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Strategic Pathways for Decarbonization: A Data-Driven Typology to Strengthen Climate Policy

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Abstract

As global temperatures approach critical thresholds and emissions continue to rise, the urgency for strategic, accelerated decarbonization grows. The climate mitigation literature is vast, but evidence on how mitigation options cluster into overarching decarbonization pathways remains fragmented. Here, we use artificial intelligence–enabled text and citation analysis on an initial corpus of over one million scientific papers (2011–2021) to derive a data-driven typology of six recurrent decarbonization pathways: Technology Breakthrough, Electrification of Uses, Integrated Policy, Decarbonization of Electricity, Demand Reduction & Co-Benefits, and Land Use & Circularity. Rather than proposing new mitigation options, this typology organizes existing work into a small set of archetypal strategies and maps their prevalence across regions, disciplines, and policy orientations. For example, Electrification of Uses is most prominent in the EU27, while Technology Breakthrough dominates in China, the United States, and Japan. The analysis highlights synergies and complementarities between pathways, the scientific competencies that typically underpin them, and persistent gaps—particularly in Land Use & Circularity. We illustrate the policy relevance of the typology by comparing pathway profiles with stated climate policy directions, identifying areas where research and policy emphases are misaligned. This framework can support policymakers and researchers by benchmarking policy portfolios against the typology and highlighting research needs associated with national decarbonization goals.

Keywords: climate policy, decarbonization pathways, low-carbon innovation, machine learning, regional mitigation strategies.

JEL Classification: Q54, Q58, O33, Q48, O44.

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Key Policy Insights

- The typology provides a diagnostic to benchmark national pathway portfolios in research and policy and identify underweighted pathways.
- Regional variation in pathway emphasis and scientific capacities calls for tailored strategies aligned with national profiles.
- Combining complementary pathways can strengthen system-wide impacts (including emissions and efficiency), e.g., by pairing Electrification of Uses with Decarbonization of Electricity.
- Land Use & Circularity is comparatively underrepresented relative to other pathways, despite offering mitigation, ecosystem, resilience and resource-efficiency co-benefits.
- The typology can diagnose research–policy gaps and guide timing (sequence or fast-track), recognizing that policy and research co-evolve.

1. Introduction

Despite the Paris Agreement's goal to limit global warming to well below 2°C—and ideally to 1.5°C—global emissions have continued to rise. With global mean temperatures having temporarily reached 1.5°C above pre-industrial levels in 2024 (Tollefson, 2025), the urgency to accelerate decarbonization strategies is greater than ever. Yet, in a context marked by geopolitical tensions and shifting political priorities, the challenge lies not only in acting faster, but in choosing the right combinations of strategies. To be effective, climate change mitigation must draw on a broader and more coordinated mix of decarbonization pathways, tailored to regional contexts for feasibility and implemented across different levels of governance.

While prior studies have examined decarbonization through sectoral lenses (Ekins, 2024; Clarke et al., 2014), outlook scenarios and scenario markers (Skea et al., 2021; Riahi et al., 2017), or sequential sectoral approaches (Markard & Rosenbloom, 2022; Sachs et al., 2019) and the 2022 IPCC WG3 report provides one of the most comprehensive syntheses of mitigation options to date, there has been relatively little effort to systematically identify and classify how the diverse strategies in this literature converge into a set of overarching decarbonization pathways. This lack of a structured typology limits our ability to compare, combine, and scale mitigation efforts effectively across contexts. Without a clear understanding of the strategic pathways available—along with their defining characteristics and trade-offs—policymakers face greater uncertainty in designing coherent and impactful climate actions (Van den Bergh et al., 2021). Recent evidence further shows that successful climate policies remain limited, often fragmented, and disconnected from broader strategic frameworks (Fernández-i-Martin et al., 2026; Stechemesser et al., 2024).

This paper contributes to that effort by developing a data-driven typology of decarbonization pathways—recurrent combinations of mitigation options that tend to appear together in the literature. Our aim is not to propose new solutions, but to show how existing mitigation strategies cluster into six archetypal pathways and how these pathways vary across regions, disciplines and policy emphases. This typology provides a structured lens to compare national and regional decarbonization approaches and to identify where research and policy priorities are concentrated or comparatively underrepresented. In this way, it can help policymakers and researchers situate national efforts within a broader landscape of strategies and consider how scientific and technological capabilities relate to different decarbonization pathways, while recognizing that deeper analyses of transitions and mitigation dynamics remain beyond the scope of this study.

As climate research expands rapidly—over 350,000 papers were published in the eight years prior to the IPCC's AR6 (Callaghan et al., 2020)—there is a growing need to distill strategic insights from this expanding knowledge base. Machine learning and big data provide useful tools for organizing this vast knowledge base. They enable systematic clustering and mapping across a corpus far larger than manual review, while making classification rules explicit and reproducible. This complements expert

syntheses by revealing recurring pathway configurations and their characteristics and co-occurrence patterns. It also supports climate policy research by helping to identify where research and policy emphases align or diverge and where strategic options are comparatively underrepresented. While earlier work has tracked the evolution of research topics or focused on specific areas such as demand-side mitigation (Creutzig et al., 2021), a gap remains in systematically identifying and organizing the spectrum of decarbonization strategies discussed in the literature.

We apply natural language processing (NLP) and clustering techniques to a large corpus of scientific publications, extracting structured decarbonization pathways based on their underlying logic and content. This data-driven approach reduces reliance on expert judgment, ensuring a more objective and comprehensive mapping of the strategic landscape.

The resulting typology can support more targeted and context-sensitive approaches to decarbonization. It offers a structured view of how mitigation strategies cluster into pathways, helping decision-makers in public and private sectors reflect on trade-offs and complementarities when designing climate policy portfolios.

The paper is structured as follows. Section 2 outlines the methodological approach based on artificial intelligence techniques. Section 3 presents the six decarbonization pathways identified, along with their regional patterns, interdependencies, capacity requirements, and alignment with existing policies. Section 4 discusses the main findings, highlights key policy implications, and proposes directions for future research.

2. Methodology

We developed a three-stages approach to derive a typology of decarbonization pathways (Fig. 1). First, we conducted a computational literature review to acquire the relevant set of research. Second, we used automatic linguistic processing to delimit the literature. Finally, we analyzed the results through the derivation of the typology, the detection of research communities, and the elicitation of expert input. Once the typology of pathways was created and validated through community detection and expert elicitation, we assessed the time and regional trends in decarbonization pathways, as well as the pathways' interactions, scientific content, and alignment with the policies.

