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Phase-out: Mapping the evolution of an emerging bridging concept for sustainability

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Summary

"Phase-out" is garnering increasing attention as a policy approach for gradually abolishing various causes of unsustainable development, be they toxic substances like lead and mercury, polluting practices like ocean dumping, or fossil fuels and associated technologies. Knowledge on historical and contemporary phase-out experiences has accumulated across science, but much remains confined within particular disciplines. To synthesize these debates and spur interdisciplinary dialogues, we systematically examine 870 publications, tracing this concept's evolution over 50 years, from the 1970s to the present. Using a coding-based mapping approach, we examine the disciplines discussing phase-outs, technologies and substances targeted, drivers, policy instruments and geographic and industrial contexts. We find a rapidly growing body of literature whose historical focus on polluting or hazardous substances has shifted to phase-outs conceived in response to climate change. Moreover, findings suggest phase-out is an emerging bridging concept with potential to mobilize transdisciplinary dialogues and transformative action towards greater sustainability.

INTRODUCTION

To achieve sustainable development within planetary boundaries, current systems of production and consumption must undergo deep transformation [1, 2]. Recognizing the deep running and long-term nature of path dependencies that perpetuate incumbent systems [3, 4], a growing body of research underscores the need to downscale and even *abolish* the specific technologies, materials and practices that compromise sustainability goals. With emergence and decline both being critical and intertwined drivers of innovation [5-8], strategies to deliberately catalyze the decline of unsustainable socio-technical configurations and their components are mustering increasing interest from scholars and policymakers [9-14].

This study focuses on one particular strategy that has garnered considerable attention across diverse scientific disciplines and policymaking contexts: *phase-out.* In studying phase-out, we refer to a policy intervention aimed at sequentially terminating a specific technology, substance or process that causes negative externalities [9]. Not only is this policy approach attracting growing interest in the literature [11, 13, 15-18], but for decades, phase-out has provided the driving paradigm steering practical efforts to mitigate a broadening array of sustainability challenges. This list includes the destruction of the stratospheric ozone layer caused by ozone-depleting substances [19]; human and environmental health risks posed by chemicals like mercury [20], lead [21] and cadmium [22]; and anthropogenic climate change and air pollution caused by fossil fuels and associated technologies like coal-fired power plants [23] and internal combustion engines [24]. Furthermore, amidst accelerating climate action across the world, recognition of the importance of phase-out as a tool for advancing sustainability and climate goals has been further crystallized by prominent international institutions. Consider, for instance, efforts to formalize a global phase-out of coal-power and internal combustion engines at the Glasgow Climate Change Conference (COP26) in late 2021 along with the IPCC's Sixth Assessment Report's [25] emphasis on phasing out fossil fuels—especially coal—by mid-century.

Yet, although phase-out has risen in prominence as both a strategy and concept for tackling sustainability challenges, much of the relevant scientific discourse remains scattered across disciplinary perspectives and scientific fields. Moreover, this research has made limited attempts to systematically leverage insights from diverging disciplinary communities in order to learn from past empirical experiences with phase-out and to take stock of the core features and changing nature of this policy approach. Indeed, prior research [9] has found that of multiple concepts capturing the process of socio-technical decline, phase-out is the most prominent, but also the most disparate and undertheorized. There is thus a need to draw together multiple disciplinary insights on phase-out to comprehensively carve out its evolving character while linking the disparately occurring scientific debates with a view to enrich both theory and practice.

In response, this review seeks to systematically analyze research from diverse scientific fields and disciplinary perspectives to deepen understanding of phase-out and its practical transformative potential for sustainability. Concretely, our objective is to map out the core features of phase-out interventions evoked within the scientific literature and elucidate their changing nature from inception to present day. To achieve this, we use a mapping approach [26], coding and analyzing peer-reviewed articles in English that were extracted from Scopus and then screened in accordance with explicit inclusion criteria (see **Experimental Procedure**). The resulting corpus consists of 870 papers accumulated since 1970 across the entire scientific spectrum, stretching from the humanities and social sciences to engineering and the life sciences. Our analysis is guided by five interrelated research questions: 1) what is the nature of the phase-out target; 2) what drivers are associated with its discussion or implementation; 3) in which industrial contexts are phase-outs being implemented and studied; 4) what policy instruments are associated with the discussed phase-out; and 5) in which geographical region are phase-outs implemented and studied?

This review reveals a marked evolution in the practice and conceptualization of phase-out over the five decades studied. Early studies portray a historical focus on environmental degradation and toxicity challenges, principally targeting specific substances. While such applications continue, climate change has become the dominating rationale for contemporary phase-outs. Consequently, the scope of targets has rapidly broadened to fossil fuels, refrigerants, technologies, subsidies, processes, and even entire industries. Both change and continuity mark this evolution. Although voluntary and market-based approaches increasingly feature in debates and descriptions of practice, the science has consistently described the process of phase-out as dependent on state-intervention via instruments of authority and planning. Results equally point to a global proliferation of phase-out programs, evidenced by a growing volume of targets and geographies. Phase-out has thus stood the test of time as a critical concept and policy approach for advancing sustainable development, consistently appearing in the discussions of diverse scientific fields, policymaking communities, and societal movements.

Moreover, findings suggest that phase-out shows promise as an emerging “bridging concept” [27, 28] that could help strengthen connections across these diverse communities of science and practice. Akin to other bridging concepts such as “sustainability” [29] and “resilience” [30, 31], which provide a common language and frame of reference to various stakeholders faced with complex socio-environmental challenges, the continuing and evolving study and application of phase-out embodies a similar opportunity. That is, the concept of progressively abolishing the materials, technologies, processes and socio-technical systems that hamper progress towards sustainable development has important potential to serve as a coordination device and shared paradigm for envisioning and pursuing transformative change.

RESULTS

Emergence and Evolution of Phase-out Literature

We identified 870 publications (available in **SI Data S01**) that evoke phase-out in the context of tackling sustainability challenges. The first appeared in 1970, describing how U.S. electricity utilities sought to address chronic air pollution and associated societal pressures by expediting the retirement of coal-fired power plants in favor of nuclear [32]. Then, after accumulating gradually over four decades, research on phase-outs has accelerated rapidly after 2016 (**Fig. 1**). The last two years are no exception, with 230 studies (26% of the sample) published in 2020 and 2021 alone. In the following, we trace the literature's evolution by firstly examining the academic disciplines contributing to debates, then turning to the targets, drivers, affected industry sectors, policy instruments, and geographies of phase-out.

A diverse spectrum of academic disciplines has contributed to this body of literature. Over the five-decade period, the contribution of environmental science (shown in blue in **Fig. 1**) is by far the most prominent. However, the relative share of individual disciplines has varied over time. While environmental science's engagement with phase-out has expanded in absolute terms, its relative share peaked at 39% in 2010, then decreasing to 25% in 2021 (see **SI Document S1 Fig. S1**). Engineering has peaked even earlier. Accounting for 15% of papers over 1970-2000, its share has since fallen to around 6% over the last two decades. However, recent figures for 2020 and 2021 suggest a renewed interest in phase-out from engineering scholars. In parallel, other disciplines have consistently strengthened their focus on phase-out both in absolute and in relative terms—particularly energy studies and the social sciences.

This disciplinary diversity also means that phase-out is approached from different perspectives. In the natural sciences, we find a strong tendency towards empirical work. This is typified, for instance, by the widespread use of environmental indicators to examine the need for or impact of phase-out interventions [22, 33, 34]. Scholarship from the social sciences, business studies and economics tends to encompass theoretical perspectives, frequently focusing on governance processes or societal drivers and barriers to phase-outs [9, 23, 35, 36]. This said, a considerable volume of work from the natural sciences [21, 37-42] engages with governance and societal aspects as well.

In sum, discussions about phase-outs have taken root in diverse scientific fields, consequently involving divergent disciplinary perspectives and methodologies. Attracting growing attention over five decades, the notion of phasing out the production and use of unsustainable materials, technologies and activities has instilled diverse scientific fields across the natural sciences, engineering, humanities and social sciences with a common vocabulary and understanding of a pivotal policy approach for advancing sustainability aims. Moreover, descriptions of dialogue and joint actions across science, policy and society abound in the literature [21, 37, 43-45]. Phase-out thus performs a role consistent with the defining features of a bridging concept [27, 28].

Amidst this disciplinary diversity, we also find attempts to conceptualize the mechanisms that contribute to the process of phasing out unsustainable artefacts and practices [15, 21, 43, 46]. Yet, although the idea of phase-out per se is actively discussed across diverse disciplines as a common paradigm for advancing environmental sustainability, the scholarship is yet to coalesce around a coherent or unified set of concepts, theories and methods that could be equated with the study or practice of this policy approach.

