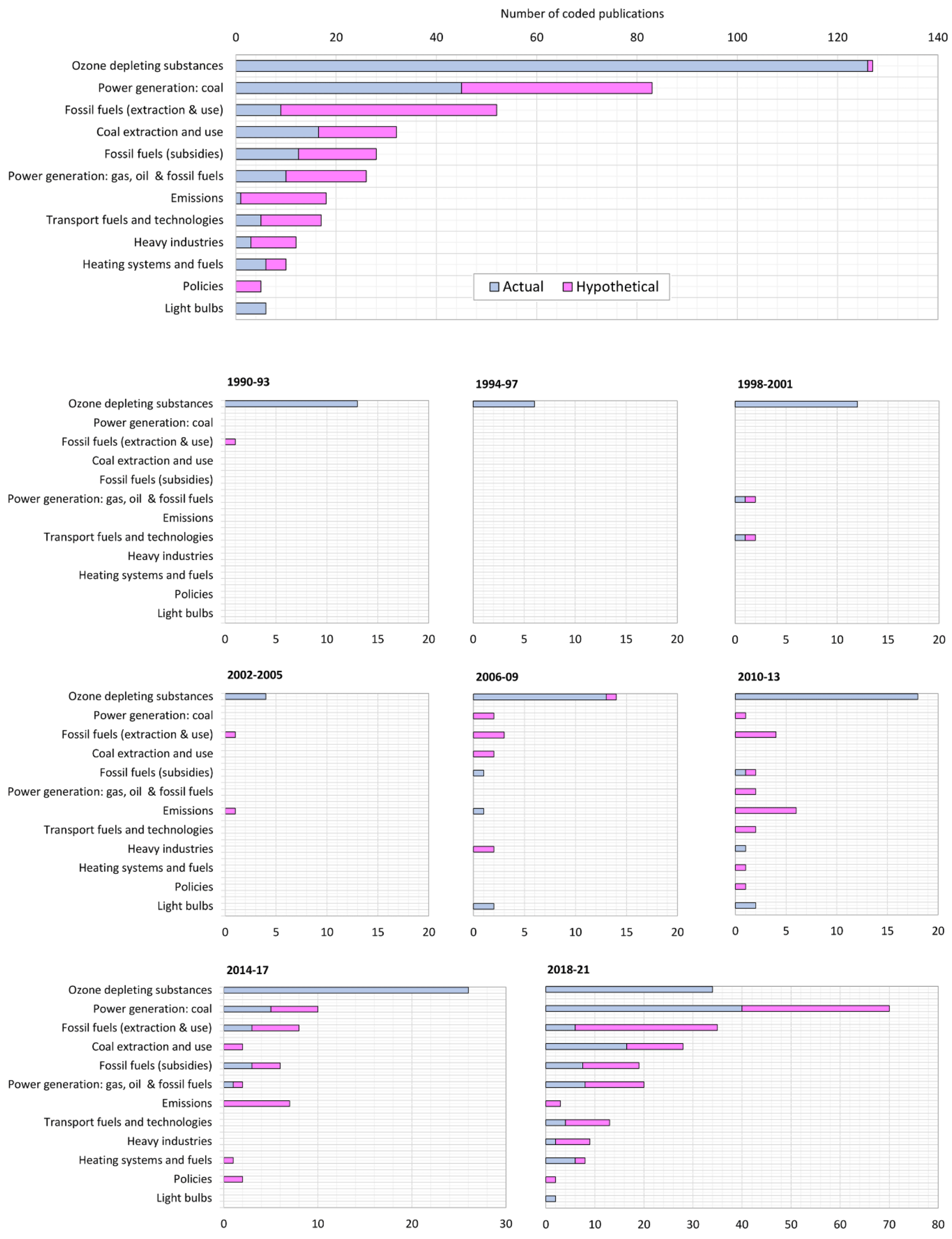

Figure 3. Temporal distribution of publications for the 12 most frequently discussed phase-out targets.
Note: figures show aggregated categories for a full list of phase-out targets found in appendix table A1. There were four papers that discussed both actual and hypothetical phase-outs. To deal with these cases, we split the value of each paper's code into two, allocating half (0.5) to the 'actual' portion of the figures and the other half (0.5) to the 'hypothetical' portion. A further five publications could not be classified and are omitted from the figures.

even wider range of less frequently discussed phase-out targets. Briefly considering these accentuates the magnitude of societal transformations required for the decarbonisation challenge, since these targets reflect the vast scope of human activities that produce GHG emissions or exacerbate climate change. To illustrate, some scientists call for phase-outs that target dark-coloured roofs (which contribute to the heat-island effect (Sproul *et al* 2014), red meat (due to methane and other GHG emissions caused by enteric fermentation, manure and other activities along the production chain (Bryngelsson *et al* 2017) and biofuels. On the latter, some call into question its climate neutrality and point to problematic land use impacts (Mathews 2008, Limenta 2020).

The ever-growing diversity of targets featured in phase-out discussions is further accentuated in recently emerging scientific debates. Looking at targets only appearing in the last three years, we find mentions of gas extraction, gas-fired power plants, waste incineration, synthetic fertilizers, blast furnaces in iron and steel making, fossil fuels in aviation and additional classes of ozone-depleting substances (e.g. SF6, R22, R410a, etc). Some of these mentions reflect recent phase-out efforts. For example, discussions of new classes of halons evoke strengthening measures to curb climate warming gases in the Montreal Protocol, notably via the Kigali Amendment in 2016. This targets a complete termination of hydrofluorocarbon (HFC) production by 2040. Meanwhile, discussion of a phase-out targeting waste incineration describes efforts by the City of Madrid in Spain to terminate this emissions-intensive waste treatment method by 2025 (Istrate *et al* 2021). Finally, discussions on phasing out natural gas reflect both hypothetical investigations (Brear *et al* 2020) and actual policy in the Netherlands to progressively abolish consumption of this fuel in households (Mashhoodi 2021). With a still limited presence in the literature, such targets hint at important topics for future research.

While discussions of some phase-out targets are anchored to actual policies, others are discussed in a hypothetical light. The grey and pink bars in figure 3 reflect this distinction. Results show that discussions of phase-outs in the early literature were based almost entirely on empirical experiences with actual policies, particularly those surrounding the cases of ozone-depleting substances and light bulbs. But as the literature has grown, contemporary scholars are increasingly discussing or advocating for phase-outs for which policies do not yet exist in a particular region. Furthermore, this tendency towards hypothetical discussions is strengthening in recent years (see also supplementary data 2 figure 2). Targets that are increasingly evoked from a hypothetical perspective notably include fossil fuels (extraction and use), fossil fuel subsidies, emissions, transport fuels and technologies, heavy industries and policies.

Given the potentially abstract nature of these hypothetical debates, there is merit in briefly outlining the contours of these publications. Discussions of hypothetical phase-outs include contributions that: advocate for the phase-out of a particular target based on normative stances (Kartha *et al* 2018, Burke and Fishel 2020) or results of an analysis (Tanaka *et al* 2019); simulate the impacts of a hypothetical phase-out policy in models that predict implementation costs or the potential volume or speed of subsequent GHG emission reductions (Monasterolo and Raberto 2019); and consider the drivers, barriers or impacts of a hypothetical phase-out (Rinscheid *et al* 2020). Mentions of hypothetical phase-outs also stem from studies that evoke the phase-out of fossil fuels as common task for humanity without focusing on any specific policy cases that pursue this goal (Sharma *et al* 2021) as well as those that consider phase-out as a generic policy tool when examining governance dimensions of energy transitions (Rosenbloom and Rinscheid 2020, Blondeel *et al* 2021).