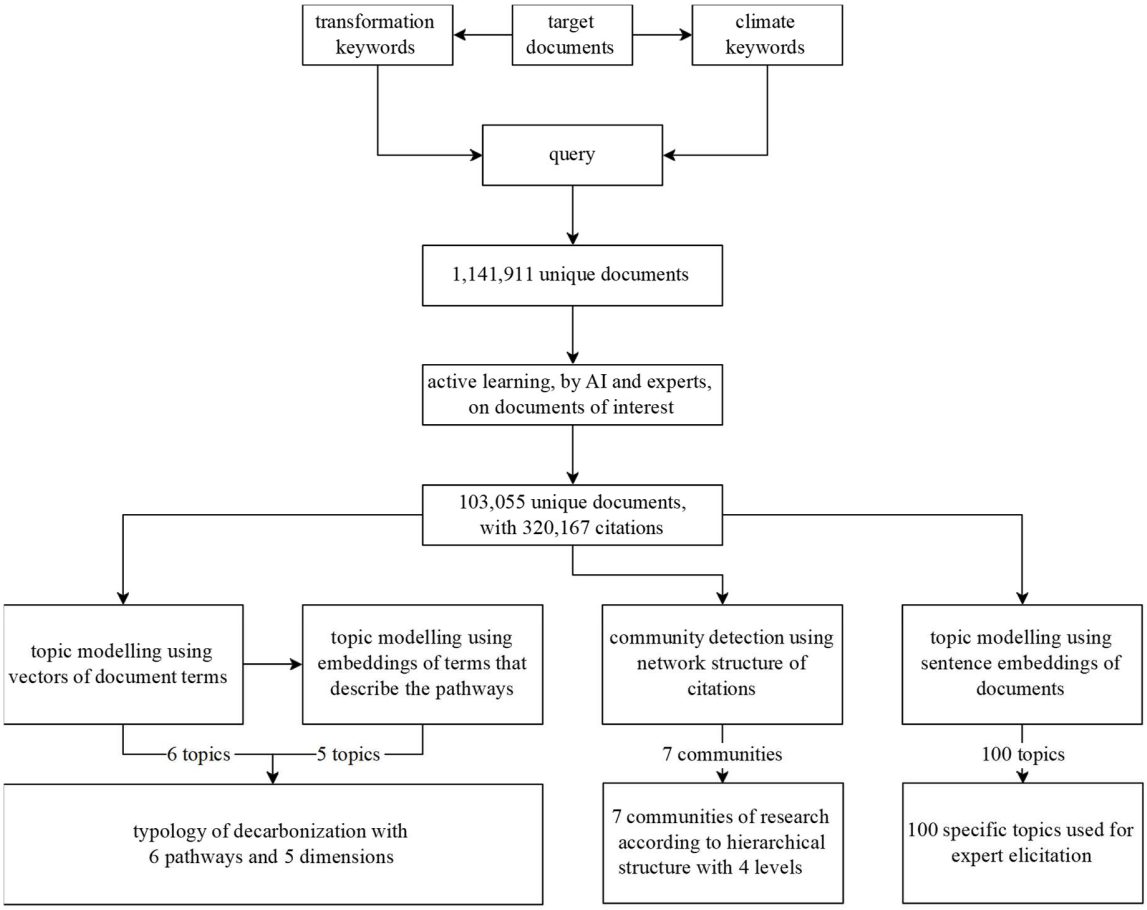


Figure 1. Flow chart of the approach. *The approach can be divided into 1) query design, 2) literature delimitation with automatic methods, and 3) analysis. The latter encompasses a) typology creation, b) community detection, and c) expert elicitation.*

2.1 Computational literature review and data

The research methodology employed in this study began with the selection and acquisition of a diverse range of research articles relevant to the topic of net-zero transition and decarbonization pathways. A comprehensive search strategy was designed considering two main aspects: transition, by including terms such as change or adaptation; and climate, which sought terms like temperature, green, or carbon. The search query[2] was structured as "(transition1 OR transition2 …) AND (green1 OR green2 …)" and was tested to capture a list of known articles of interest.

[2] Query used on the Scopus platform: TITLE-ABS-KEY ((pathway* OR transition* OR strateg* OR scenario* OR roadmap* OR plan* OR goal* OR outlook* OR narrative* OR mitigation OR adapt*) AND

A total of 767,608 articles were downloaded from Scopus, using *pybliometrics* (Rose & Kitchin, 2019), and 1,035,136 from WoS, manually in batches. Only the information related to the DOI, title, abstract, keywords, and release date of the articles was used for analysis. These data points were merged to create a database of 1,141,911 unique DOIs.

2.2 Literature selection

To narrow down the research universe, we employed the machine learning tool ASReview (van de Schoot et al., 2021). This tool leverages natural language processing methods to more efficiently guide researchers in identifying relevant articles by assigning a ranking to the articles according to our inclusion criteria for decarbonization pathways (Section 2.1). Three specialists evaluated 250 articles each and the tool generated suggested articles based on their assessments, resulting in a slightly different sample of articles reviewed by each specialist, totaling 296 unique articles. Our configuration followed ASReview's recommended settings, using a Naïve Bayes classifier, feature extraction with TF-IDF, and a certainty-based sorting order that prioritizes the documents most likely to be relevant.

We proceeded by treating the specialist's opinions as labels. Whenever the three agreed, their evaluations were considered as part of a training set used to retrain ASReview models with different classifiers and feature extraction techniques. The analysis of the importance scores revealed that around 20% of papers were relevant regardless of model configuration. Based on this insight, we intersected the ranked 250,000 article picks of each model and arrived at the 103,055 articles that constituted our subset of interest (see Fig. S.5 in Supplementary Materials or SM).

2.3 Identification of pathways and dimensions

In order to identify the pathways present in the set of research abstracts, we used *Latent Dirichlet Allocation (LDA)* (Blei et al., 2003) for topic modeling on the pre-processed texts. This process resulted in the identification of six transition pathways, as determined by the stabilization in coherence and perplexity scores from the sixth pathway onward.

We further characterized transversal dimensions using the *BERTopic library* (Grootendorst, 2022), a methodology combining topic modeling, dimensionality reduction, and clustering techniques. Dimensions represent transversal thematic categories that enhance the interpretability and comparative analysis of the pathways. The BERTopic approach enabled us to analyze cross-pathway axes and identify five significant dimensions by rejecting irrelevant or insignificant groupings.

To ensure a meaningful interpretation of the typology, we studied each cell at the intersections of pathways and dimensions. This included grouping frequent and

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(climate OR (energy AND (suppl* OR demand* OR global)) OR carbon OR warming OR emission* OR sustain*)) AND LANGUAGE (english) AND DOCTYPE ("ar") AND PUBYEAR > 2010

representative terms, extracting relevant titles, and incorporating expert descriptions of prevalent topics to construct narratives for each axis intersection (see Table S.1 in SM).