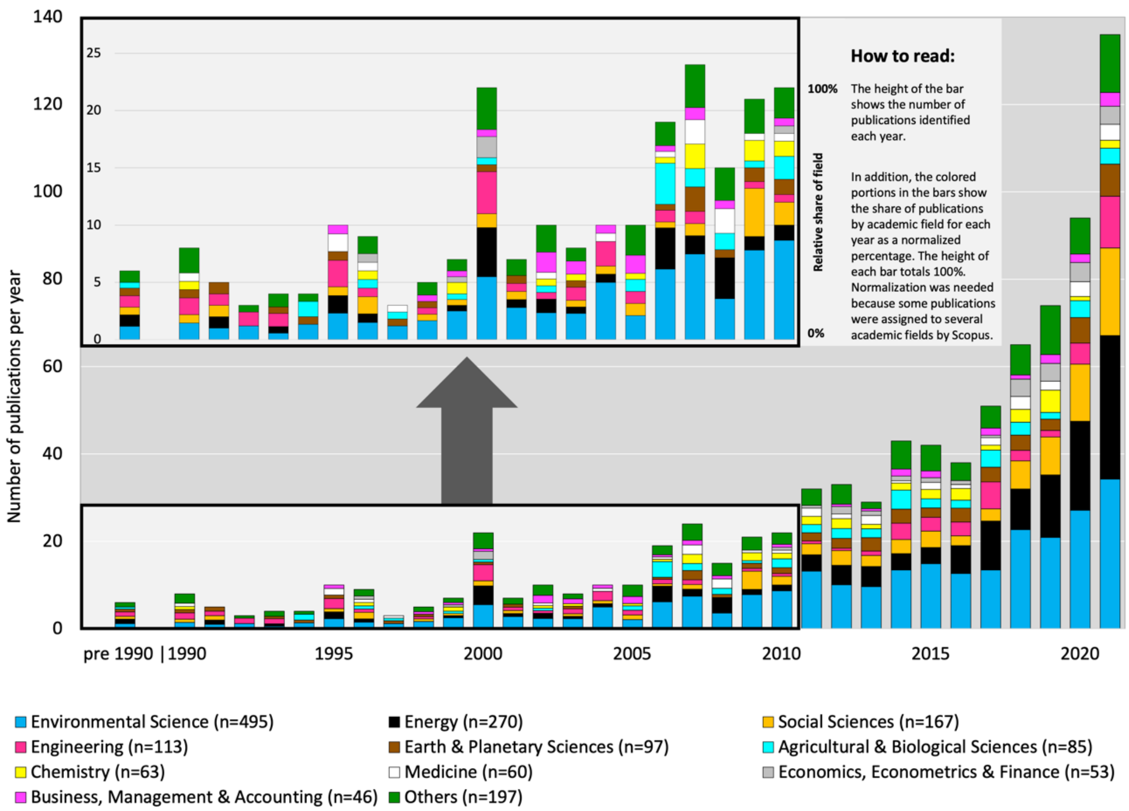


Figure 1. Number of annual publications and breakdown by academic field
This shows the number of studies published each year (n=870) that discuss phase-out as an approach to tackling sustainability challenges. Academic fields reflect categories provided by Scopus. For the relative share of each field see **SI Document S1 Fig. S1.**

Targets

Following a review of several decline-related concepts in the context of decarbonization [9], we classified the targets of phase-outs into three broad categories: substances, technologies, and processes. Our findings reveal a distinct evolution in the foci of scientific debates, evidenced by the following three trends.

First, discussions of substances (e.g. flame retardants, lead, agrochemicals) have attracted the most attention overall (**Fig. 2a**), making up 61% of all publications. Technology targets (e.g., nuclear power plants, lightbulbs) are also widely discussed, comprising 31% of studies. Phase-outs targeting processes (e.g. timber production, crop residue burning, ocean dumping of waste) are evoked less frequently, representing only 5% of publications. Cutting across our three-tiered classification, targets relating to fossil fuels increasingly dominate the literature in recent years. These phase-outs either concern technologies, like power plants [47-51], heating systems [36, 52] and internal combustion engines [24, 42, 53] or relate to fossil fuels as a substance. In the latter case, phase-out discussions focus on the extraction and use of fossil fuels per se [54-58], with frequently discussed approaches being subsidy removal [59, 60] or regulatory instruments like air quality regulations [23].

Second, we find a marked increase in the volume and diversity of targets discussed over time (**Fig. 2b**). This reflects increased attention to phase-outs in scientific debates as much as a proliferation of actual policies around the world. Specifically, we identified over 120 distinct descriptions of phase-out targets (**Dataset S02**). This diversity is striking, testifying to the many areas of application in which phase-outs are nowadays considered. In particular, our dataset covers targets as diverse as dark-colored roofs (which contribute to the heat-island effect) [61], battery cages in poultry farming [62, 63] and plastics [45, 64] along with per- and polyfluoroalkyl substances (PFAS), often also called “forever chemicals” [44].

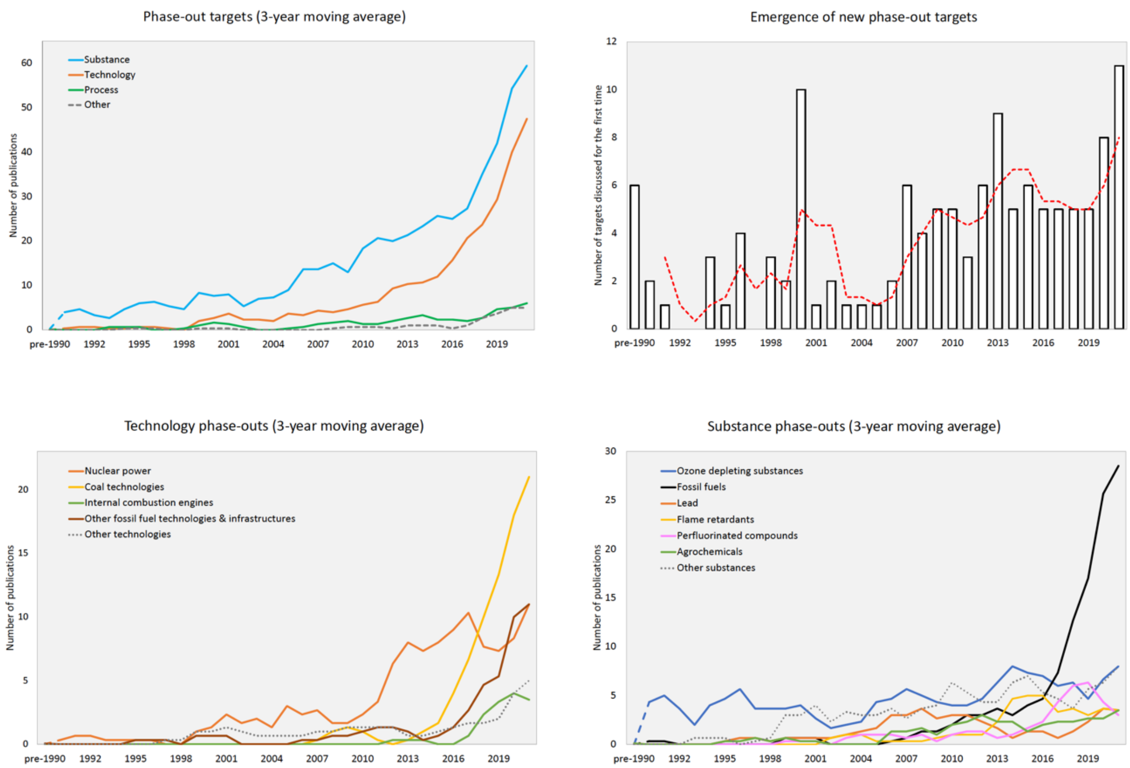


Figure 2. The evolution of phase-out targets
The top graphs show (a) elements targeted by the phase-out; and (b) the volume of new phase-out targets each year (i.e. those discussed for the first time in the literature). The red dotted line shows the three-year moving average. The bottom graphs show the number of publications each year that discuss the 10 most recurring targets in the dataset, organized into (c) technologies and (d) substances. These display aggregated coding results for a complete inventory of phase-out targets and those making up at least 5% of codes for either technology or substances (see **SI Data S02**). All lines show 3-year moving averages.

Third, the literature's evolution has been punctuated by several waves of scientific attention to specific phase-out targets (**Fig. 2c-d**). Furthermore, the timing of such waves is frequently attributable to progress in scientific knowledge or societal events such as accidents, political debates or governance initiatives. For instance, publications discussing nuclear phase-outs exhibit two distinct rises, each influenced by nuclear accidents. The first, extending over a decade from around 1998, reflects a swell of scientific interest in the consequences of phase-out programs and political debates that emerged in several European countries after the Chernobyl disaster in 1986 [65, 66]. The second and more prominent wave begins immediately after 2011, the year of the nuclear accident in Fukushima. Once again, this surge of literature reflects increased attention to reinvigorated phase-out programs and political debates—especially in Europe—as well as simulations of the consequences of nuclear-free electricity systems [67, 68]. In terms of substances, the sustained interest in the phase-out of ozone-depleting substances is attributable to the adoption of the Montreal Protocol (1987) and successive amendments that have kept the goal of achieving a complete phase-out on the global governance agenda for decades [46, 69]. Scholarly interest in curbing the production and use of perfluorinated substances, rising strongly after 2013 and peaking around 2019, reflects the mounting scientific evidence of environmental accumulation and human health impacts as much as the global propagation of phase-out policies triggered by this evidence [34, 44]. Similarly, the spike of attention to phase-outs targeting both fossil-fuels as a substance and their related technologies and infrastructures since the mid 2010s reflects the dual influence of the Paris Climate Agreement (adopted in 2015) and the Powering Past Coal Alliance, launched in 2017 to accelerate the global phase-out of coal power [56, 70, 71]**.** The recent surge of interest in phasing out fossil fuels is also propelled by recurring commitments within the G7 and G20 to progressively abolish fossil fuel subsidies [60, 72]. In sum, our analysis suggests a tight linkage between scholarship and policy in that scientific inquiry often mirrors governance initiatives or broader debates in society, but also informs the policymaking process leading to a phase-out [34, 37, 46].