The temporal distribution in figure 3 exhibits clear trends with respect to periods during which scientific attention to particular phase-out targets emerges and wanes. As indicated with the abovementioned case of ozone-depleting substances, the timing of scientific discussions is frequently triggered by real-world events. Coal power is another relevant example, appearing consistently since 2014 but spiking abruptly after 2017. Coal extraction and use also follows the same trajectory. This sudden rise of scientific interest can be explained by the Paris Agreement, entered into force in 2016, and the Powering Past Coal Alliance, established the following year by England and Canada (Blondeel *et al* 2020). Coinciding with these international developments, a spurt of phase-outs targeting the coal power and extraction industry have emerged in regions such as Canada, Europe, Asia (Hong Kong) and South America (Chile). As noted above, these interventions have attracted considerable attention in the literature (Rentier *et al* 2019, Durmaz *et al* 2020, Nasirov *et al* 2020), reflected in a rising share of publications coded as 'actual'. Heating systems and associated fossil fuels are another target demonstrating a distinct entry into phase-out debates. Absent from scholarly discussions until 2010, the need for phase-outs aimed at fossil-fuel based heating systems was first examined from a hypothetical perspective (Wilson *et al* 2012). But mirroring the trajectory for coal extraction and use along with fossil fuels in general, after 2017 the publications surge, this time driven by discussions of actual policies. This timing reflects a suite of pioneering efforts at the city or district level in Europe to phase-out fossil fuels from district or household heating systems (Reda *et al* 2021). Similarly, phase-out policies and discussions targeting transport systems have also increased notably after 2018. Underlying this rise is the proliferation of policies targeting ICEs in various countries and cities across the globe.

4.3. Policy instruments

Findings indicate that while nearly half of contributions focus on a single policy instrument, particularly command-and-control approaches, there is a trend toward policy mixes within the literature on phase-out (figure 4 and supplementary data figure 3). Indeed, a diverse range of policy approaches—stretching from command-and-control to voluntary—are seen to contribute to phase-outs. That said, three policy categories dominate the results: command-and-control, management and planning, and economic instruments.

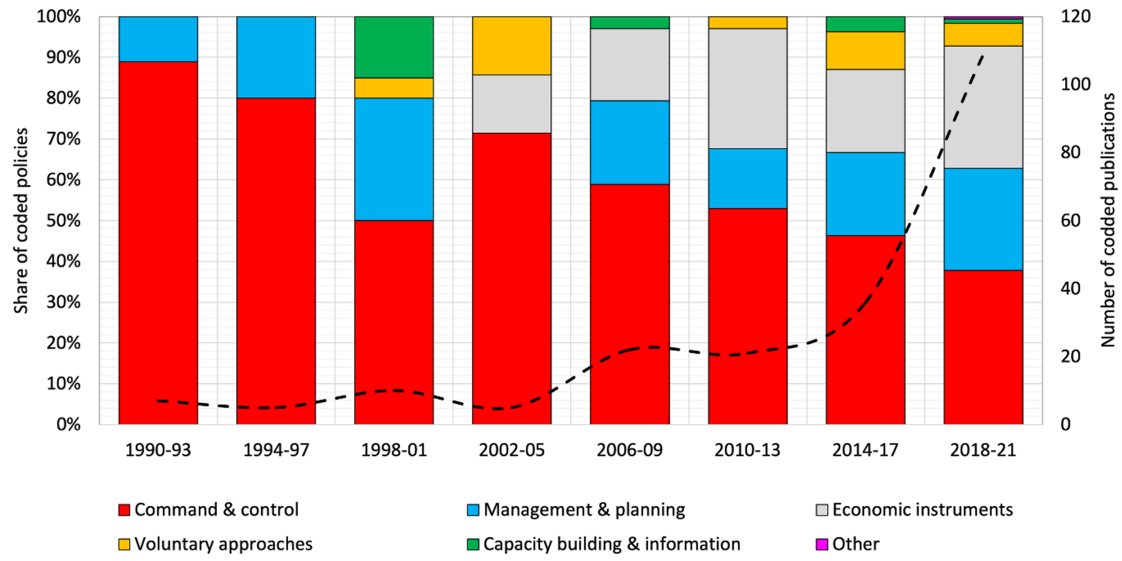

Figure 4. Temporal evolution of phase-out policies described in literature (4 year intervals).
Note: papers citing multiple instruments received more than one code. Papers not mentioning instruments are omitted. Dotted line shows 4 year moving average for the number of coded publications.

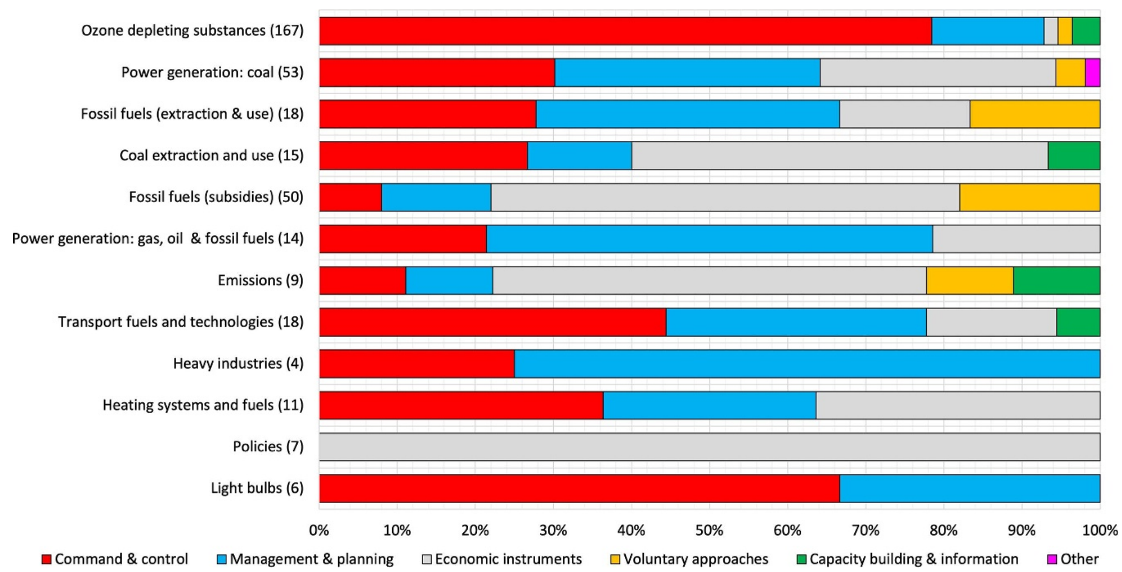

Figure 5. Phase-out policies for the most frequently discussed phase-out targets.
Note: numbers in brackets indicated total coded mentions for that target. The low number of codes for some categories should be heeded when interpreting results.

A number of temporal trends emerge from this analysis. The share of command-and-control approaches begins to decline after around 2005. On the other hand, the share of economic instruments grows in the same period after being virtually absent from scientific discussions for the first decade. Nevertheless, the predominance of command and control along with management and planning points to a strong role of the state in catalysing and managing the consequences of phase-outs. Although voluntary and capacity-building tools are sometimes discussed, their limited presence in the coding results suggests their role in inducing phase-outs is considered secondary to the other approaches.