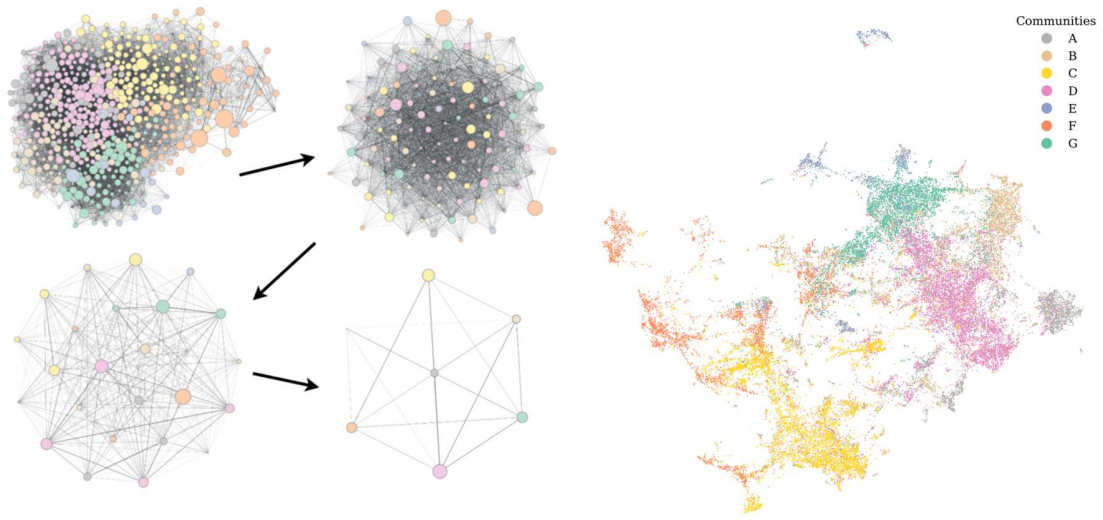
Details about the LDA methodology, hyperparameter selection, coherence and perplexity measures, and the BERTopic-based dimensional analysis are provided in the SM (see Box 1).

Finally, papers can have elements of different strategies and therefore were assigned to primary and auxiliary pathways according to their respective z-scores. Primary pathways are those with the maximum z-score per paper. Auxiliary pathways include all non-max pathways with a z-score above 20%. Alternative thresholds for defining primary and auxiliary pathways were tested and produced similar aggregate patterns (see Figs. S.2–S.3 in the SM).

2.4 Validation of the typology

We further validated the typology of pathways (including the dimensions) with the examination of the underlying research communities and with the help of expert elicitation.

As for the research communities, we applied network science (Silva et al., 2019) to understand the scientific literature cited in the publications that were relevant for decarbonization. We constructed a citation network with the available information of 79,922 DOIs, which amounted to 78% of our universe of interest. The Scopus platform indicated that these articles referenced a total of 1,315,793 unique cited articles, of which 49,235 were in the initial set. By merging smaller nodes into larger groups based on their similarity, we could uncover a hierarchy of research types at different levels of resolution (see Fig. 2). We used this notion to reveal the structure of the research under study. This strategy can serve as a validation role of the typology as it does not take into account the linguistic content of the research articles. Graph-tool (Peixoto, 2017), a Python module for manipulation and analysis of graphs, allowed us to perform this statistical inference with its nested stochastic block model.



(a) (b)

Figure 2. Partition of the literature in hierarchical communities. *Hierarchy of communities of research (a). Top-level communities in the literature (b). From least to most aggregated, the nested levels contain 569 communities which are grouped into 113, then 25, and lastly into 7 blocks. There is a noteworthy overlapping of the pathways, as plotted in a 2D representation of the linguistic content of the literature of interest, and the top-level communities as inferred from citation behavior. Table S.3 in SM provides the quantification of the overlaps.*

Additionally, we employed an expert elicitation methodology to further gain insights into 100 broad and representative topics generated using the BERTopic algorithm on the same data from the typology creation. We recruited one expert to analyze and describe each topic using his own language, which allowed for a more nuanced understanding of the content (see Table S.4 in SM). Furthermore, the expert was tasked with classifying each topic under several accepted dichotomies, including granular vs lumpy technology and supply vs demand side (Wilson et al., 2020). This approach enabled us to gain a better understanding of the underlying patterns and themes present in the data, and to identify commonalities and differences between the topics.

2.5 Analysis of the scientific fields

To analyze the scientific fields underlying each decarbonization pathway, we covered data for 99.36% of the articles used in the typology, from OpenAlex (https://docs.openalex.org). Additionally, we compiled information from 1,002,105 articles cited by these 102,400 articles, providing both first and second order scientific areas with converging results (see Figs. S7-8 in SM). We homogenized these areas using the system developed by Shen *et al.* (Shen et al., 2018), and now maintained by OpenAlex, which offers a comprehensive and open catalog of global

research concepts, among other types of article metadata, such as citation counts (see Table S.2 in SM). This platform allowed us to identify hierarchical concepts within each article, with 19 root-level concepts and six descendant layers, totaling about 65,000 concepts.

To aggregate the conceptual information at the pathway level, we developed three alternative methods to present the research areas. The main method is called the "Zero Method" and uses the level 0 concept with the highest probability of association, which may not be the concept with the absolute highest probability, as concepts from other levels may score higher. The other two alternative methods were used to validate the results of the previous one. The "Root Method", on the one hand, accounting for the root-level field of the concept detected with the highest probability (*e.g.*, "economic geography" at level 1 roots back to "economics" and "geography" at level 0). And the "First Method," on the other hand, identifying the concept with the highest probability directly, which could be any of the 65,000 concepts, unlike the more limited scope of "zero" and "root" methods. These three methods provide different perspectives for representing the literature present in our typology pathways and the references underlying them. The results do not significantly change across the different methods (see Figs. S7-8 in the SM).

2.6 Comparison with national climate policies

We then compared the decarbonization pathways with national climate policies by developing a large (though not exhaustive) dataset of representative climate-relevant policies for major world regions and matching their content to the six pathway profiles.

Climate-relevant policies were compiled from the European Environment Agency (EEA) and International Energy Agency (IEA) public policy databases. A total of 3,402 policies from Europe, the United States, China and Japan, dating from 1990 onwards, were identified (more details and dataset in Sousa et al., 2023).

The alignment of these policies with the decarbonization pathways was assessed using automated content analysis powered by large language models (LLMs). Further methodological details are available in Fontes et al. (2025). Out of the total, 3,154 policies were found to align with at least one decarbonization pathway—3,068 aligned with one pathway, and 86 aligned with two.

3. Results

3.1 Mapping a typology of decarbonization pathways from the literature

The systematic analysis of the literature using topic modeling of the processed titles, abstracts, and keywords suggests the existence of six decarbonization pathways: Integrated Policy, Technology Breakthrough, Demand Reduction & Co-Benefits,

Decarbonization of Electricity, Electrification of Uses, and Land Use & Circularity. These pathways span the entire landscape of relevant literature (Figure 3) and connect, to varying extents, with ongoing debate on decarbonization. We describe below each pathway by analyzing common themes (or dimensions) that best describe each strategy around: energy services, economics, planning, infrastructure, and transition (this one capturing system-level changes, including alternative development models, justice debates, behavioral change and institutional reform). These five dimensions were also found in an agnostic and systematic manner (see Box 1 of the SM). Table 1 synthesizes the typology of decarbonization pathways by these dimensions.