The rich archive of discussions about diverse phase-out targets, accumulated over five decades throughout the literature's evolution, offers opportunities to learn from historical experiences. Along these lines, scholars from multiple disciplines are increasingly attempting to generate lessons from past cases, including in the context of coal extraction [23, 73], lightbulbs [35], leaded gasoline [33, 74] and ozone-depleting substances [75-78]. Overall, we find a strong inclination towards the study of well-known targets or individual cases. However, scholars are making increasing efforts to generate knowledge from multiple cases or by generating cross-cutting knowledge by looking at heterogenous phase-out targets in parallel [see 79]. For instance, scholars from social-science disciplines have endeavored to identify the common conditions that facilitate the implementation of state-led phase-out interventions while elucidating impacts on innovation and industry behavior [11, 16]. This said, the tendency to focus on well-known or same-type targets (coal and heating systems etc.) points to an important opportunity for scholars to not only engage more with emerging or less-studied cases, but also to systematically interrogate commonalities and differences in the conditions and processes of socio-technical decline that affect multiple instances of heterogenous phase-out targets.

Moreover, the reviewed literature also indicates that academic researchers play an active role in proposing or advocating for the phase-out of particular targets. This is evidenced by the observation that a number of phase-out targets evoked by scientists—e.g. kerosene in air transport or insecticides like malathion—have not (yet) been subject to an actual phase-out policy [see 80]. Indeed, over its evolution, the scientific literature has often advocated for the application of phase-out policies for a wide range of targets, encompassing all categories in our analysis—i.e. substances, technologies and industrial processes [40, 59, 81, 82]. This also suggests relevant interactions between science, society and policy, with the literature describing numerous cases where scientific investigations and calls for a particular phase-out initiative have provided important evidence or stimuli for public debates and policy introduction efforts [21, 41, 43, 46, 76, 78].

Drivers

Under the rubric of drivers, we examine factors discussed in scholarly work as motivating the consideration or implementation of phase-out policies, such as environmental concerns like air pollution or economic rationales like energy security. We find that over time, the nature of different drivers has shifted somewhat. Historically, phase-outs have been predominantly described and implemented as a means of tackling environmental or toxicity risks caused by specific substances (**Fig. 3a**). Such phase-outs typically aimed at reducing air or water pollution, preserving wildlife and eco-systems, or protecting humans and the environment from hazards posed by chemicals like ozone-depleting substances, lead and pesticides. Although such applications continue today, most of the phase-out discussions in the last decade have been driven by climate change [see 9, 80, 83]. Indeed, 56% of the studies published in 2020 and 2021 discuss phase-out as decarbonization strategy. Although substances continue to be targeted by policies, phase-outs implemented in response to climate change have broadened to encompass a much wider range of targets. Driven by early successes in targeting specific substances deemed harmful to environmental and human health, phase-out has thus evolved into a critical tool by which contemporary scholars and policymakers are tackling the climate crisis.

Beyond environmental or health-related concerns, phase-outs also emanate from other driving forces. These notably include aspirations to advance innovation or economic, social and broader sustainability goals **(Fig. 3b).** Of particular note is the growing recognition that phase-outs can play a role in creating room for innovation processes and the diffusion of alternative arrangements (coded as “Technology and Innovation”) [48, 84]. Some emphasize the role of phase-outs in driving *substitution* [40, 43, 85, 86], which involves replacing an established technology, substance or process with an alternative, such as shifting from internal combustion engines to electric drivetrains or from lead ammunition to non-toxic alternatives [21]. Others describe phase-outs motivated by aspirations to trigger broader, more *systemic change* [36, 87]. With such policies aiming to overhaul an entire socio-technical system, the transformative effect of a phase-out intervention can extend far beyond the target singled out for elimination [see 88]. Take, for instance, the potential of phase-out to eliminate harmful chemical substances in manufacturing as a means of promoting a more fundamental shift towards sustainable chemistry [38] or efforts to phase out single-use plastics to spur progress toward realizing a circular economy [89]. Discussions of the innovation-inducing potential of phase-out strategies are rapidly gaining prominence within the literature, even becoming an emerging subfield within interdisciplinary studies of technology, innovation, and socio-technical systems [11, 16, 17, 63, 90, 91].

Economic motivations are also frequently invoked, particularly regarding cost savings and economic growth. For instance, the plummeting cost of renewables along with opportunities to create new industries and employment provide an oft-cited rationale for the phase-out of fossil-fuel and nuclear power [92, 93]. Meanwhile, phase-outs targeting fossil-fuel subsidies or harmful practices in agriculture and other primary industries are often pursued to reduce economic burdens caused by environmental externalities and public expenditures, all while spurring a broader shift towards more sustainable development and a decarbonized economy [60, 94-97].

Analyzing the ten most recurring targets featuring in our dataset unveils associations with particular sets of drivers (**Fig. 3c)**. As mentioned, *enviro-toxic* drivers typically underpin targets in the substance category; namely lead, flame retardants, agrochemicals and perfluorinated compounds [37, 39, 40, 44]. *Climate-enviro* drivers tend to be associated with fossil-fuel technologies and substances, in addition to ozone-depleting refrigerants such as CFCs and HCFCs, which are also powerful greenhouse gases. Defying this classification, the phase-out of nuclear power is associated with a noticeably broad set of drivers. These include not only interlinked issues of safety, sustainability and societal demands, but also economic and innovation-related considerations [84, 91], which result from nuclear's tendency to impede the emergence of cheaper, more flexible and diversified renewable-energy sources [50].

With all ten of the most recurring targets in our dataset being characterized by the co-occurrence of several drivers **(Fig. 3c)**, our findings suggest that the implementation or advocacy of a particular phase-out intervention will typically result from multiple triggering factors. Furthermore, some studies have started to illustrate how different drivers tend to influence each other, in some cases, become mutually self-reinforcing [23]. Take, for instance, the association between concerns about risks to environmental or human health and the societal mobilization against certain substances, technologies or processes. This interaction has repeatedly been described in relation to nuclear power, hazardous chemicals like pesticides and mercury, and battery cages in the poultry industry [81, 98, 99]. Moreover, while public attitudes and sentiments (e.g. post-Fukushima fears about nuclear accidents) have often created the societal impetus for pursuing phase-out policies [63, 100, 101], discoveries from the natural and environmental sciences have also become a key driver of social and political change. Indeed, recent work offers explicit reflections about the roles played by scientific evidence and scientific advocacy in driving phase-out interventions [41]. These roles tend to occur in the stages preceding the introduction of a policy, when scholars may propose phase-outs that are then put to debate by the public and stakeholders [21, 102]. Such cases are especially prominent amidst efforts to confront societal dependance on fossil fuels. To this end, scholars have developed evidence or problem framings focused on negative social and economic consequences, which then enter into public debates, subsequently becoming levers for exerting pressure on policymakers [60, 103]. Illustrating this, scientists working have become members or even chairs of commissions dedicated to developing phase-out policies in tandem with actors representing policy, public administration, industry, and civil society. Initiatives targeting coal power in Canada and Germany [see 104, 105] and calls for a global Fossil Fuel Non-Proliferation Treaty that targets extraction activities [see 59, 106] are all prominent examples. To summarize, while analyses of interactions between different phase-out drivers are increasingly surfacing in scholarly work, much more needs to be done to interrogate how actors, their motivations and problem framings, scientific evidence, and broader economic and social conditions can collectively lead to the emergence of phase-outs to confront sustainability challenges. The intensifying scholarly engagement with these intersections underscores how phase-out is beginning to take shape as a shared vocabulary and bridging device between science, society and policymaking.