Closer inspection of the literature evoking command-and-control approaches reveals frequent mention of legally binding treaties (namely the Montreal Protocol) followed by regulations, bans, laws and environmental standards. Such instruments are commonly described as affecting targets like ozone-depleting substances, transport fuels and technologies as well as light bulbs (figure 5). Regarding the association with transport, announcements of imminent bans by national-level governments for ICEs in passenger vehicles, buses and trucks has triggered scholarly interest in this phase-out process (Meckling and Nahm 2019), notably in the context of the United Kingdom (Brand *et al* 2020), the

United States (Rinscheid *et al* 2020) and New Zealand (Horrocks and Wilson 2021). Modellers have simulated the speed and magnitude of GHG emissions reductions of various command-and-control interventions aimed at road vehicles (Bahn *et al* 2013). Still others have examined aviation, considering how a mandatory quota for synthetic fuels could accelerate decarbonisation (Gossling *et al* 2021). For light bulbs, the European Commission's Regulation 244/2009, enacted in 2009, has been discussed both during the initial introduction (Frondel and Lohmann 2011) and as a retrospective learning experience for innovation scholars (Koretsky 2021). Command-and-control approaches like power-plant emissions standards and halting the issue of mining permits are also discussed in relation to fossil fuel phase-outs, particularly for coal (Kittel *et al* 2020, Diluiso *et al* 2021).

Accounts of management and planning approaches mainly refer to timetables and targets set by national or regional governments. These reflect scheduled completions years for phase-outs (Fermeglia *et al* 2020) as much as targets that establish the quantity by which emissions must decline or alternative technologies increase (e.g. portfolio standards). We also found frequent mention of two types of management plans. The first type concerns overarching policies like climate action plans that formalise national or regional commitment to a phase-out (Durmaz *et al* 2020). The second involves comprehensive policy packages aimed at managing the phase-out process by planning the restructuring of carbon-intensive industries or mitigating negative consequences like unemployment. Widely discussed in the literature, management and planning approaches feature in policy descriptions for all targets examined (figure 5). In particular, we find a strong association with phase-outs targeting fossil fuel (extraction and use) and power generation (coal as well as gas, oil and fossil fuels). Mentions of management and planning instruments are tied to actual phase-out efforts in various regions. For instance, the objective to terminate the use of all lignite coal in power generation in Greece by 2028 is formally enshrined into the *National Energy and Climate Plan* (Ministry of the Environment and Energy 2019). This management plan positions this phase-out of coal as Greece's flagship decarbonisation tool leading to 2030 (Marinakis *et al* 2020). Management strategies are also inextricably linked to coal phase-outs. Germany provides a case in point. Behind this country's highly co-ordinated and ongoing phase-out of coal extraction and use in the power sector is an integrated package of measures recommended by the so-called 'Coal Commission' (Keles and Yilmaz 2020). This planned approach combines reshuffling budgets that formerly supported the coal industry, economic diversification strategies and retraining and compensation programs for mines and workers to mitigate side-effects like unemployment.

Mentions of economic policies especially concern instruments such as subsidy reform and removal, financial support and pollution pricing (e.g. carbon taxes) along with emissions and permit trading (e.g. cap-and-trade schemes). These instruments too can be traced to particular targets; notably coal extraction and use, fossil fuel subsidies, policies, emissions, and to a lesser extent, heating systems and fuels. Conversely, economic levers are virtually absent in discussions of ozone-depleting substances and light bulbs. The withdrawal of financial support is a cornerstone of discussions about phasing out fossil fuel subsidies, but is also described as contributing to phase-outs of coal extraction. The case of hard coal mining in Germany is a notable example (Oei *et al* 2020). Meanwhile, economic approaches like subsidy withdrawal and carbon pricing have also been viewed by modellers as an important but hypothetical means of inducing measures to phase-out GHG emissions from energy systems (Johnson 2010, Kharecha *et al* 2010). Economic approaches to phase-out are also discussed in the domain of heating systems. Hypothetical in nature, these discussions have taken place within simulations of various policy intervention choices that include both pollution pricing instruments such as carbon taxes and subsidies to spur the installation of new heating technologies (Nageli *et al* 2020). Finally, economic instruments are the sole focus of the 'policy' category, reflecting discussions about policy features deemed to compromise decarbonisation outcomes. Notably, these discussions have centred around proposals to phase out free allowances to industry in emissions trading regimes (Nachtigall 2019) along with other types of subsidies (in this case, direct payments to agriculture (Popp and Jambor 2015) that exacerbate high-carbon practices.

As hinted above, the bulk of publications mentioning command-and-control or management and planning instruments are those evoking actual phase-out experiences. Conversely, descriptions of phase-outs induced by economic instruments are more likely to occur in discussions of a hypothetical nature. This tendency can be confirmed from figure 6. If marrying this evidence with that presented in figure 4, a stronger picture emerges for the observation that phase-out policies in the real-world tend to rely on the traditional tools of the state (namely command and control instruments, such as regulation and laws) and management and planning instruments (such as timelines, target setting and management plans). Meanwhile, although scholars actively discuss economic instruments as a way of pursuing phase-outs, such discussions are not entirely reflective of real-world experiences.

4.4. Affected industries

Our analysis found that a small number of sectors dominate discussions about the industries affected by phase-out interventions (figure 7). The two most

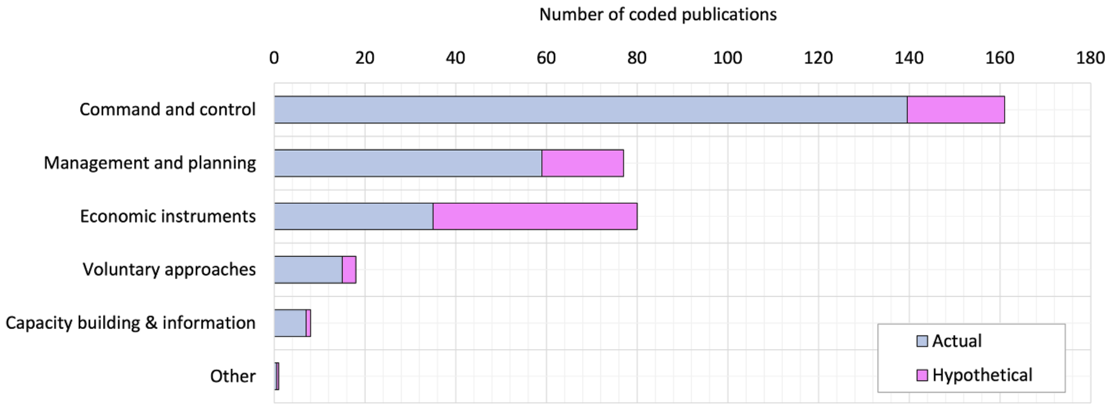

Figure 6. Policy categories by phase-out type.
Note: there were four papers that discussed both actual and hypothetical phase-outs. To deal with these cases, we split the value of each paper's code into two, allocating half (0.5) to the 'actual' portion of the figures and the other half (0.5) to the 'hypothetical' portion. A further five publications could not be classified and are omitted from the figures.