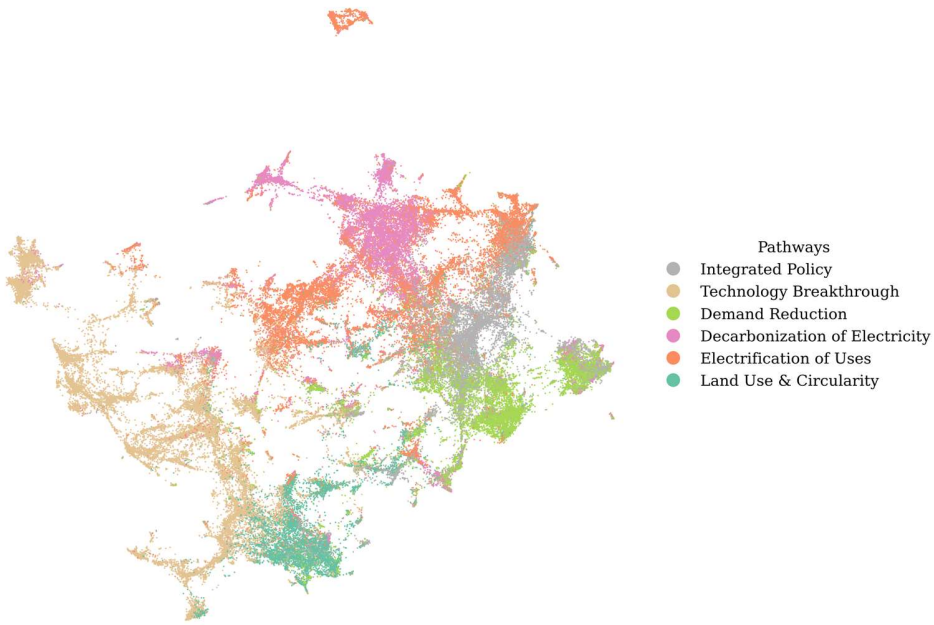


Figure 3. Decarbonization pathways identified in the systematic literature review. *This figure displays one hundred thousand articles, as points in a 2-dimensional embeddings space, colored according to their most representative pathway.*

Technology Breakthrough. This is the most prevalent pathway that was found in the literature (27%) (Fig. 4a). It emphasizes the adoption of technological innovations, especially emerging technologies and under formation, as essential tools for decarbonization. Thus, the focus is on advancing the efficiency and the sustainability of innovations like microbial fuel cells, electrocatalysis and lithium-ion batteries, or developing the commercial potential of technology innovations, such as carbon capture and sequestration (CCS) (*e.g.*, (Azevedo et al., 2021)). The adaptability of technological innovations to different urban and regional contexts is also a concern that is often found in the studies included in this pathway (*e.g.*, (Williams et al., 2021)). Infrastructural evolution towards smarter grids and advanced energy storage

systems underlines this shift. In a nutshell, the overall journey is marked by swift technological innovations, often spurred by a proactive technology policy such as the launch of ARPA-E and the SunShot Initiative for renewables in the United States.

Electrification of Uses. This pathway, which features in 20% of the literature, underlines the importance of a comprehensive electrification across multiple sectors to progress in the transition from fossil fuels. Electric solutions, spanning from the electrification of heating in buildings, to industrial processes and transport, are underscored. The economic feasibility of such a path, with cost-benefit analysis of higher shares of renewable energy sources, is often put forward (*e.g.*, (Markard, 2018)). As electric demands surge, infrastructural changes to support this upswing are considered, including the rapid growth of charging infrastructures for electric vehicles and of smarter electric distribution grids. The overarching narrative speaks to a societal shift towards electrification (under the ambition of "electrifying everything"), enhancing efficiency and decarbonization, with a special nod to the untapped potential of solar energy (*e.g.*, (Sachs et al., 2019)).

						
Pathways / Domains	**Technology Breakthrough**	**Electrification of Uses**	**Integrated Policy**	**Decarbonization of Electricity**	**Demand Reduction & Co-Benefits**	**Land Use & Circularity**
Energy Services	Advancing innovative technologies in energy supply	Replacing fossil fuels with electricity in end uses	Integrating policies for supply and demand	Transitioning to low-carbon power generation	Multi-sectorial energy demand and co-benefits	Land-based mitigation via reduced deforestation, soil restoration, and bio-based production
Economics	Costs and benefits of innovative technology diffusion	Costs and benefits of end-use electrification	Macroeconomic and multisectoral optimization	Costs and benefits of low-carbon transition	Co-benefits of demand reduction and efficiency	Resource use efficiency and circularity
Planning	Science & Technology policy and regulation	Incentives for electrification	Policy measures and regulatory frameworks	Ensuring grid flexibility and resilience	Behavioral change and technology adoption	Land-use planning to reduce deforestation and soil degradation
Infrastructure	Complementary assets for innovative tech deployment	EV infrastructure and charging networks	Coordination of multi-sectoral transformation	Renewable energy sources and storage tech	Support for consumer interaction	Support for sustainable land and resource management (incl. carbon)
Transition	Adoption of innovative tech for decarbonization	"Electrifying everything"	System-level transition to low-carbon economy	Transition to low-carbon power sources	Technological and behavioral change	Sustainable transition in land and resource use

Table 1. Typology of decarbonization pathways. *The pathways represent distinct strategies or approaches to achieve decarbonization. The dimensions are key themes that are transversal to the different pathways. While the dimensions offer perspectives, the pathways provide direction. Each pathway intersects with the dimensions, offering actionable strategies that leverage insights from each dimension (i.e., central topics). By understanding and implementing these pathways, stakeholders can situate their strategies and identify uncovered areas towards a decarbonized future.*

Integrated Policy. This approach, seen in 15% of the literature, seeks harmonized policy frameworks to guide every aspect of decarbonization. Top-down green regulations and market-based instruments (e.g., carbon taxes) play a central role in this approach, which links energy and broader sustainability measures. There is also a preoccupation to develop strategies that resonate with specific urban and regional needs (*e.g.*, Meister et al., 2020). Likewise, there is a search to create synergies between technological innovation and infrastructural revamp (Mercure et al., 2019). Large undertakings, exemplified by the European Emissions Trading Scheme (EU ETS), are emblematic of the broad-based drive of this pathway, which is strongly associated with the Transitions dimension and emphasizes system-wide change rather than isolated sectoral measures.