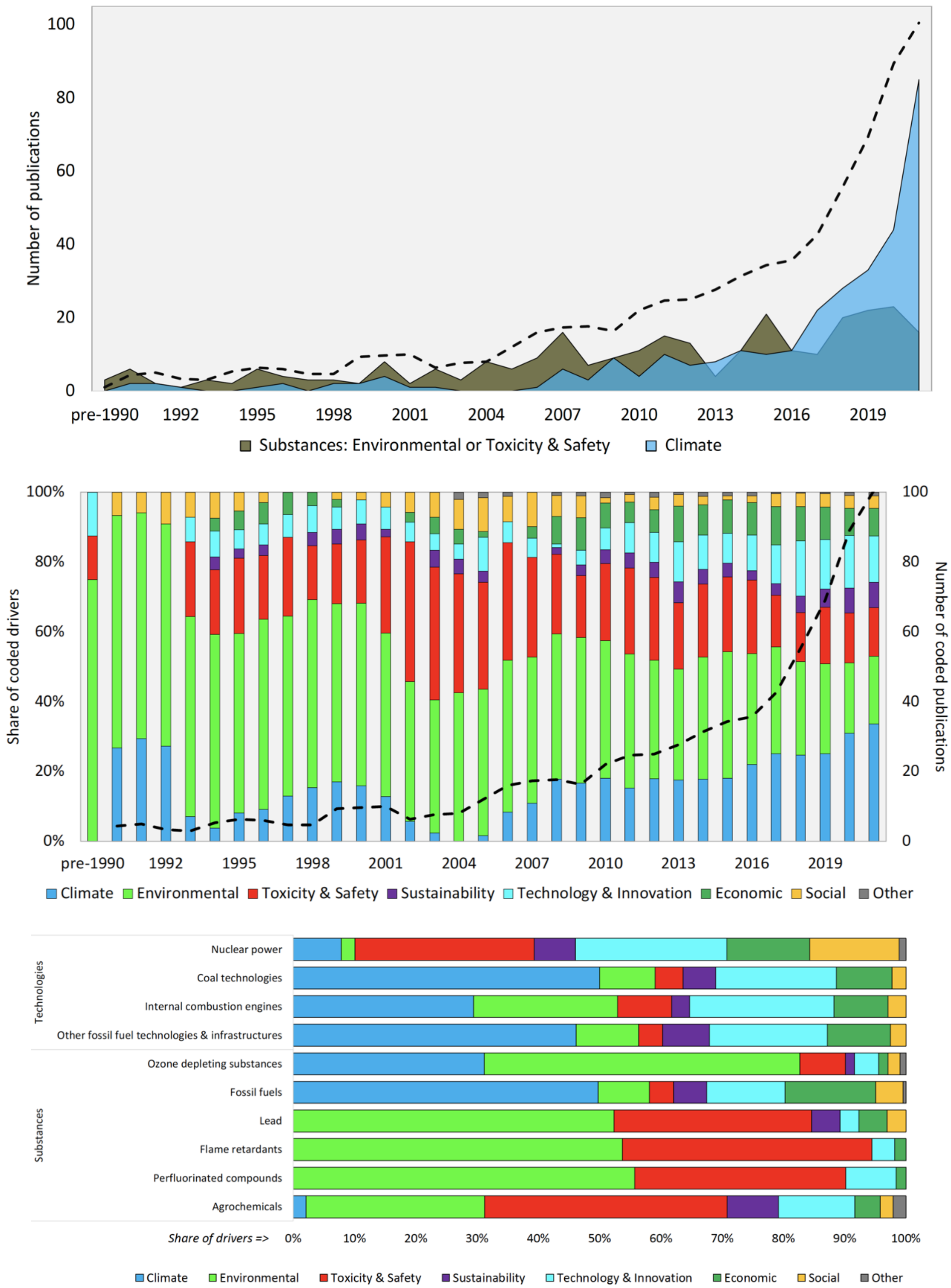


Figure 3. The evolving nature of phase-out drivers
The top figure (a) shows the total number of papers that discuss a phase-out targeting polluting or hazardous substance (khaki green) or a phase-out conceived in response to climate change (blue). Yearly results are smoothed to a 3-year average. For reference, the total number of publications receiving a code each year appears as a dotted line, also smoothed to a 3-year running average. The middle figure (b) shows

the relative share of codes for 745 papers mentioning drivers, smoothed with a 3-year average. The bottom figure (c) shows the relative share of coded drivers for the 10 most frequently mentioned targets. Papers citing multiple drivers received more than one code. All figures show aggregated results for coding that included more specific driver categories (see **SI Document S1 Fig. 2**).

Affected Industry Sectors

Power generation, fossil-fuel extraction (including refining and supply) and chemical manufacturing are the industry sectors that are most frequently discussed as affected by or relevant to phase-out interventions (**Fig. 4**). Power generation features the most prominently, reflecting the prevalence of studies discussing nuclear phase-outs in addition to the rapidly increasing scholarship on coal and other fossil fuels. In addition, the literature includes numerous descriptions of phase-outs affecting primary industries such as agriculture [41, 107] and hunting [21, 37, 108] along with chemical or electronics manufacturing [86] and waste management [109, 110]. Yet such work tends to originate from engineering and the natural sciences. Meanwhile, scholars from innovation and policy fields along with economics and social sciences have historically not engaged extensively with these domains due to a continuing tendency to focus on fossil fuels and related technologies [see 79]. Recognizing this opportunity to expand empirical and conceptual boundaries, innovation scholars are increasingly engaging with cases of phase-outs in industries outside the realm of power generation and fossil-fuel extraction [11, 63, see 79].

Our analysis suggests that while some phase-outs affect a limited number of sectors, others necessitate the involvement of a much broader spectrum. For instance, many technology phase-outs (nuclear power, coal technologies, internal combustion engines) tend to affect individual “mono-industries” such as power generation, fossil-fuel extraction or transportation manufacturing. In contrast, substance phase-outs are described as affecting a broader range of sectors. In this vein, phase-outs targeting ozone-depleting substances are associated with a strikingly vast array of industries including agriculture (where methyl bromide was widely used as a fungicide) [111], electronics, machinery and industrial-gas manufacturing, cement production [112], transportation manufacturing [113, 114], waste management [115] and construction [116]. Similarly, the scope of efforts to reduce human exposure to lead have expanded over time to impact multiple sectors. After initially focusing on leaded gasoline supplied by oil refineries [33] and wheel weights [117] produced in transportation manufacturing, the focus of recent phase-outs efforts has shifted to lead shot used in hunting [21, 37]. These results reinforce a point made by Andersen and Gulbrandsen [90], who emphasize the need to acknowledge how the impacts of phase-out interventions can be wide reaching, spilling simultaneously across multiple industries or sectors.

From a political-economy perspective, the diversity of affected industries could help explain resistance against phase-out initiatives. While political resistance is an under-researched topic

[17], existing accounts give little indication that a limited number of affected sectors will reduce political and economic barriers to introducing phase-out policies. Rather, those targeting individual industries reliant on the production or use of a specific technology or substance will often confront concentrated, well-organized and powerful opposition. Indeed, several studies [23, 24, 39, 118, 119] highlight how the political activities of the nuclear, fossil fuel, agrochemicals and transport manufacturing industry have delayed, weakened or derailed phase-out policies. These sizable sectors contribute significantly to local and national economies, cultural identity, and social prosperity [see 79].

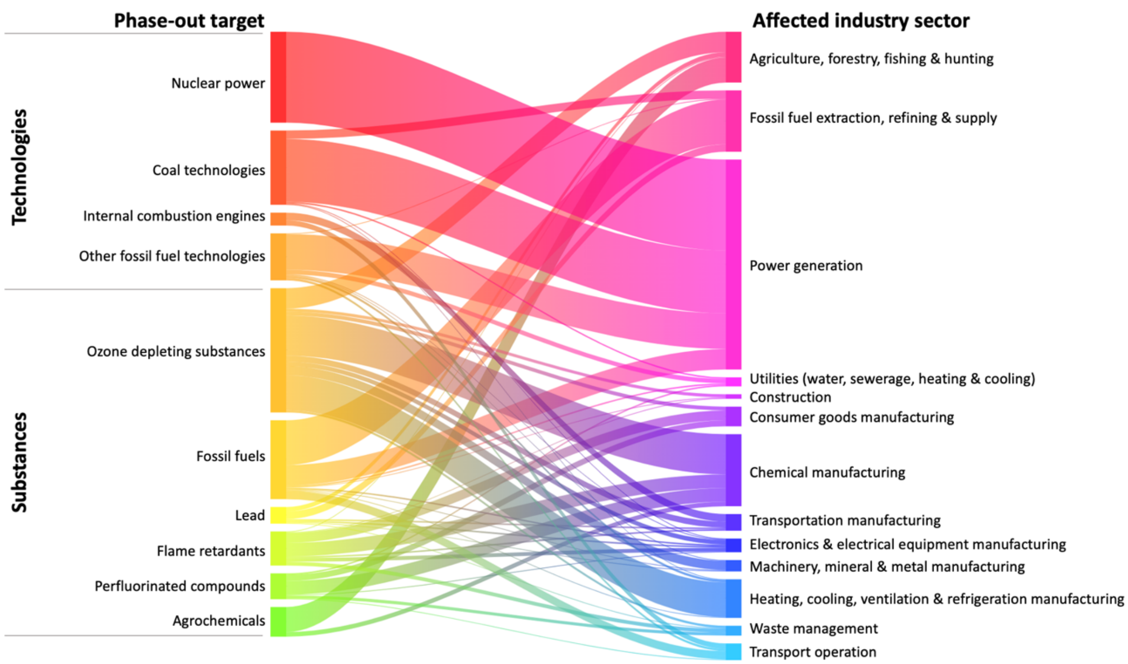


Figure 4. Industry sectors affected by the most common phase-out targets
The relative share of industry sectors described in the literature as producing, using or emitting the 10 most frequently mentioned phase-out targets (n=705 papers). Papers mentioning multiple industries received more than one code.