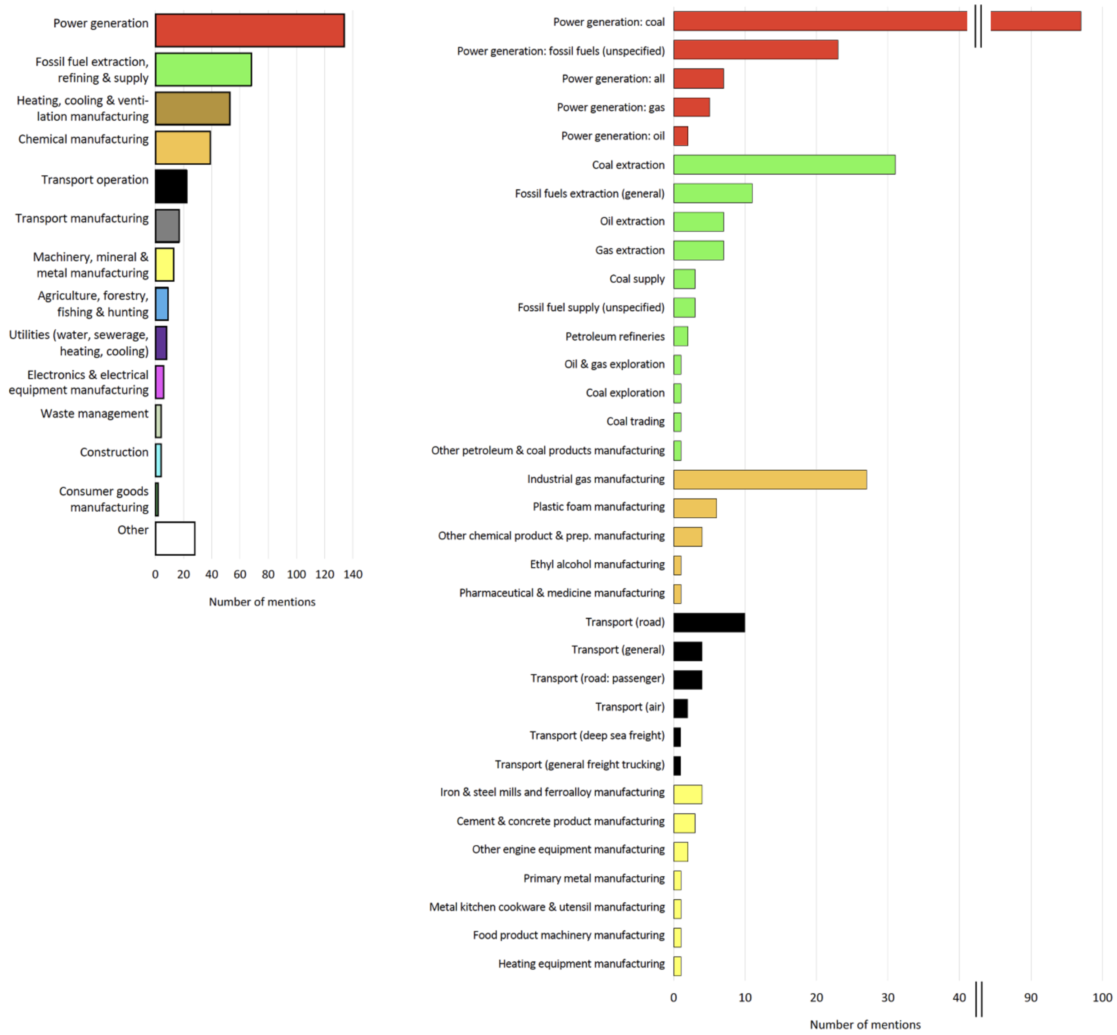

Figure 7. Aggregated industry sectors affected by phase-outs (left) and sectoral breakdown by specific industries (right). Right graph shows breakdown of sectors with at least ten codes and a composition of finer-grained industries in the classification scheme used (United States Census Bureau 2017b).

prominent are power generation (consisting mainly of coal-fired electricity generation) and fossil fuel extraction, refining and supply. This reflects the overwhelming presence of fossil-fuel related targets noted earlier (see section 4.2). But beyond these expected sectors concentrated around fossil fuel extraction and power generation we find a surprising diversity of industries. These notably include the heating,

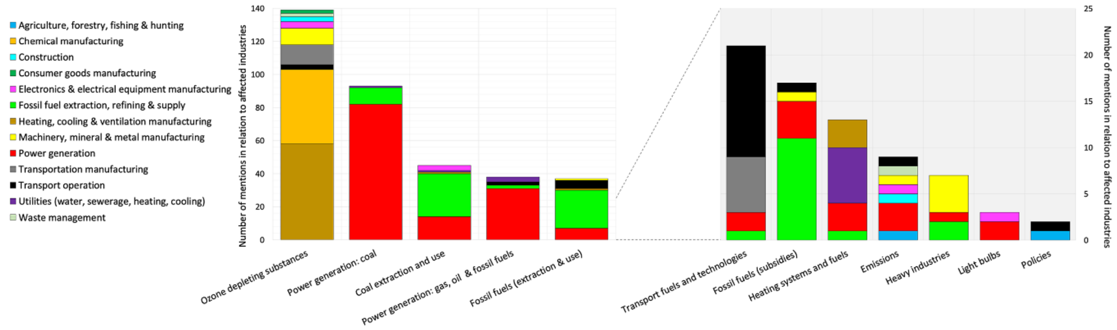

Figure 8. Industry sectors affected by the 12 most frequently discussed phase-out targets.

cooling and ventilation sector, chemicals manufacturing, transport, machinery and metal making, agriculture and other utilities (heating, cooling, etc) along with electronics and waste management. Once again, this heterogeneity of industry sectors points to the vastness of economic activities that contribute to climate change. Yet, for many of these we find only limited coverage in the literature. This situation appears to mirror a bias in climate change mitigation and scholarly debates in that the greatest attention is directed at the electricity sector or fossil fuels more broadly. Meanwhile, despite their considerable contribution to global GHG emissions, phase-out debates are yet to focus on other sectors like agriculture, construction and waste management.

Using a standard classification scheme (United States Census Bureau 2017b), the right-hand side of figure 7 presents a finer-grained breakdown of the specific industries featuring in phase-out discussions. Beyond the domination of coal power and coal mining, the broader sector of fossil fuel extraction shows considerable heterogeneity when broken down. Not only does this include studies focused on oil and gas extraction, some scholars have described how phase-outs targeting fossil fuel production affect specific activities such as exploration (Heede and Oreskes 2016, Piggot *et al* 2018) and seaborne trading (Parra *et al* 2021). The chemical manufacturing sector also exhibits some variety when disaggregated into specific industries. Aside from the industrial gas manufacturing responsible for production of ozone-depleting substances, plastic-foam makers receive some coverage in the literature due to their use of these substances in products like insulation materials (Li *et al* 2016). Discussions of transport related phase-outs encompass both the production of vehicles as well as their use, for example in fleets like bus agencies. Scrutinising this more closely, the literature on transport phase-outs reveals a tendency to focus on the road sector over more difficult to decarbonise sectors such as air transport, shipping and trucking. This can likely be explained by the faster development and deployment of low-carbon fuels and electric drivetrains relative to other transportation modes and by the proliferation of climate policies targeting this sector. Meanwhile, other hard-to-abate industries like iron, steel and cement receive far less attention than the power sector, for example, where the phase-out of fossil fuels is proceeding at a much faster pace due to the deployment of reliable, low-cost renewables. Indeed, we find that mentions of phase-outs affecting iron, steel and cement are either discussed recently (Vogl *et al* 2021) or from the perspective of pollution-abatement programmes in China (An *et al* 2018).