Decarbonization of Electricity. This pathway, which accounts for 14% of the literature, places a carbon-neutral electricity sector at the heart of carbon mitigation. The increase of the part of renewable energy sources in the generation of low-cost electricity, eventually made more competitive through subsidies or a carbon price, is of primary policy concern. The integration of higher shares of intermittent renewable energy sources into existing electrical systems is a key challenge of this pathway, which brings forward the need of energy storage systems (*e.g.*, Khaloie et al., 2020). The envisioned infrastructural shift towards renewable sources and adaptive grids encapsulates the essence of this pathway.

Demand Reduction & Co-Benefits. This pathway, making up 13% of the literature, emphasizes energy efficiency and the multiple co-benefits it brings such as emission and cost reductions, job creation and enhanced energy security. Many articles in this pathway also load on the Transitions dimension, framing conservation-oriented technologies—Japan's Top Runner Programme has inspired several studies—and lifestyle change as elements of broader socio-economic transformation. Tailored strategies, from urban planning to public transport initiatives, aim for more efficient energy use (*e.g.*, Grubler et al., 2018). In this realm, infrastructure is expected to function reliably as energy inputs scale down, supporting a societal tilt towards low energy demand and eventually energy sufficiency.

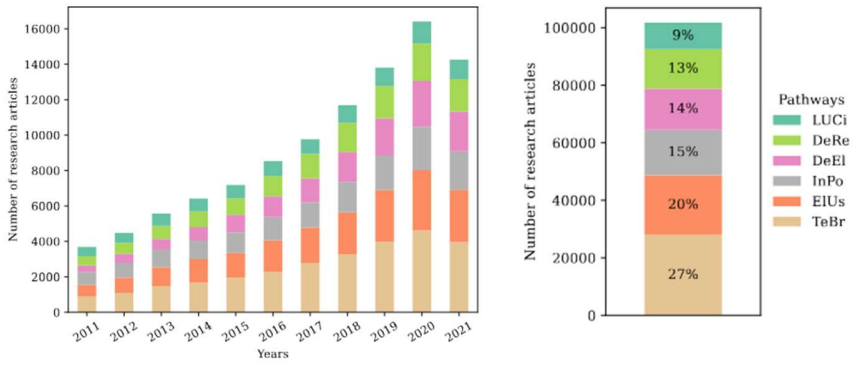
Land Use & Circularity. Lastly, this pathway, featured in 9% of the literature, brings together land-use interventions and circular economy approaches. The conversion of waste to energy and the sustainable usage of resources, such as biomass, emerge as central tenets. Across these studies, the focus is on improving resource efficiency, reducing pressures on land and other natural resources, and enhancing carbon sequestration. Infrastructure and planning measures that enable these circular and land-based practices—such as sustainable land-use planning, soil and ecosystem restoration, and resource-efficient material use (e.g., Wiedmann et al., 2015)—are central to this pathway's vision of low-carbon, resource-efficient systems.

These archetypes of decarbonization pathways appear as different points of departure that have been considered in the literature. These pathways may appear more or less separate in reality. Like climate policies that are often mixed to achieve synergistic

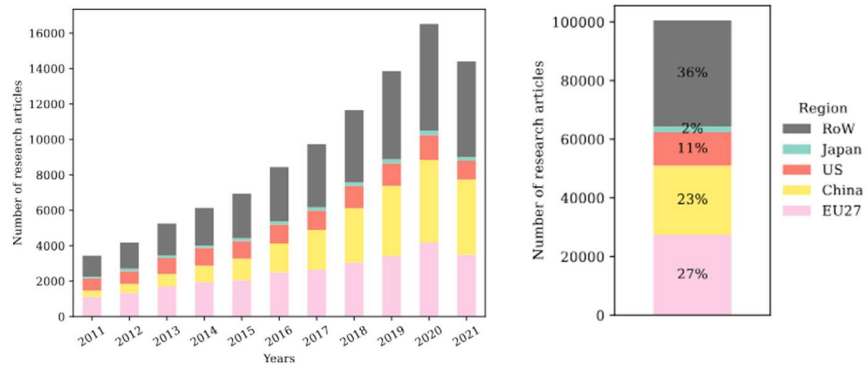
effects (Van den Bergh et al., 2021), countries and companies may combine features of several pathways or change the main locus of action over time. For example, from a more integrated policy to a more sectoral approach, from energy demand reduction and electrification of uses to decarbonization of electricity and material resources circularity.

3.2 Time and regional trends in the decarbonization literature

From 2011 to 2021, there has been a consistent uptrend in the number of published articles, although 2021 (COVID year) witnessed a slight decline (Fig. 4a). To gauge the geographical distribution of research across pathways, we analyzed the countries linked to first authors' research institutions. First-author affiliation is used here as a rough proxy for where research is produced and funded, not necessarily where policies are implemented. Alternative indicators (e.g., corresponding author) are not consistently available across databases, and authorship order carries different meanings across fields. We focus on four main regions (the European Union (EU27 countries without the United Kingdom), China, the United States, and Japan), since two thirds of the identified publications originate from institutions within these areas.



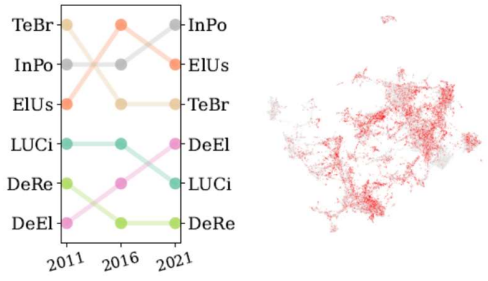
(a) Pathways



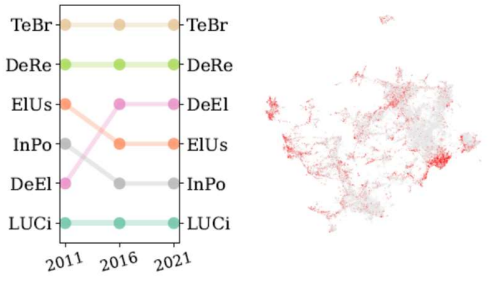
(b) Regions

(a) Pathways

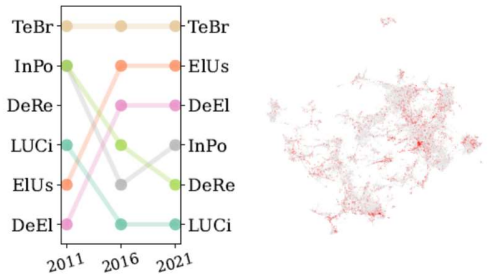
(b) Regions



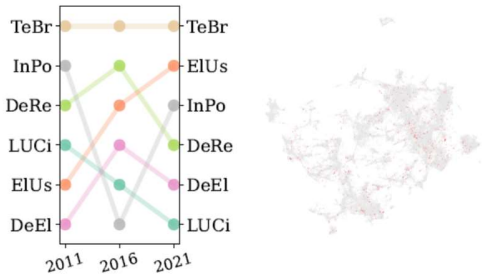
(c) EU27



(d) China



(e) US



(f) Japan

Figure 4. Time and regional trends in the decarbonization literature. *Evolution of the share of the different decarbonization pathways between 2011 and 2021 (a). Number of research articles by main publishing regions in the same period (b). Trends in the pathways in the EU27 (c), China (d), US (e), and Japan (f). Integrated Policy (InPo), Technology Breakthrough (TeBr), Demand Reduction & Co-Benefits (DeRe), Decarbonization of Electricity (DeEl), Electrification of Uses (ElUs), and Land Use & Circularity (LUCi). Results for the Rest of the World (ROW) are available in Fig. S.1 in SM.*