These insights point to the importance of strategies to alleviate the negative side-effects that can arise in the industries targeted or affected by phase-out interventions, be these lay-offs, forced asset write-offs or other ripple effects of industry contraction on local economies. Our analysis finds that such dimensions are commonly discussed in studies from both the social and natural sciences. Furthermore, the literature has started to engage with approaches to cope with these consequences at the different stages of a phase-out process. First, when it comes to building political support for a phase-out proposal during the early stages of the process, Cromie et al. [21], for instance, detail a strategy for building societal consensus and confronting opposition in industry. Leveraging insights from environmental politics, this study underscores the pivotal role of scientific evidence in creating a sense of urgency and the need to mobilize supportive coalitions and leaders with positive visions of change. Second, in terms of strategies to alleviate socio-economic disturbances, scholarship on fossil-fuel phase-outs provides some insights. During the stages of policy formulation and implementation, the literature places much emphasis on financial compensation, worker retraining, and the creation of new industries to replace those "destroyed" [23, 73, 90, 120]. As a general trend, we find that scholars have predominantly investigated such strategies from the perspective of isolated industries. Although we recognize that phase-outs should be tailored to the specific circumstances of individual localities and sectors [121, see 122, 123], this inclination toward analytical siloes points to a need for cross-cutting analyses that distill generalizable lessons based on common experiences and coping strategies used across heterogenous industries.

Policy Instruments

Slightly more than half of the scientific work examined (443 out of 870 publications) entails descriptions of the policy instruments that induce or contribute to phase-outs. While these descriptions are often directly informed by policy practice, some works are more prescriptive and recommend specific instruments or approaches. Overall, our analysis unveils both consistency and change with regard to the policies described over the evolution of the literature.

First, as a constant, command-and-control instruments are the dominant form of intervention described (**Fig 5a** and **SI Document S1 Fig. S3**). These include regulations and restrictions, legally binding treaties and protocols (e.g. the Montreal Protocol for Ozone Depleting Substances) and mandatory environmental standards. Emphasis on command-and-control is especially strong for substances (**Fig. 5b**). Technology phase-outs are more strongly tied to management and planning instruments, the next most discussed class of instruments. On the one hand, these approaches range from planning instruments like political targets, timelines and roadmaps to managerial strategies, such as reporting mechanisms. Policies that set progressively tightened restrictions for the production of chlorofluorocarbons under the Montreal Protocol [124] and the sale of internal combustion engines [24] both typify this approach. On the other hand, management and planning instruments may also comprise the formulation of broad policy packages that guide phase-outs by setting priority areas and countermeasures for side-effects like economic disturbances and unemployment. Efforts to mitigate adverse consequences of coal phase-outs in Germany notably integrate such policies [125]. In sum, the literature's dual emphasis on command-and-control instruments and management and planning approaches portrays phase-out as a process predominantly driven by state intervention.

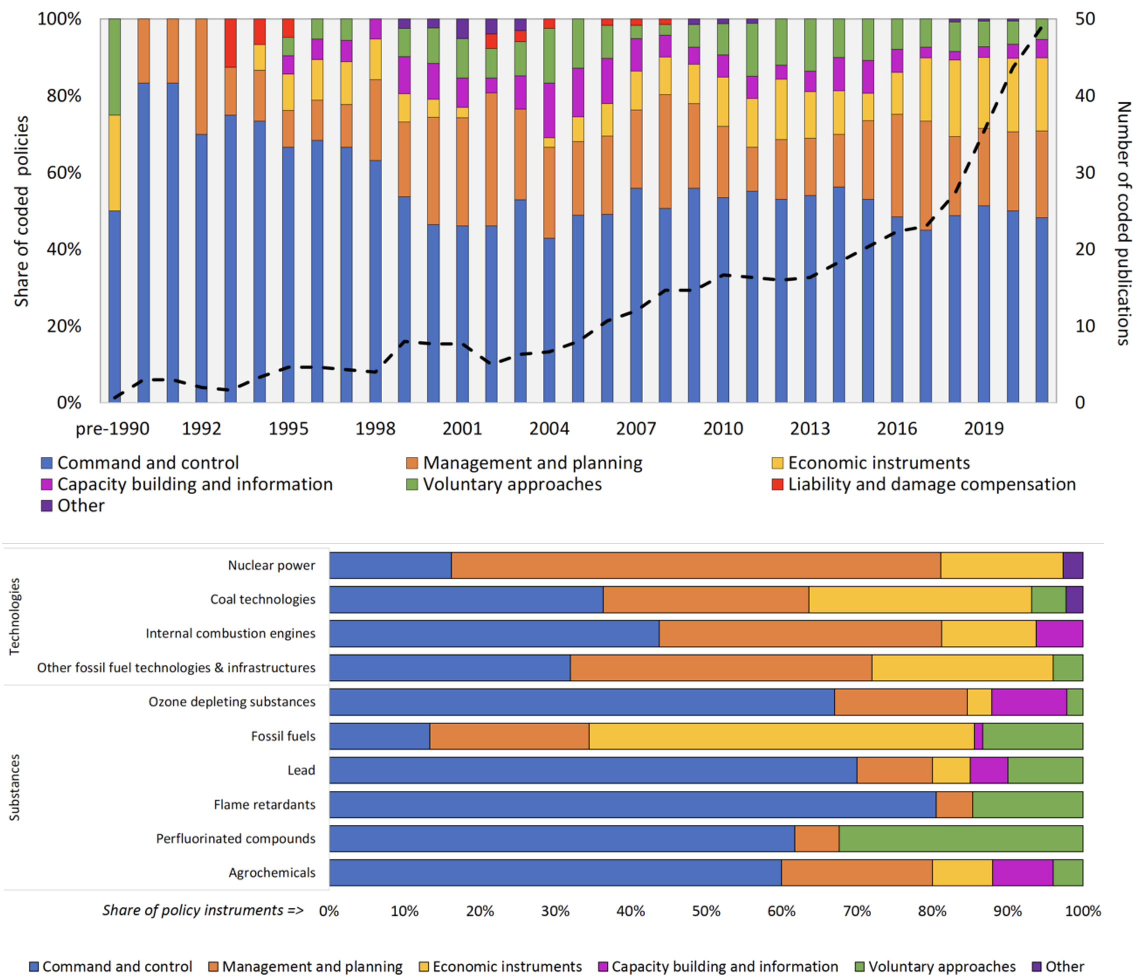


Figure 5. The evolving nature of phase-out policies
The top figure (a) shows the relative share of codes each year for 443 papers mentioning policies, smoothed with a 3-year average. For reference, the total number of publications receiving a code each year appears as a dotted line, also smoothed to a 3-year running average. The bottom figure (b) shows the relative share of codes for the 10 most frequently mentioned targets. Papers citing multiple policies received more than one code. Policies in both figures show aggregated results for coding that included more specific categories (see **SI Document S1 Fig. 3**).

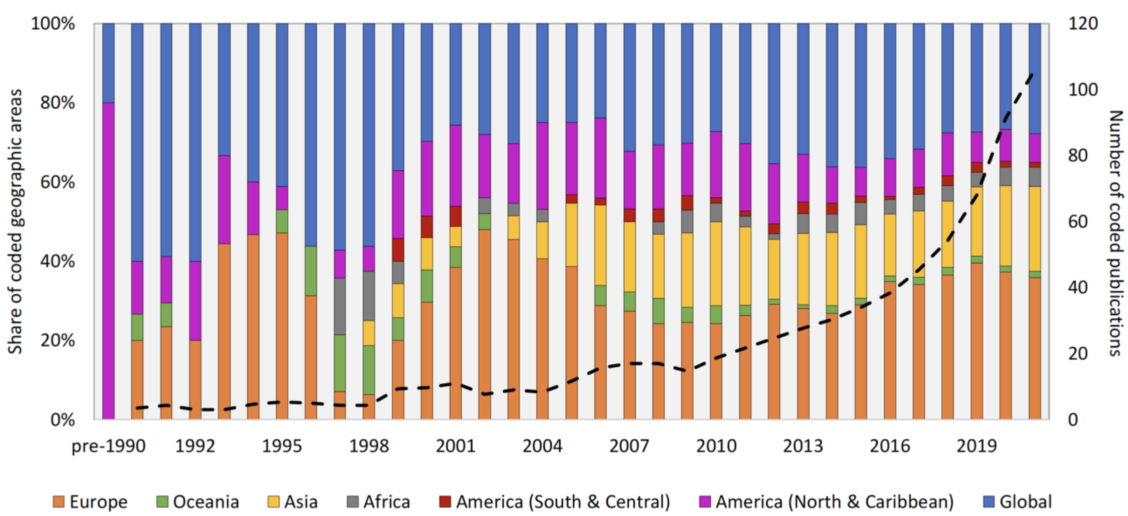
Second, in terms of change, we find that the literature has expanded its initial focus on the traditional tools of the state (i.e. regulation and planning) to engage with an increasingly diverse range of instruments. This reflects a broader tendency to conceptualize and pursue phase-outs as part of mixes rather than single policies [23, 36, 83]. In this vein, phase-out research has increasingly considered economic instruments and voluntary approaches since the 2000s. The former consists of four types that can be mobilized for phase-out goals: subsidy reform and removal, pollution pricing (e.g. carbon taxes), financial support (e.g. loans, subsidies), and emissions trading. Of these, subsidy reform and removal are frequently referenced in relation to accelerating the phase-out of fossil fuel extraction and related technologies [60, 94]. Meanwhile, voluntary approaches tend to be associated mostly with substance phase-outs (**Fig. 5b**); a prominent example being perfluorinated compounds [34]. Typically involving negotiated agreements with industry to expedite substitution with alternatives, voluntary approaches often emerge to fill gaps left by missing or weak regulation [38, 81].