We also considered the industries associated with the phase-out of particular targets (figure 8). Two patterns can be distilled. At one of end of the spectrum we see a cluster of phase-out targets that affect a narrow range of industry sectors. These notably concern power generation targets, which might be conceived as highly concentrated 'mono-industries' (IEA 2021). At the other end of the spectrum, we see a situation where efforts to phase-out other targets will affect a much wider array of industries. An exemplary case is ozone-depleting substances. Phase-out efforts targeting the use of climate warming halons, HCFCs, HFCs and methyl bromide are described as entangling a sweeping list of industries that extend far beyond the above-mentioned sectors of heating, cooling and ventilation and chemical manufacturing. This is because such substances are widely used in transport manufacturing (for air-conditioners), transport operation (for mobile refrigeration systems), machinery making (for cleaning equipment) and border control (for disinfecting). Meanwhile, the collection of these gases requires cooperation from the waste treatment industry. This finding calls into question the assumption that the success of global efforts to phase out ozone-depleting substances is largely the result of their use being confined to a narrow range of industries (Stadelmann-Steffen *et al* 2021). Rather, the success of this global phase-out effort may be attributed to the ready availability of affordable alternatives that provided an easy drop-in substitute for their predecessor (Andersen *et al* 2013). In addition to ozone-depleting substances, the tendency for phase-out efforts to generate ripple effects over a wider range of industries is also somewhat

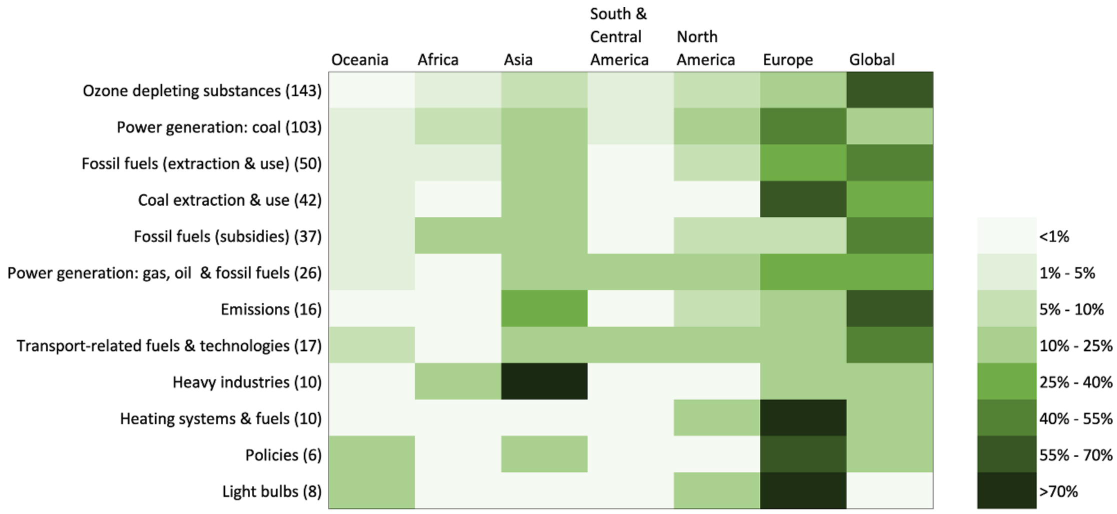

Figure 9. Geographic focus of the most frequently discussed phase-out targets.
Note: numbers in brackets indicate total coded mentions for that target. The low number of codes for some categories should be heeded when interpreting results.

visible for the case of heating and transport (Brand *et al* 2020)—two targets now coming into the focus of climate change mitigation measures worldwide.

4.5. Geographic regions

Findings indicate that climate-focused phase-outs are most frequently discussed from a global perspective (figures 9 and 10). Accounts of such phase-outs make up just over one-third of all contributions in our sample. The other two thirds refer to various world regions. Of these, mentions of phase-outs in Europe dominate the results, making up 26% of all codes. Moreover, the presence of the European region in the literature is growing rapidly, expanding five-fold during 2018–2021 compared to 2014–2017 (figure 10 and supplementary data 2 figure 4). The bulk of this scholarship describes initiatives affecting the European region as a whole, followed by Western Europe (Germany makes up 86% of codes) and Northern Europe (mainly United Kingdom, Sweden and Finland). Phase-outs in Asia are the next most discussed. Mainly articulated in relation to Eastern Asia (dominated by China), the Asian region makes up 13% of codes (when excluding the global category). Like Europe, papers discussing Asian countries are similarly experiencing a period of rapid growth, swelling four-fold over 2018–2021 compared to the four preceding years (supplementary data 2 figure 4). Somewhat surprisingly, North America receives less attention than Europe and Asia, comprising only 8% of all codes. Furthermore, the accumulation of studies for North America is considerably sluggish compared to Europe and Asia. Conversely, initiatives in the global south (especially Africa) are seldomly evoked. It is unclear if the weaker attention to these regions reflects a lack of on-the-ground phase-out activity or a scientific gap.

Our analysis also identified the phase-out targets featured in various geographic contexts (figures 9 and 10). For phase-outs initiatives described at the global-level, we find an emphasis on targets like emissions, fossil fuel extraction and transport in addition to ozone-depleting substances. Investigations about phasing out emissions are mainly hypothetical and occur in the context of global climate simulations by modellers (see also section 4.2). Inspecting this literature closer reveals a tendency to view carbon and other climate pollutants as universal substances that are phased out of future societies under simulations of various changes to society and technologies (Kharecha *et al* 2010, Brooks *et al* 2021). With respect to transport related phase-outs, though regulations targeting specific technologies like ICEs are often described from a national or sub-national level, the transport sector as a whole is mainly discussed from the global level. Again, this can be attributed to the attention that the transport sector has received in global climate models (Teske *et al* 2018, Gossling *et al* 2021) or in papers focused on identifying worldwide trends (Graaf *et al* 2021). Similarly, although phase-outs targeting fossil fuel extraction would also be expected to occur at the national or sub-national level, scholars frequently evoke the imperative of phasing-out fossil fuels as a global challenge (Heede and Oreskes 2016, Gupta and Arts 2018).

Conversely, discussions of some phase-out targets are strongly entwined with particular regions (figures 9 and 10). For example, scholarly work about phase-outs targeting heating systems tend to relate exclusively to policy initiatives and hypothetical debates in Europe that have emerged mainly since 2018 (Frank *et al* 2020, Lindroos *et al* 2021). Likewise, Europe also dominates discussions of other phase-outs targets. These include power generation