Several overarching trends emerge from the analyzed research corpus. Over half of the total publications on decarbonization originate from institutions in the EU27 and China (Fig. 4b). In terms of the strategies revealed (Figures 4c-f), at the end of the period, while the European Union published more on Integrated Policy, the other three countries focused more on Technology Breakthrough.

When evaluating the dynamics of research by region over time, most regions devote relatively more attention to Decarbonization of Electricity and Electrification of Uses. The latter is particularly important in the EU27 reaching the top here in 2016, becoming the second pathway in the US (as well as in the Rest of the World, see in Fig. S.1 in the SM) and the third in Japan at the end of the period. China is the only region where Electrification of Uses reduced importance over the period despite ranking fourth at the end. Conversely, Land Use & Circularity has received less attention over the period relative to other pathways, maintaining the lowest rank in China. The EU and the US exhibit a more malleable research trajectory, with relatively less focus on Land Use & Circularity and Demand Reduction in the latter, and Technology Breakthrough in the EU. Likewise, Japan shows a greater variability in pathway emphasis across publications, with relatively less attention to Decarbonization of Electricity at the end. Conversely, China, with increasing CO_2 emissions until very recently (Climate Action Tracker, 2024), maintains a more steadfast approach, with the research direction remaining relatively stable. These results also provide indications about the sequence of pathways as countries progress on decarbonization at different paces.

Overall, the analysis reveals discernible yet distinct decarbonization pathway patterns across regions..

3.3 Interactions between decarbonization pathways and scientific fields

We examine the co-occurrence of pathways in the paper as a sign of interactions between the strategies (Fig. 5). Technological Breakthrough has the highest number of papers as the single most referred pathway (“Top”). Electrification of Uses appears as the most often associated with other, auxiliary (“Auxiliary”), pathways, particularly Decarbonization of Electricity. Additionally, Electrification of Uses is the most frequent (transversal) auxiliary to other pathways, followed by Decarbonization of Electricity.

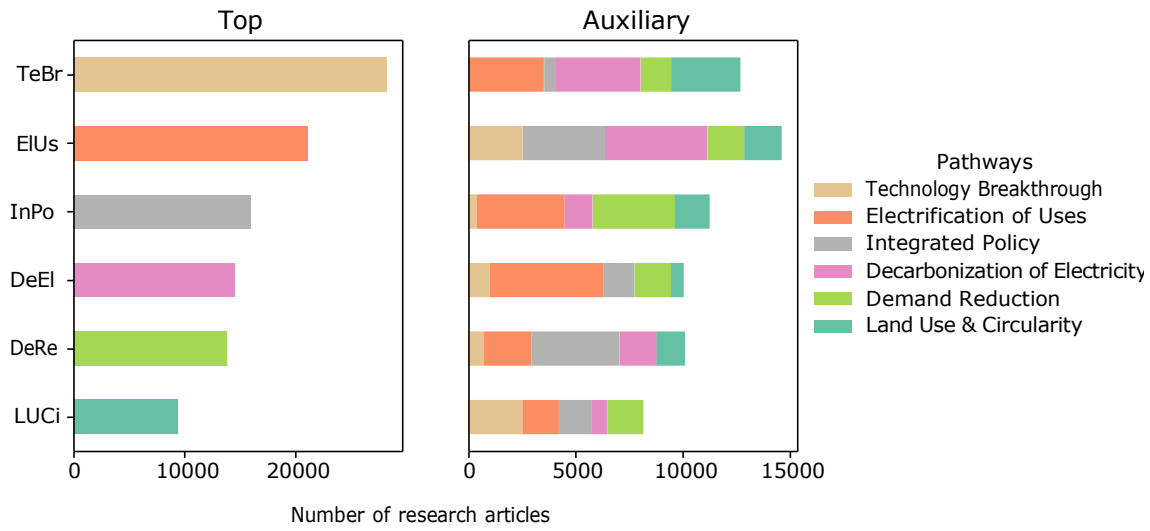


Figure 5. Analysis of the complementarities between decarbonization pathways. *The left-hand graph displays the results for the primary pathways ("top" or the one with the maximum score) per paper, while the right-hand graph shows the results for the "auxiliary" pathways featured in the papers associated with the respective primary pathways. "Auxiliary" refers to all non max paths with a z-score above 20%. Alternative approaches to estimating "top" and "auxiliary" show similar results (see in Figs. S.2-3 in SM).*

We study the scientific fields associated with papers in each decarbonization pathway (Figure 6, left-hand). Some scientific fields are transversal like Environmental Science and Business, others more specific to particular pathways such as Material Science and Chemistry for Technology Breakthrough or Business and Economics for Integrated Policy. Interestingly, Computer Science has an important role in Decarbonization of Electricity. More generally, physical sciences dominate and appear associated with all pathways, while social sciences appear particularly associated with Integrated Policy and Demand Reduction & Co-Benefits (Fig. S.4 in SM).