The diversity of instruments described in the literature points to the absence of any one-size-fits-all approach. It also suggests that political-economy conditions in each context will influence not only the ability for a state to implement a phase-out in the first place, but also the feasibility of a certain policy instrument over another. Such political considerations have been consistently acknowledged during the literature's evolution, appearing in work from diverse disciplines [9, 63, 75, 126, 127]. This said, we observe a scholarly inclination towards studying small sets of cases, with detailed studies of policy instrumentation still lacking overall. Consequently, there is a dearth of knowledge about the effectiveness of one instrument or approach over another. Such knowledge may be especially warranted if considering the strongly heterogenous character of phase-out interventions. As highlighted so far, not only does this heterogeneity arise from the particular elements targeted by phase-outs, it also concerns the scope of phase-out ambitions, which may range from the mere substitution of specific components within socio-technical systems to transformative agendas that seek broader and system-level change.

More broadly, the evolving nature of scientific attention to particular classes of policies mirrors wider trends within the career of environmental policy. Meadowcroft [128] describes how during the 1980s and 1990s, neoliberal approaches to environmental management proliferated as state control was weakened in favor of market-based approaches. Indeed, during the 1990s, our dataset shows a marked decline in mentions of command-and-control approaches as attention increased to economic and voluntary instruments. However, this decline is only temporary, since from around 2000 onwards, descriptions of command-and-control approaches consistently make up around half of the coded policies. We thus find that command-and-control instruments have remained the dominant force behind phase-out interventions over the last five decades. These results concur with views that the process of phase-out typically emerges as a result of deliberate and mandatory actions that rely on state authority (laws, regulations and bans, etc.) [9]. Moreover, our results equally suggest that the phase-out approach has consistently occupied an important place within the policymaker's toolbox of regulatory responses to various sustainability challenges over the past 50 years. Indeed, if considering the more recent mainstreaming of alternative approaches to tackling climate and environmental problems (carbon taxes, emissions trading etc.), the continuing debates and descriptions of actual policies within the surveyed literature indicate that phase-out possesses a long and established career in the environmental governance realm.

Geographies

The science has diversified its geographic scope of enquiry over time. Prior to 1990, the limited literature (n=7) focused on phase-outs in North America (namely the United States) and globally, attending to substance-based targets like leaded gasoline and pesticides (**Fig. 6a**). After this period, the scope of enquiry expanded to new geographic terrain, integrating the experiences of Europe, Asia and Oceania. Today, all world regions are represented in the scientific discourse on phase-out, with the presence of emerging economies seeing considerable growth in absolute terms since around 2000. Taken together, these findings point to a global proliferation of phase-out as an approach to confront sustainability challenges. At the same time, studies evoking the global dimension of phase-outs, such as the Stockholm Convention on Persistent Organic Pollutants and other international frameworks, have remained frequent over the past five decades. Besides ozone-depleting substances and fossil fuels (especially subsidies), other frequently discussed targets of global phase-out efforts include perfluorinated substances and flame retardants (**Fig. 6b**).



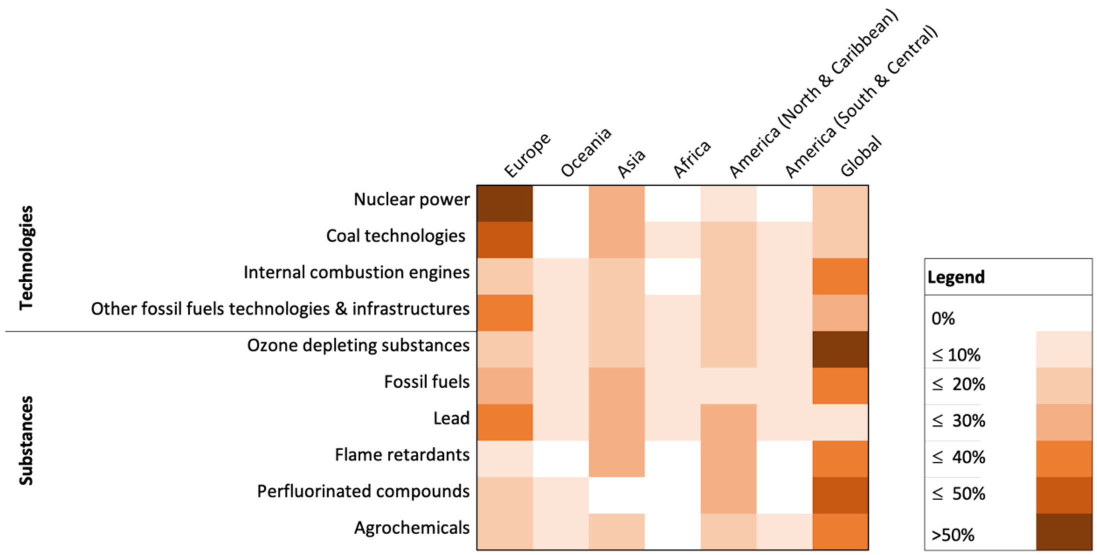


Figure 6. The evolving geographical focus of phase-out discussions
The top figure (a) shows the relative share of codes each year for 743 papers that mentioned a geographical focus, smoothed with a 3-year average. For reference, the total number of publications receiving a code each year appears as a dotted line, also smoothed to a 3-year running average. The bottom figure (b) shows the relative share of codes for the 10 most frequently mentioned targets. Papers citing multiple regions received more than one code. Regions in both figures show aggregated results for more specific coding categories (see **SI Document S1 Fig. 4**).

In terms of world regions, Europe has attracted most attention, featuring in 30-40% of annual publications over the last two decades. The phase-out efforts documented in Europe frequently focus on specific targets (**Fig. 6b**) such as nuclear power [120, 129, 130], fossil fuels and associated technologies like coal power [125, 131], and lead [33, 108]. The prominence of European experiences mirrors respective policy developments and indicates its value as a source of instruction for other countries [37, 39].

Asia's relative presence in the dataset expands rapidly after around 2005, becoming the second most discussed region after Europe. This literature covers the perspectives of both industrialized nations and emerging economies, but concentrates especially on East Asia; particularly China and, to a lesser extent, Japan and South Korea. Phase-out efforts in South Asia, namely India, are also discussed [132, 133]. The increased scientific attention to phase-outs targeting Asian countries appears to be a corollary of the accelerating economic development and industrialization of the region. Driving an increased production and consumption of fossil fuels, chemicals, materials and resources, economic growth has triggered externalities like air pollution, environmental contamination and greenhouse gas emissions [134, 135]. Consequently, phase-out is now featuring in the various policies and debates emerging in developing Asia in response to such challenges.

Our mapping-based review reveals several gaps in the geographic focus of scholarly work. In addition to developing countries in Asia beyond China, also underrepresented are Africa and South America. To some extent, this trend may indicate that experiences with domestically enacted phase-outs are still less common in these regions, some of which are still in the process of building up exactly those assets that are in the process of being phased out in Europe or North America [136, see 137]. While the science contains several descriptions of historical, ongoing or proposed phase-outs in developing Asia, Africa and South America [138-141], overall, limited scholarly effort has been devoted to building understanding of the role that phase-outs may play for tackling sustainability challenges in the context of developing countries. Thus, our review replicates a pattern pervading science as a whole, which is a strong bias toward perspectives of the global north. Not only does this concern the scope of geographical interest, but this bias also extends to the conceptual framings used in scholarly works, which overwhelmingly rely on established Western conceptions of environmental science and governance at the expense of other perspectives [see 142].