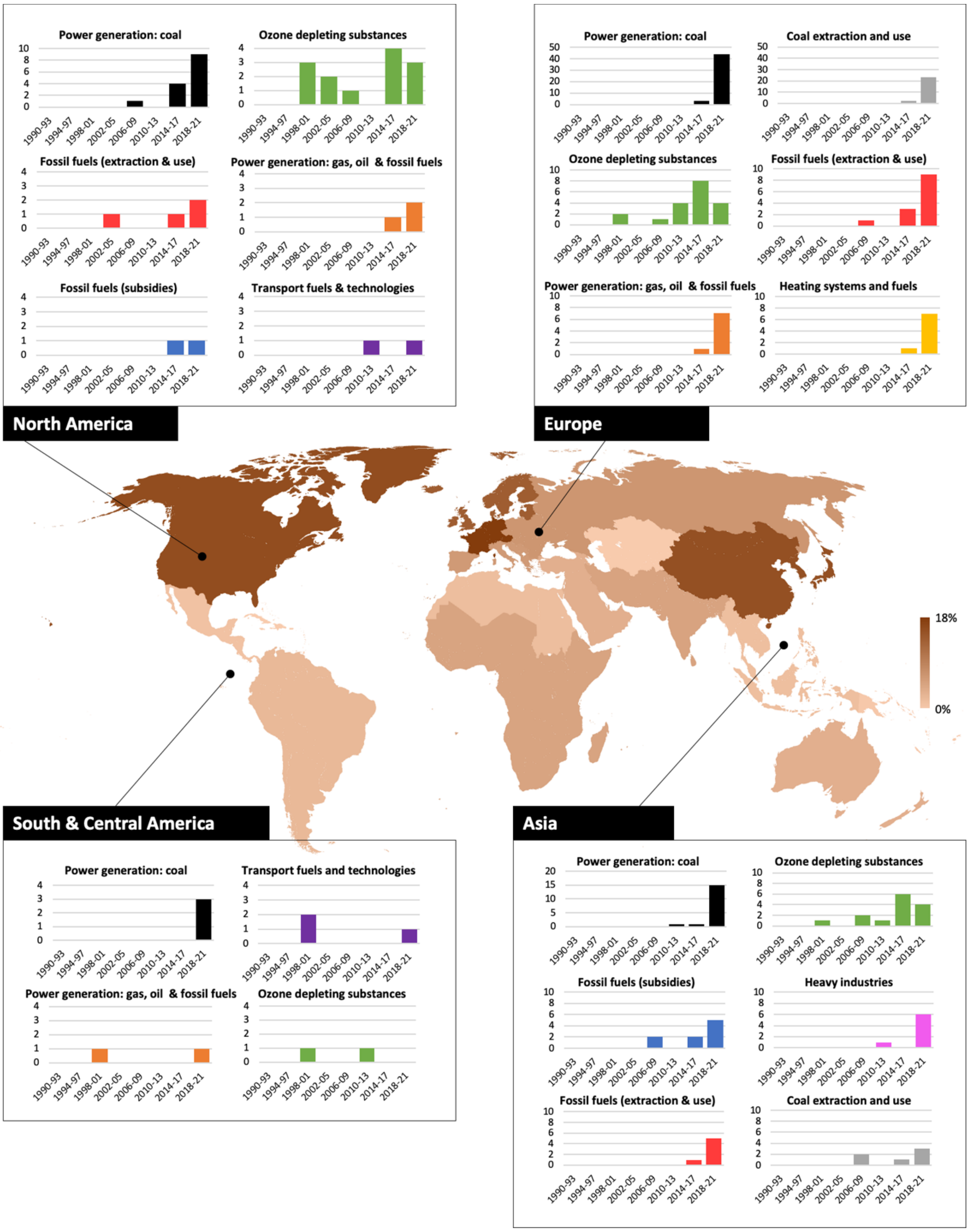

Figure 10. The geographic regions affected by phase-out initiatives and the most frequently described targets for each.

(including from coal, fossil-fuels in general, and oil and gas), coal extraction and use, policies and light bulbs. The strong presence of the European context in our dataset suggests this region is a global hotspot for phase-out activity and debates. Meanwhile, we find that descriptions of phase-outs affecting heavy industry are predominantly anchored to the East Asian region. These have surfaced especially since 2018. Indeed, of the eight papers coded in this category, five describe initiatives by the Chinese state to coordinate the forced downscaling of inefficient and high emitting industries at the root of China's historically poor air-quality levels and soaring GHG emissions (Qian *et al* 2021). While these interventions may affect specific industries such as steel and iron (Li *et al* 2020), scholarship also describes these clean-up efforts as simultaneously targeting a cohort of heavy industries, (e.g. cement, chemicals, power, and steel production) (Zhang *et al* 2011, Qian *et al* 2021). Unique to the Chinese context, such sweeping phase-out initiatives that target entire clusters of economic activity are reflective of this country's top-down approach to planning and transforming industrial structures

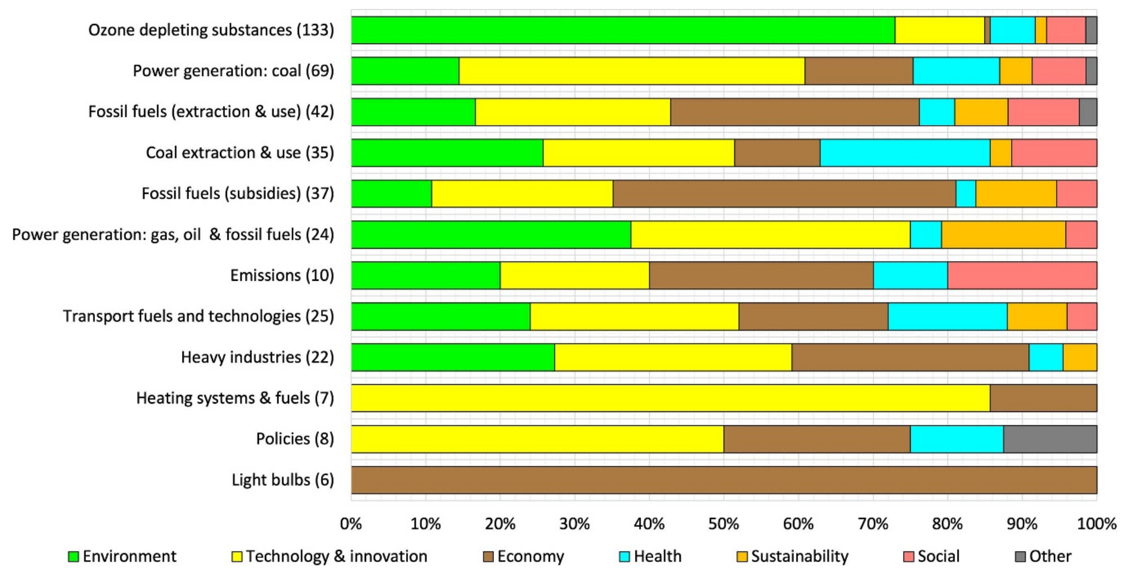

Figure 11. Non-climate co-benefits ascribed to the most frequently discussed phase-out targets.
Note: codes indicate all benefits cited besides climate change mitigation, which is the common driver of all phase-out targets. Numbers in brackets indicate total coded mentions for that target. The low number of codes for some categories should be heeded when interpreting results.

in accord with changing climate and innovation goals.

4.6. Co-benefits and multiple aims

Our analysis reveals that besides positive outcomes for decarbonisation, phase-outs targeting the various technologies, energies and practices at the root of the climate crisis are also propelled by awareness of diverse co-benefits (see also supplementary material 2 figure 5). Several patterns emerge when examining associations with specific targets (figure 11). The most striking finding is that dominant descriptions of co-benefits are not environmental (e.g. air quality or biodiversity) as one might expect given the domination of fossil-fuel related phase-out targets. Instead, the bulk of co-benefits are evoked in terms of technology and innovation or economic improvement. Concretely, mentions of technology and innovation make up just over 25% of all codes, while economic benefits are cited for 18%. The glaring exception is ozone-depleting substances, where the environmental motivation of preserving stratospheric ozone is stressed. Meanwhile, for all targets, we find much less attention to social and health benefits.