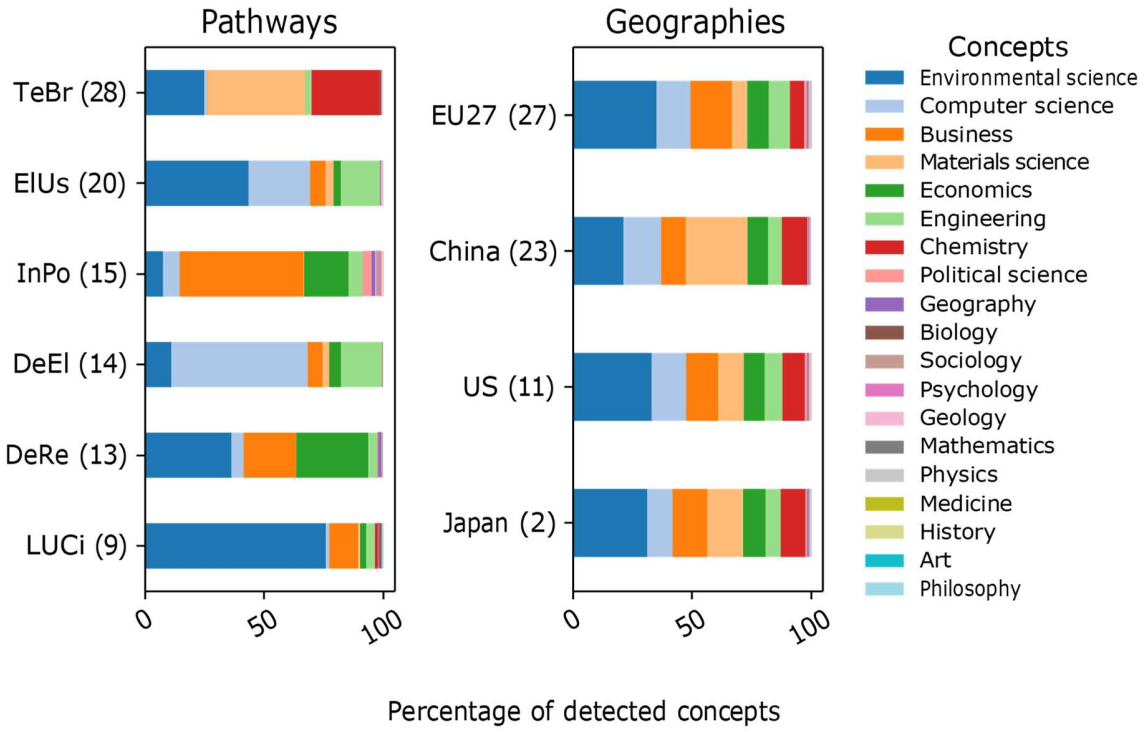


Figure 6. Scientific concepts underlying each decarbonization pathway. *We were able to identify the scientific areas underpinning 99.36% of the papers used to extract the typology. See methods in Section 2.5.*

Figure 6 (right-hand) shows the distribution of scientific concepts in the publications of the countries. The countries have a similar distribution of the scientific fields, with the EU27 showing a relatively higher share of social sciences such as Business and Economics (see also Fig. S.4 in SM), and China relatively more publications in Material Science. The analysis of the scientific concepts of the countries' publications is an indicator of the local competencies that are available to develop the chosen pathway(s) or direction.

Overall, the co-occurrences of decarbonization pathways show the possibility of interactions between them. Indeed, pathways can complement each other such as emerging innovations in Technology Breakthrough facilitating Electrification of Uses. On the other hand, the analysis of the scientific fields by pathways shows to what extent some competencies are needed to pursue certain strategies. The higher share of social sciences in the EU's publications relates to the increasing focus on Integrated Policy and Electrification of Uses in this region (Fig. 4c). These results highlight the importance of competencies for exploring certain directions and indicate more likely strategies of decarbonization by region to reach the objectives for 2030. They also highlight the importance of policies to promote the development of key competencies necessary for pursuing several pathways.

3.4 Comparing the decarbonization pathways with the climate policies of the countries

We assess the extent to which climate policies are aligned with the decarbonization pathways identified through our literature review. Countries may focus their policies on certain decarbonization strategies, which can reflect—or diverge from—their actual climate research priorities. To explore this relationship, we used a new dataset of climate-relevant policies, compiled from the European Environment Agency (EEA) and the International Energy Agency (IEA) public policy databases.



Figure 7. Policy and publication orientation by major regions. *The numbers represent the share of policies aligned with each decarbonization strategy for Europe, the United States, China and Japan, while the color gradients indicate the share of related publications per strategy, by country. Numbers in bold denote the strategy with the largest share of policies in each country. See methods and data sources in Section 2.6.*

The focus of climate policies varies by region, with the dominant strategy in each country shown in bold (Figure 7). Only the United States and Japan coincide, with a greater share of policies targeting technological breakthroughs in both countries. Additionally, China's policies are more heavily concentrated in a single strategy—Decarbonization of Electricity (43%)—whereas the EU27 follows a more balanced approach, with policies more evenly distributed across strategies. In the EU, Land Use & Circularity receives the largest share (27%). While China has increased renewable energy targets and integrated them into national development strategies, especially under the 12th (2011–2015) and 13th (2016–2020) Five-Year Plans, the EU has moved beyond energy-focused measures such as the 2009 '20-20-20' targets and the 2014 Climate and Energy Package for 2030. The European Green Deal widens the

scope to economy-wide decarbonization by 2050, which is consistent with the stronger emphasis on integrated and land-use-related measures in EU policy.

The alignment between policy shares and publication shares by decarbonization pathway varies across countries. For the US ($r = 0.72$, p-value = 0.34), Japan ($r = 0.68$, p-value = 0.13), and to a lesser extent China ($r = 0.37$, p-value = 0.48), policy shares tend to correlate positively with publication shares. In contrast, Europe shows a general misalignment between the two ($r = -0.48$, p-value = 0.34). Across all four regions the correlations indicate no robust alignment.

These findings suggest two possible interpretations. On one hand, a mismatch between the focus of policies and the research literature may help explain the limited effectiveness of current climate efforts (Stechemesser et al., 2024). Misalignment appears particularly pronounced in the EU27, where policies emphasize Land Use & Circularity, a strategy not among the top three most researched pathways in the region. From this perspective, greater alignment between policy and research priorities could help avoid fragmentation and accelerate decarbonization efforts.

On the other hand, policy sequencing—such as progressing from subsidies to pricing mechanisms—is often employed to navigate political and societal barriers (Heyen & Wicki, 2024; Meckling et al., 2017). This means the order in which policies are implemented may reflect strategic or political considerations, potentially preceding shifts in research focus. From this perspective, research may adopt a more forward-looking approach, while policy tends to prioritize strategies that are immediately feasible. Nevertheless, the potential benefits of such sequencing—such as reducing mitigation costs and building support for low-carbon transitions—should not come at the expense of significant environmental costs or the entrenchment of technological lock-ins (Meckling et al., 2017).

Discussion

This paper provides an AI-enabled, large-scale mapping of the decarbonization literature into six recurrent pathways and five cross-cutting dimensions, offering a structured lens for comparing how mitigation strategies cluster across themes, regions and fields. Rather than being an exhaustive or definitive classification, these pathways are archetypes that summarize recurrent combinations of mitigation options in the literature. We use this typology to explore complementarities between pathways, associated scientific competencies, and implications for climate policy design.