A growing body of research has attempted to advance explanatory knowledge on why certain types of phase-outs are more likely to appear in some countries than others. This question has especially attracted the attention of coal phase-out scholars. Within this literature, socio-political and economic conditions—particularly the existence of liberalized electricity markets, carbon pricing schemes and public pressure—have all been found to be conducive to the emergence of phase-out policies [123]. Conversely, countries characterized by conditions such as coordinated economies, state-owned markets, coal extraction industries, weak environmental governance and missing societal debates are more likely to see phase-out attempts derailed by vested interests [23, 70, 131]. Meanwhile, a study on the global proliferation of announcements to abolish gasoline vehicles finds that phase-out ambitions are tightly linked to industrial policy, being most likely to take root in countries perceiving a competitive advantage in accelerating the electrification of their automobile industry [24]. While these findings enrich our understanding of the many interlinked conditions that can promote or hamper the introduction of phase-out policies, the literature suffers from a dearth of explanatory power beyond specific targets like coal-power or internal combustion engines. Understanding of the various conditions that influence the ability for particular countries to introduce and achieve phase-outs could thus be considerably deepened if scholars made efforts to link the experiences of multiple targets (i.e. substances, technologies, processes etc.) and regions beyond Europe, North America and Asia.

DISCUSSION AND CONCLUSIONS

Drawing on nearly 900 peer-reviewed articles published over five decades, this systematic review mapped the evolving nature of scientific discussions about phase-out as an approach for pursuing sustainability goals. Our analysis traced the targets and drivers of phase-out interventions, associated policy instruments and then the industrial and geographical contexts within which these experiences have been implemented and examined. This review contributes to the scholarly and societal debates around the deliberate decline of unsustainable socio-technical systems, responding to the growing interest in the intentionally “destructive” side of innovation processes as researchers and policymakers seek more effective tools to accelerate progress in the face of worsening sustainability challenges.

Our findings show that the rapid growth of scholarship on phase-out has seen both change and continuity mark the evolution of research and practice. Emerging from historical efforts to tackle environmental degradation and human-health risks caused predominantly by hazardous substances, climate change has become the dominant driver of phase-outs within the literature. Consequently, fossil fuels and associated technologies, subsidies and industries are increasingly mentioned as key targets for deliberate decline. Testifying to a global proliferation of phase-out initiatives, the volume and diversity of actual and potential targets articulated within scientific research continues to grow. Reflecting this, the geographic scope of studies has expanded beyond an early focus on North America and the global level, with Europe and Asia now featuring more strongly in contemporary discussions. With respect to policies, phase-outs are consistently described as a process of state intervention, the primary tools being regulation, enforceable agreements and planning. Though increasingly diverse instruments are discussed, in aggregate, the scientific literature does not emphasize voluntary approaches as the most promising way to eliminate unsustainable substances, technologies or processes.

Our findings also show that the study of phase-out increasingly spans diverse scientific communities, extending to engineering, the natural sciences, social sciences and humanities, and beyond. Despite differing disciplinary roots and methodological orientations, contributions from these disciplines are bounded by a common interest in how this policy approach can be leveraged to curtail the production and use of substances, technologies and processes that contribute to climate change along with a multitude of sustainability challenges. Our review underscores that phase-out has provided diverse research and practitioner communities with a common problem framing, concept and policy approach.

From this, our review indicates that phase-out shows promise as an emerging bridging concept alongside other more established ones like “pathways” [143], “resilience” [30, 31] or even "sustainability" [29] itself. Not only has phase-out stood the test of time throughout its nearly five-decade development within scholarly discourse and environmental governance practices, but this policy approach has proliferated as a shared idea and a widely recognized strategy across multiple domains and constituencies**.** Concretely, the concept of phase-out provides diverse actors in science, policy and society with a common frame of reference when problematizing and debating various causes of unsustainability. And by directing attention to the important task of pursuing sustainability goals by purposively unravelling unsustainable systems of production and consumption, the concept of phase-out helps to crystallize the importance of decline-related activities as complements to innovation. Moreover, its action-focused nature offers policymakers and the public alike a practical means of carrying out such functions. And within the scientific community itself, our review indicates that today phase-out is playing a growing role in linking multiple scientific disciplines in such efforts, opening up new avenues of cross-disciplinary dialogue and research efforts.

Yet, despite this potential, the scientific literature has not yet fully seized the bridging power of phase-out to develop truly cross-cutting perspectives. Future work will need to do far more to exploit opportunities for convergence both within differing scientific communities as well as across the science-policy interface. Our findings offer a foundation upon which to build this effort, but much more can be done to theorize and conceptualize phase-out, understand its interactions with other key decline-related concepts, and contrast empirical cases from different contexts and sustainability domains. Such an agenda could mobilize different research and practitioner communities to deepen our understanding of phase-out, systematically integrating contrasting methodologies, scientific evidence and knowhow accrued from historical and ongoing experiences. For instance, this agenda could more systematically combine the perspectives and expertise from engineering (e.g. regarding the technical feasibility of phase-outs) and the natural sciences (e.g. for measuring environmental impacts) with knowledge from practitioner communities and the social sciences (e.g. regarding policy instrumentation).

To guide such a cross-cutting research agenda, our mapping-based review revealed several gaps in scientific attention that merit tackling. Perhaps most importantly, our review underscores a need for overarching perspectives that compare the experiences of a greater heterogeneity of targets, aiming to deepen understanding of phase-out as a governance mechanism. This would break from the continuing tendency to study homogenous phase-out initiatives in isolation, particularly well-studied cases like coal, nuclear, ozone-depleting substances, pesticides etc.. Specifically, such work might tackle questions regarding causal mechanisms and effects, examining the differing outcomes achieved by varying configurations of policy instruments. There is also a need to deepen knowledge of promising strategies for managing well-known obstacles such as economic repercussions and resistance from society and industry [144]. Additionally, future research could more systematically reflect on the technological, institutional, political and behavioral factors that influence the ability for a region or country to introduce a phase-out strategy or attain successful outcomes. In addition to empirical knowledge, this endeavor equally requires theory-building efforts, drawing on other conceptualizations of socio-technical decline, such as destabilization, exnovation, or discontinuation. Though emerging [13, 18, 145], such theoretical work has lacked so far, especially when it comes to integrating insights from across the natural and social sciences [77]. Consequently, our understanding of the breadth of functions performed by phase-out interventions and how these contribute to the unravelling of unsustainable systems of production and consumption is still immature.

There is also a deficiency of knowledge on experiences implementing phase-outs in geographical contexts beyond the global north. Filling this gap will be a critical step in expanding the utility of phase-out as a bridging concept and governance strategy for decline. Indeed, such regions may offer some unique theoretical or empirical insights, including the important dialectical relationship between innovation and decline in the context of efforts to “leapfrog” rather than follow the unsustainable development trajectories embarked upon by the global north. It remains unclear, however, whether or how phase-out can help complement such efforts in geographies where the incumbency of certain technologies, practices, and systems may be less pronounced than in advanced economies.

Our review also raises some cautions in relation to the promise of phase-out as a bridging concept and governance strategy. For example, phase-out efforts have successfully eliminated first-generation ozone depleting substances. But many have only been replaced with climate warming halons. These, in turn, have necessitated a new generation of phase-out programs. Moreover, phase-out policies can trigger a dash for temporary solutions with short-term benefits but limited long-term prospects for transformative change [122]. Consider, for instance, the recent rush to gas driven by coal and nuclear power phase-outs, which risks locking-in a new generation of carbon-intensive infrastructure [146, 147].

These historical and ongoing experiences point to the need for a broader understanding of phase-out and its application within society, one that more explicitly embeds scientific discussions and policy interventions into innovation-inducing strategies aimed at triggering broader socio-technical change [17]. Such policies should avoid the trap of targeting problematic technologies, substances and processes as individual components, with limited efforts to confront the broader systemic forces that sustain their production and use [38, 148]. Taken together, it seems promising to understand phase-out as a key tool to induce wider systemic change rather than as a narrow effort to eradicate the worst offenders. And in this fashion, this emerging bridging concept could become the catalyst for an explicitly transdisciplinary enterprise that engages with the relationship between old and new, emergence and decline, as well as creation and destruction. In a practical sense, this research would contribute to work on policy mixes [6] capable of generating innovative and disruptive pressures to move society towards sustainable futures. Specifically, such work could seek to identify effective portfolios of intervention instruments (regulations, incentives, research support, institution building, etc.) along with the appropriate timing for their implementation.

Finally, our employed method raises two further opportunities for future research. First, our unit of analysis was scientific discussions rather than phase-out policies or empirical cases per se. As a result, although the themes evoked by the literature are for the most part closely linked with the experiences of phase-outs in practice, a similarly comprehensive analysis based on empirical cases could help complement or extend the trends highlighted by our mapping approach. Second, we also see a need to more clearly disambiguate between phase-out and similar approaches and policies. For instance, bans and moratoria lack the sequential character of phase-out, whereas the idea of phasing *down* aims at reduction rather than termination. Yet these differences and conceptual overlaps have not yet been thoroughly explored.

Taken together, our review and the research directions identified therein suggest that phase-out holds much promise as a bridging concept and governance approach. The rapid growth of literature and descriptions of practice therein suggest that its significance may continue for more decades as society seeks to confront increasingly grave sustainability challenges.