The literature unanimously portrays phase-out as a critical lever for inducing innovation and technological progress (Rogge and Johnstone 2017, Reda *et al* 2021). Moreover, it describes policies that support creation and transformation (e.g. new clean technologies) and phase-outs (e.g. fossil fuels) as an intertwined and twofold process towards the same decarbonisation goals (Blondeel *et al* 2021, Hermwille 2021). Positive outcomes for technology and innovation are emphasised for most targets, notably for power generation (coal as well as other fossil fuels), heating systems and fuels as well as policies. Following the discussion in section 2, this coding category captures different objectives. *Substitution* refers to the relatively seamless replacement of a targeted element with another—as exemplified by switching from coal to gas in power generation or from CFCs to ozone- and now climate-friendly refrigerants. In contrast to substitution, ambitions to trigger *systemic change* seek to use phase-out as a lever to drive broader socio-technical transformations beyond the element targeted. We also coded instances of *creation*, capturing the idea of enacting phase-outs as a means to kickstart the search for, and development of, novel technologies, materials or social arrangements.

In terms of such co-benefits for technology and innovation, we found that *systemic change* is the predominant descriptor (see supplementary material 2 figure 5). Numerous studies help contextualise these findings. For instance, desires to phase-out fossil-fuel power are frequently described as part of a broader ambition to trigger the transition to an energy system based on decentralised renewable energy or to accelerate the transition to a low-carbon economy (Blondeel *et al* 2021). Next, while some studies describe phasing out oil or ICEs in the transport sector as a substitution exercise, others frame this as part of a broader signalling strategy aimed at catalysing the transformation of the entire automaking industry (Meckling and Nahm 2019). Meanwhile, in the illustrative case of district heating in Hamburg in Germany, the phase-out of fossil fuels is framed as the lynchpin of a ‘transformation path’ towards so-called ‘fourth-generation’ systems, which rely on renewables, lower temperatures and smart controls (Kicherer *et al* 2021).

Economic benefits are frequently expressed in terms of gains for conserving energy, material or resources. Though this tendency is also visible for light bulbs (Frondel and Lohmann 2011), in the case of fossil-fuel subsidies, fossil-fuel extraction and emissions, the described benefits are much broader. For instance, the literature dealing with fossil-fuel subsidies describes how phase-outs are justified by views that subsidies promote excessive energy consumption and divert private and public investments away from alternative and clean sources while negatively affecting their competitiveness (Karaev *et al* 2020, van Asselt and Skovgaard 2021). Other studies describe how phase-outs of fossil fuel extraction and associated power generation are driven by prospects of creating new employment opportunities in a renewables-based economy (Patrizio *et al* 2018), lowering energy production expenses by capitalising on plummeting costs for renewables (Nasirov *et al* 2020), boosting energy security (Duan and Wang 2018), and finally, mitigating financial concerns such as 'stranded asset risks' faced by coal-fired power plants and fossil fuel infrastructure (Heede and Oreskes 2016, Edenhofer *et al* 2018).

In sum, while the literature does not ignore the barriers to introducing phase-outs or potential adverse consequences, the frequent mention of diverse co-benefits besides climate change mitigation may largely explain why phase-out policies have proliferated across the globe and why these practices are increasingly studied by scientists.

5. Conclusion and implications

Several key insights emerge from this review of the vast body of scholarship that has engaged with 'phase-out' as a concept and strategy for advancing decarbonisation goals. Of central importance, the rapidly growing literature points to a rapid uptake of phase-out as a concept and policy approach that bridges multiple scientific disciplines and fields of practice. Spanning both science and policy, phase-out is playing an increasingly important role in operationalizing the politically difficult task of 'creative destruction' (Kivimaa and Kern 2016) by deliberately triggering the decline of artefacts, materials and practices contributing to climate change.

In this way, while an important inter- and even trans-disciplinary programme is taking shape around phase-out (McDowall 2022, Rinscheid *et al* 2023), more work needs to be done to build bridges across conceptually fragmented lines and contrasting disciplinary orientations (Rosenbloom and Rinscheid 2020). Toward this end, several areas of enquiry could guide future scholarship. In particular, we note a persisting dearth of theoretical explanations about the mechanisms underpinning the process of phase-out. Although research is moving to tackle this area (Koretsky and van Lente 2020, Bento *et al* 2021, Koretsky *et al* 2023a), there is an additional need to further elucidate the conditions that enable or prevent the introduction and smooth implementation of phase-out policies. For instance, why is it that some geographies like the European Union, Canada and Brazil have succeeded in implementing measures to phase out incandescent light bulbs (Stegmaier *et al* 2021) while such policies have lagged in technologically advanced and wealthy nations like Japan and New Zealand?

Moreover, the diverse policy instruments underlying phase-outs that are uncovered in this study raise questions about their comparative or complementary roles and impacts. There is also a need to deepen understanding of the potential benefits and trade-offs of phase-out. While this policy approach is characterised by its gradual, long-term and explicit commitment to completely abolishing a problematic artefact or practice, what are the merits and problems compared to other interventions by state or societal actors, which also catalyse the decline of socio-technical systems (e.g. bans, moratoria, divestment)? We also expect some interaction between these complementary approaches. For instance, outright bans are frequently integral to phase-out programmes. Consider for instance the cases of incandescent light bulbs and internal gasoline engines. Meanwhile, public- or investor-led divestment initiatives too have created the political impetus to implement formal phase-out policies targeting fossil-fuels and their associated technologies and subsidies. In parallel, a highly related concept—'phase-*down*'—has also garnered attention in climate governance. Notably, this term entered the global stage by replacing the commitment to phasing *out* unabated coal power in the Glasgow Climate Pact that emerged from the United Nations climate change conference in 2021 (UNFCCC 2022, p 5). Of note, this replacement was deliberately intended to weaken the commitment to stipulating a complete end for coal power (UN 2021). Future research should tease out the conceptual and empirical differences between phase-out and phase-down, especially clarifying the appropriateness of the latter for accelerating progress to climate neutrality targets by mid-century.

Another key finding is that phase-out scholarship is rapidly broadening in terms of methodological approaches and empirical terrain. Our review found that contributions stretch from case studies of real-world policies and their outcomes to hypothetical explorations of phase-out as a generic approach for climate change mitigation and innovation. We found engagement with diverse phase-out targets, ranging from fossil fuels in general to light bulbs and agricultural practices. Beyond frequently studied industry sectors like power generation and energy extraction, phase-outs are also described as affecting transport, heavy industry, agriculture and more.

The broadening study and practice of phase-outs reflects the growing recognition of this approach as a critical tool for advancing decarbonisation. This heterogeneity also sheds light on the pervasiveness of human activities that contribute to climate change—all of which must be progressively reconceived during the transition to carbon neutrality. And with the proliferation of net-zero commitments and efforts to accelerate change (Seto *et al* 2021), no sector or industry is likely to escape transformative adjustments and the accompanying use of phase-outs to deepen and propel processes of change.