These patterns suggest that accelerating decarbonization involves, among other things, changing the provision of energy services such as mobility, sustenance or thermal comfort to become more efficient and economical; aligning incentives and regulations to promote technological and behavioral change; adapting or creating infrastructure (*e.g.*, energy, transport) in a timely manner; and managing the barriers

and complexities of large transitions such as the sociotechnical challenges of the substitution of combustion engines and fossil fuels in transportation (Bento et al., 2025). In this sense, the data-driven typology offers a complementary, high-level perspective on the diversity of strategies to decarbonize large systems, extending existing work focused on specific research communities (*e.g.,* Callaghan et al., 2020), energy systems (*e.g.,* Sachs et al., 2019), or particular parts of the energy supply (*e.g.,* Davis et al., 2018) and demand side (*e.g.,* Creutzig et al., 2018). However, it should be seen as a first-step mapping that invites more detailed, sector- and country-specific analyses of transition dynamics.

Unsurprisingly, the relevant literature for decarbonization grew exponentially over the past decade. Technology Breakthrough and Electrification of Uses account for about half of the papers, reflecting an existing research and policy bias towards the supply side already reported in previous studies (*e.g.,* Wilson et al., 2020). The dynamics of publication were different among the main publishing regions, revealing national specificities in the direction of research. Integrated Policy became the main pathway in the EU27 (the region with the most publications), whereas Technology Breakthrough remains in the top rank in China, the United States and Japan. This likely reflects differences in policy history and governance traditions (Averchenkova et al., 2016). For example, this may reflect the EU's broader focus on integrated sustainability strategies under the European Green Deal, compared with more technology-driven climate and energy programs in the other three countries. A common trait to the four regions surveyed is the increase in importance of Decarbonization of Electricity and Electrification of Uses (apart from China) over time.

We further analyzed the interplay and required competencies of various pathways for achieving the decarbonization goals. The co-occurrence of decarbonization pathways reveals interactions between strategies, such as Technology Breakthrough facilitating Electrification of Uses, or Decarbonization of Electricity enhancing the impacts of Electrification of Uses and Demand Reduction. Analyzing the scientific fields by pathway shows the competencies needed for each strategy. Comparing these with country competencies highlights alignment and gaps, emphasizing the importance of these scientific competencies for pursuing specific pathways and suggesting likely regional decarbonization approaches to meet net-zero objectives.

Finally, climate policy portfolios do not always align with the research emphases captured in our corpus, which may help explain their limited effectiveness (Stechemesser et al., 2024). Research and policy likely co-evolve: policy priorities shape funding and publication patterns, while research signals feasibility and helps legitimize emerging policy options. Misalignment may therefore reflect either delayed policy uptake (sequencing) or research agendas moving ahead of implementable policy. Unless the benefits of policy sequencing outweigh its environmental and economic costs, aligning climate policy with scientific and technological priorities could foster stronger synergies and enhance decarbonization outcomes (Van den Bergh et al., 2021).

The use of first-author affiliation for regional allocation of papers is a standard bibliometric approach (Dominković et al., 2022) but remains a limitation. Many articles involve multi-country co-authorship and cross-regional case studies. As a result, this indicator is more about where research capacity is located than where pathways are implemented.[3] Future research could use more fine-grained bibliometric and text-mining methods of the articles' body text to link case-study locations and policy examples more directly to decarbonization pathways.

Our literature review is exhaustive, but the scholarship on decarbonization pathways is growing fast. Future efforts could incorporate additional databases, other gray literature (*e.g.*, proceedings of conferences), and non-English sources. Regarding the methods, our unsupervised machine learning technique provides an initial data-driven perspective but also has important limitations. It operates mainly on patterns of word co-occurrence, which may only partially capture nuance, context and emerging themes, and its output depends on the training data and model choices. At the same time, a potential advantage of this approach is that it can reveal cross-cutting associations that are difficult to detect through manual reviews at scale.

Future work could address these limitations through several complementary approaches. First, researchers could combine unsupervised models with semi-supervised or active learning, allowing experts to iteratively refine and validate clusterings. This process could involve comparing expert assignments with algorithmic outputs to assess where ML reveals non-obvious linkages versus where it misclassifies. Second, newer large language models (LLMs) could be employed to better capture semantic relationships and enrich the typology. Such models could test whether new publications fit the existing pathways or signal the emergence of additional ones.

Conclusion

This study maps major strategies and cross-cutting dimensions for decarbonization using a data-driven typology that can inform climate policy design. We applied AI-enabled text-mining and natural language processing to an initial corpus of over one million research papers relevant to decarbonization and, via a systematic screening process, derived six recurrent decarbonization pathways: Technology Breakthrough,

[3] We performed a small exploratory concordance check of the first-author affiliation proxy on 26 decarbonization-scenarios documents (used in the initial stage of the research underlying this paper). Using two LLM-based coders, we compared the first-author affiliation country with the study region identifiable from titles/abstracts. Only 5/26 documents had a clearly codable study region; among these, concordance was 5/5 (100%), counting macro-regions as concordant when they included the first-author country. Given the small codable sample—and the prevalence of global or multi-regional studies, which makes this a relatively conservative test of concordance—this is presented as an initial consistency check only. See SM Box 2 for details.

Electrification of Uses, Integrated Policy, Decarbonization of Electricity, Demand Reduction & Co-Benefits, and Land Use & Circularity. The analysis also revealed five cross-cutting dimensions that represent transversal aspects of the decarbonization pathways. Together with the pathways, these dimensions provide a structured lens for understanding how mitigation strategies relate to key themes such as technology, governance, infrastructure, demand and broader transitions across sectors.

The use of the typology to analyze scientific publications reveals discernible time and regional trends. Technology Breakthrough and Electrification of Uses represent a high share of the papers. Similarly, Decarbonization of Electricity and Electrification of Uses (this one apart from China) increased over time in the four regions. However, publication dynamics differ among the main publishing regions (*e.g.,* Integrated Policy dominant in the EU27 vs. Technology Breakthrough prevailing in the other regions), revealing national specificities in the direction of research.

The results reveal that decarbonization pathways are not universal but vary based on factors such as local competencies and the status of decarbonization. Additionally, they show that climate policies do not always align with the research emphases captured in our corpus. A practical implication is that policymakers and researchers can use the typology to benchmark policy portfolios, identify underweighted pathways, and highlight research needs for coherent strategy mixes.

For future research, it would be valuable to compare pathways in terms of policy and technology requirements, feasibility, potential, and co-benefits—including for the economic competitiveness (Venmans et al., 2020). In addition, understanding how pathways can be combined to deliver the level of emissions reductions needed by 2050 is crucial. Comparing the impacts of these pathways for achieving sustainability and wellbeing goals—also in other geographies, particularly in the Global South—will provide a more comprehensive view of their effectiveness and equity impacts.

Data availability

Data in tabular form will be stored in a public repository and will be publicly available.

Code availability

Code in Python format will be stored in a public repository and will be publicly available.

Author contributions

Conceptualization (NB, TA, RR). Operationalization (TA, RR). Analyses and writing (NB, TA, RR, MF).

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Declaration of Interest Statement

The authors declare no competing interests.

Supplementary Information

The supplementary material documenting the analysis, as well as the datasets and the code, will be made available in a repository online.

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