EXPERIMENTAL PROCEDURE

Resource availability

Lead contact

Further information and requests for data should be directed to the lead contact, Gregory Trencher (trencher.gregory.2s@kyoto-u.ac.jp).

Materials availability

This study did not generate new unique materials.

Data and code availability

The publications comprising our sample, our coding procedure and coding results are publicly available in the Supplementary Information.

Overview of method

To review the literature in a transparent and replicable manner, we employed an approach known as "systematic mapping" or "evidence mapping" [149, 150]. Residing within the broader methodological category of systemic reviews, a distinguishing feature of the mapping method is the use of quantification (typically based on coding) as a means of systematically distilling, depicting and interpreting patterns from large corpora of textual data [26]. In addition to defining explicit inclusion and exclusion criteria to determine the scope of relevant literature, the mapping approach is more rigorous, objective and replicable than a conventional literature review by virtue of transparent protocols for identifying thematic trends. Going beyond the core idea of systematic mapping, which is to produce a high-level synthesis of an encompassing body of literature [151], our analysis also follows principles of qualitative literature reviews [152, 153] in that it provides additional interpretations and deeper reflections on important themes found in the reviewed works.

Originating from the social sciences, mapping-based reviews have propagated into diverse fields, including sustainability, environmental management and energy studies [23, 154, 155]. We draw methodological guidance and inspiration from all these studies, also following best practices from systematic reviews in general [156]. Concretely, we adopted the following best-practice principles: (1) Before starting to systematically survey the literature, we thoroughly engaged with the concept of interest, closely reading a variety of works to gain a sense of the review scope and the nature of the evidence available; (2) We defined broad but explicit research questions to guide the review and analysis; (3) Based on the research questions and several rounds of testing and refinement, we developed a search string and a set of inclusion and exclusion criteria that ensure the replicability of our dataset; (4) Also based on our research questions, we developed clearly specified coding frameworks (see below); (5) Three researchers took charge of systematically coding the entire text corpus; and (6) To ensure transparency and replicability, all coding decisions are described in a detailed report (**SI Document S1 Note 2-3**).

Our review employed three broad steps as follows.

1. Review Design, Scope and Search Query

First, after establishing a concrete research aim—which is to understand how scientific literature has described the key features of phase-outs to tackle various sustainability challenges, and how these conceptions have evolved over time—we iteratively developed a search string (**SI Document S1 Note 1**) to identify relevant publications. Modelled after previous research [9] that reviewed emerging trends related to the deliberate decline of socio-technical systems, our string consists of three segments that capture: (1) our main concept of interest (i.e. "phase-out") and variants thereof (e.g., "phasing out", "phased out"); (2) diverse mandatory and voluntary policy approaches (e.g. "regulation", "initiative", "plan", "incentive") to capture various approaches to pursuing phase-outs with policy interventions; and (3) the context for pursuing phase-out (i.e. "environmental", "sustainability" and "climate"). We deliberately refrained from broadening the first part of the search string to include related terms (e.g., ban, phase-down). This decision preserves conceptual consistency while serving our specific research aim, which was to map the evolution of phase-out discussions in the scientific literature. We acknowledge, however, that this decision can also be seen as a limitation, since we did not review works using terms and concepts that may be seen as related to phase-out.

To identify relevant scientific publications, we used the *Scopus* database. This was chosen over other options (e.g. *Web of Science, PubMed, Science Direct* etc.*)* due to its wider coverage of journals, abstracts and keywords than competitors [157, 158] and its superiority at extracting early publications. Since *Scopus* is frequently compared to *Web of Science*, we tested our search string on both databases. Results showed *Scopus* to be advantageous on two accounts. First, it demonstrated considerably stronger coverage in the first two decades of our study period: the first relevant paper indexed in Scopus appeared in 1970 compared to 1992 in *Web of Science*. We thus deemed *Scopus* better suited to our goal of identifying the origins and evolution of phase-out research. Second, *Scopus* yielded roughly 23% more publications than *Web of Science* over the study period (1,099 versus 892). This said, the choice to only use one database to extract literature—even if the one with the broadest coverage—induces some "database bias" [151]. We acknowledge this as another methodological limitation that could be tackled by future studies.

We carried out the search on *Scopus* with the following search conditions:

- Language: English

- Publication type: Articles and reviews
- Search scope: Title, author keywords and abstract
- Temporal scope: All papers published up to December 31, 2021
- Academic field limitations: None

This resulted in 1,099 hits. After sorting and eliminating duplicates and irrelevant papers, we obtained an initial sample of 870 publications that were subsequently coded and analyzed (available in **SI Data S01**).

When assessing publications for relevance, we relied on explicit inclusion criteria (**SI Document S1 Note 2**). To operationalize our aim of understanding how phase-out has been mobilized as a concept or tool for responding to various environmental and sustainability challenges, we included empirical and theoretical studies discussing phase-out as a policy approach in this context. Conversely, we excluded those discussing phase-out for reasons unrelated to environmental or sustainability challenges (e.g. for health, fiscal or national security reasons). To capture a broad spectrum of scientific discussions and descriptions of policy practices, we included publications that explicitly engage with phase-out as a research topic (e.g. those examining phase-out policies, their targets or impacts) as well as publications focused on other topics, which mention a phase-out intervention as part of their background statement or policy implications, etc.

2. Research Questions and Coding Frameworks

Second, to guide the coding of relevant papers and ensure replicability, we developed five sets of associated research questions and coding frameworks (see **SI Document S1 Note 3**). Summarized below, coding frameworks include aggregated parent codes and specific sub-codes. The former coarsely capture broad patterns while the latter describe these at a higher resolution. Guiding research questions and coding frameworks were developed as follows:

1. *What is the nature of the phase-out target?*
   For parent codes, we used categories defined in previous research (i.e. technology, substance, process) [9] to broadly categorize targets. To more specifically describe these, we assigned sub-codes in accord with an inductively created framework (e.g. nuclear power and internal combustion engines as technologies, flame retardants and ozone depleting substances as substances, waste incineration as a process).
2. *What drivers are associated with the discussion or implementation of the phase-out?*
   We tackled this question with an inductively created framework that categorizes both the general driver (e.g. environmental, social, technology and innovation) and the specific driver

(e.g. air pollution and climate change as environmental drivers, equity and ethics as a social driver, and substitution and systemic change as technology and innovation drivers).

3. *What industries are mentioned as producing, emitting or using the phase-out target?*
   For this task we used an existing framework, the North American Industry Classification Scheme (NAICS), from the United States Census Bureau [159]. Parent codes reflect aggregated industry sectors (e.g. chemical manufacturing) and sub-codes capture specific industries (e.g. industrial gas manufacturing as an industry in the chemical manufacturing sector).
4. *What policy instruments are associated with the discussed phase-out?*
   We adopted an established framework from the OECD [160] to capture general categories of environmental policies as parent codes (e.g. command-and-control, voluntary approaches) and specific instruments as sub-codes (e.g. environmental standards and laws/regulation as command-and-control policy, and pollution pricing as a sub-class of economic instruments). To capture further instruments that go beyond the OECD classification, we extended the latter to include descriptions of policy instruments extracted from the governance literature [e.g. 6, 10, 161]. Our coding captured both policies described as inducing or contributing to a phase-out, and policies described as desirable, including those under discussion or planning.
5. *What geographical region is targeted by the phase-out strategy?*
   To code geographical regions (e.g. Western Europe, Northern Africa) and specific countries, we used an existing framework from the United Nations, the Standard Country or Area Codes for Statistical Use (the so-called '49 Standard') [162].

3. Coding Procedure

Third, we applied the above frameworks to code evidence in the title, abstract and keywords of relevant publications. This procedure emerged after several rounds of testing and fine-tuning explicit protocols outlined in **SI Document S1 Note 3**. Care was taken to only code the content connected to a discussion about a particular phase-out. When encountering ambiguous language, we also consulted full papers. Multiple codes were assigned to papers as needed—e.g., a publication discussing several drivers accordingly received several codes to capture these. Coding results appear in **SI Data S01**.

Three experienced coders sequentially coded all publications. The first coder screened titles, abstract and keywords to highlight relevant text portions and suggest parent codes. The second (lead) coder critically evaluated the suggested codes and independently coded each publication for all five coding categories. The third coder reviewed all coding decisions. When discrepancies were encountered, these were discussed among the coders until a solution was reached. Finally, a random sample of approximately 15% of the final corpus was cross-checked once again at the end of the coding process by two coders to detect and remove remaining inconsistencies.

SUPPLEMENTAL INFORMATION

- **Document S1.** Figures S1 to S4, Note 1: Developing the search string, Note 2: Screening relevant publications, Note 3: Coding protocol
- **Dataset S1.** Literature sample and codebook
- **Dataset S2.** Inventory of phase-out targets

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AUTHOR CONTRIBUTIONS

G.T. and A.R initiated the study and designed the research with D.R and F.K.; G.T., A.R, N.T and P.T performed research; G.T. and A.R analyzed data; and G.T., A.R and D.R. wrote the paper with input from F.K.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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