However, as the prevalence of phase-out interventions become increasingly prominent in policy and science, we foresee a growing need for sensitivity toward obstacles that can impede their political feasibility and towards negative consequences that can arise (Normann 2019). While the phase-out of some targets may concern concentrated mono-industries such as coal extraction or power generation, our analysis showed that in other cases, like ozone-depleting substances and transport, phase-out interventions simultaneously affect a broad spectrum of industries. This evidence supports the idea that established technologies, materials and practices are embedded in wider socio-technical systems. Moreover, it indicates that far-reaching ripple effects may result even when policymakers single out a particular element for phase-out (Andersen and Gulbrandsen 2020). Consequently, attempts to introduce phase-out policies can encounter stiff resistance not only from industry, but also from societal stakeholders and consumers. For instance, even the phase-out of light bulbs in Europe prompted backlash from end-users attached to the nostalgic quality of traditional bulbs (Koretsky 2021). In addition, phase-outs inevitably trigger a need to manage negative socio-economic impacts like the loss of assets, factory closures, employment and economic activity (Geels *et al* 2017). But phase-outs may also damage intangible qualities like the cultural identity and socio-economic vitality of regions that emerge around particular economic activities, technologies and socio-technical systems (McDowall 2022).

This raises several critical questions for research and practice. For instance, how can the side effects of phase-outs be anticipated and actively managed (UNFCCC 2020)? How can phase-out strategies increase their political feasibility and social acceptance (Normann 2019), balancing ambitions to terminate environmental 'bads' with positive visions of desirable futures to mobilise stakeholder support? Which complementary strategies are needed to rebuild new industries and assist firms and workers to migrate from one industry to another (Andersen and Gulbrandsen 2020)? What lessons can be drawn from differing phase-out paces? For instance, can slowing the pace of phase-out trajectories offer surer or more feasible outcomes or does this potentially undermine the effectiveness of policy implementation? When pursuing desirable outcomes based on resilience and equity, are some phase-out approaches fairer than others? Finally, how can equitable phase-out strategies be developed while not compromising climate ambition?

With benefits for innovation widely evoked across our dataset, more understanding is also required on the contrasting depth of changes induced by phase-outs. We see on the one hand phase-outs targeting singular elements that are easily tackled with substitution tactics, like light bulbs and ozone depleting substances. But other targets require more transformative change, two examples being transport systems and emissions from agriculture. Future studies should thus remain sensitive to the broader transformative or more substitutive ambitions that underly the specific phase-out approaches. This is because policy approaches that each share a 'phase-out' approach may trigger entirely different degrees of change in socio-technical systems, also producing differing outcomes for long-term sustainability goals. For instance, while switching one technology or energy source with another can generate short-term gains, long-term sustainability goals can be compromised (Rosenbloom *et al* 2020). Consider the negative ecological impacts caused by the substitution of gasoline with biofuels and batteries in the transport sector, which have driven increased mineral extraction and deforestation (Limenta 2020, Sovacool *et al* 2020). Moreover, viewing phase-out as a simple lever for switching to quick-fix technologies risks missing the more important opportunity to catalyse a deeper transformation of the broader systems that drive climate change and unsustainability (Rinscheid *et al* 2021).

Finally, our review identified several underrepresented areas meriting deeper attention. Notably, there is a lack of academic engagement with phase-out activity that concerns: (a) jurisdictions beyond Europe, North America and China; (b) hard-to-abate sectors like steel, cement and aviation, which rely on fossil fuel-based blast furnaces and jet engines; and (c) non-fossil fuel targets and industries (e.g. agriculture, where emissions from livestock production are the dominant climate driver). There is also a need for more knowledge about emerging phase-outs directed at gas extraction and fossil-fuel heating systems as well as waste treatment options like incineration. The rarity of empirical cases covering such hard-to-abate sectors suggests that actual policies may be limited. Investigating how phase-out strategies can contribute to the decarbonisation of these sectors would thus generate valuable insights for practice, while advancing scholarship.

In closing, limitations of this study also suggest important directions for future research. Although the academic discussions examined in our dataset are tightly connected to actual policy developments, it is unclear if the trends identified in this review reflect the state of actual phase-out activity or the evolving foci of academic debates. Future studies could complement our work by surveying large numbers of ongoing and completed phase-out policies across the world. By examining a larger number of policies than literature to date, the trends identified in this study could be further fleshed out or even revisited. Moreover, valuable insights into causalities could be gained, especially with respect to conditions that enable or hamper successful phase-outs. Despite such limitations, this study provides a first and comprehensive examination of a policy tool that is becoming increasingly critical to efforts aimed at spurring decarbonisation.

Data availability statement

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

Acknowledgment

We are grateful to the funders that supported this study. G T received funding from the bilateral program from the Japan Society for the Promotion of Science (Grant Nos. JPJSBP120203502 and JPJSBP120229922). A R received funding from the Swiss Network for International Studies (Grant No. 191001-210930) and from the Basic Research Fund (GFF) at the University of St. Gallen, Switzerland (Grant No. 1031563). D R received financial support from the Social Sciences and Humanities Research Council of Canada.

Appendix

Table A1. Inventory of phase-out targets.

	Count	Total
Ozone depleting substances	—	**127**
Carbon tetrachloride	1	—
CFC	38	—
Halocarbons	4	—
HCFC	15	—
HCFC-22	7	—
HFC	12	—
HFC-134a (tetrafluoroethane)	10	—
Methyl bromide	3	—
R22	1	—
R123	1	—
R245fa	1	—
R404A	1	—
R410a	2	—
SF6	1	—
Unspecified ozone depleting substances	30	—
Power generation: coal	—	**83**
Coal power	83	—
Fossil fuels (extraction & use)	—	**53**
Fossil fuels (general)	39	—
Fossil fuels (general): extraction	5	—
Fossil fuels (general): infrastructure	4	—
Fossil fuels (gas): extraction	1	—
Fossil fuels (gas): general	1	—
Fossil fuels (oil): extraction	1	—
Fossil fuels (oil): technologies	2	—
Coal extraction and use	—	**34**
Coal extraction	15	—
Coal: technologies	2	—
Coal: unspecified (use etc)	17	—
Power generation: gas, oil & fossil fuels	—	**26**
Fossil fuels (gas): power	3	—
Fossil fuels (general): power	20	—
Fossil fuels (oil): power	3	—
Fossil fuels (subsidies)	—	**28**
Fossil fuels subsidies	28	—
Emissions	—	**18**
CO2/GHGs	17	—
Aerosols	1	—
Transport fuels and technologies	—	**17**
Internal combustion engines (ICEs)	11	—
Oil in transport (road or unspecified)	5	—
Oil in transport (air)	1	—
Heavy industries	—	**12**
Blast furnace (iron and steel making)	1	—
Carbon intensive industries	9	—
Cement technology	1	—
Inefficient heavy manufacturing technologies	1	—

(Continued.)

Table A1. (Continued.)

	Count	Total
Heating systems and fuels	—	**10**
Heating systems: oil-based	1	—
Heating systems: fossil fuel-based (general)	7	—
Heating fuels: fossil fuels (coal)	1	—
Heating fuels: fossil fuels (oil)	1	—
Policies	—	**7**
Policy or policy feature: subsidies	2	—
Policy or policy feature: other	5	—
Light bulbs		**6**
Light bulbs	6	—
Biofuels	—	**5**
Biofuels	5	—
Chemicals	—	**2**
Agrochemicals: fertilizers	1	—
Hazardous substances: organic rankine cycle fluid	1	—
Industrial practices	—	**4**
Biomass burning in agriculture	1	—
Fishing/fishing practices	1	—
Waste disposal: incineration	1	—
Waste disposal: land application of sewerage sludge	1	—
Other	—	**10**
Dark-colored roofs	1	—
Drivers of path-dependency	2	—
Peat	1	—
Red meat	1	—
Unspecified	2	—
Unsustainable energy	3	—
Total	442	442

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