Mixed-Method Evidence Synthesis of the Barriers to and Enablers of Climate Mitigation Policy

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ABSTRACT

Although a growing body of social science research addresses the barriers to and the enablers of climate change mitigation policy, systematic evidence synthesis is so far lacking, making it difficult to access crucial knowledge for decarbonization. We developed a novel mixed-method machine-learning procedure that facilitates uncovering core conceptual and policy-relevant in-depth knowledge from existing studies. First, we map the temporal, geographical, and sectoral coverage of existing evidence on four key barriers to climate mitigation policy based on 11,580 publications. We show that distributional dynamics barriers have become more prominent over time compared to others. Commensurate with the share of emissions, research on barriers to climate mitigation policy is lagging especially in the industry sector. Second, we select 294 articles for an in-depth systematic assessment and develop a typology of six comprehensive enablers of ambitious climate mitigation to synthesize the evidence on barrier relaxation.

Main

Reaching greenhouse gas emission (GHG) reduction targets requires ambitious cross-sectoral climate mitigation policies[1–6]. Today, climate mitigation policy research focuses prominently on the barriers to climate change mitigation policy[7–10]. However, systematic evidence synthesis of research on the barriers to climate mitigation policy and the conceptualization of enablers to overcome those barriers is so far lacking. The relevant knowledge is scattered across diverse strands of literature and sub-disciplines that focus on different sectors, such as energy, transport, and housing. This makes it difficult to obtain a coherent and concrete picture of the current state of the research on climate mitigation policies – i.e., on barriers to decarbonization and the enablers of policy adoption and implementation. Our approach seeks to overcome this deficit by adopting a holistic perspective about various research disciplines in the social sciences (e.g., political sciences, psychology, economics, sociology, etc.) and incorporating varying ontological and epistemological assumptions[11]. Thus, we ask: *What are the most prominent barriers to climate mitigation policy, and what enablers of overcoming these barriers across sectors are presented in the interdisciplinary social science literature?*

Using supervised machine learning, we first map the temporal development and the spatial coverage of the barriers as discussed in 11,580 peer-reviewed articles. The results indicate that distributional barriers, for instance, related to struggles between actor coalitions, have become more prominent over time compared to economic cost barriers. This reflects an important contemporary challenge in climate mitigation policy of how to resolve such distributional struggles between actor coalitions. Our results further show that this barrier is less often studied in Asia, Africa, Latin America, and the Caribbean than in other regions. Commensurate with the share of emissions, research on barriers to climate mitigation policy focuses more strongly on the energy sector but there are large research gaps on climate mitigation research in the industry sector.

We advance the problem-oriented literature on barriers by developing a solution-oriented typology of enablers of ambitious climate mitigation policy. This provides researchers and practitioners with a framework to understand which enablers address what barriers, how these mechanisms operate, and what the available evidence on these relationships is. For instance, to overcome distributional barriers in the transport sector, where these repeatedly hampered ambitious climate policy[12], our in-depth mixed-method review of the evidence on the new typology suggests that local bottom-up experimentation combined with participatory and deliberative governance processes can establish rules that are broadly accepted by many stakeholders. Such processes can also reduce distributional barriers by fostering a change in actor motivations, for instance, related to reciprocity[13], trust, cooperation[14], and consent[8] rather than purely economic motives. To address conflicts that may arise, governmental agencies can establish dedicated institutions, like independent regulatory agencies or multi-stakeholder platforms, to act as neutral brokers and mediate political processes.

In our in-depth mixed-method analysis of the enablers based on 292 full-article texts, we summarise the evidence on the relationship between enablers and barriers. For instance, we show that the enabler of communication and framing is often linked to distributional dynamic barriers. Our in-depth synthesis of the research articles indicates that clear communication of the benefits of climate policy among voters has positive effects while the literature on the effects of changes in the wording of the problem itself is less clear. Given the urgent need of adopting ambitious climate policies, we provide important results that show which enablers can reduce specific barriers to climate mitigation policy by means of a novel mixed-method evidence synthesis procedure that we have developed. This novel mixed-method approach can also be used by other scholars to synthesise key research results and develop evidence-based policy recommendations.

As the number of academic publications is rising sharply, systematic evidence synthesis is becoming increasingly important[15–17] for making knowledge accessible. Such research is crucial for the work of the Intergovernmental Panel on Climate Change (IPCC) which grapples with the challenge of the fast-growing literature. Over time, the IPCC represented a decreasing share of the entire body of climate change research[18]. For the evidence synthesis of large bodies of inter-disciplinary and cross-sectoral literature, machine-learning approaches promise to leverage scientific publications in the form of big data[16,17,19,20]. Big data evidence synthesis can provide robust, reliable, and transparent summaries of evidence[21] using systematic maps that provide an overview of research topics[22] and systematic reviews that summarize the direction or strength of a relationship between explanatory factors and an outcome[23,24]. While in recent years machine-learning-based approaches have become more popular to map the rapidly growing academic literature, these methods often fall short of identifying core conceptual and policy-relevant in-depth insights from existing studies. To overcome these challenges in evidence synthesis and make crucial interdisciplinary knowledge for decarbonization accessible to policy-makers, we developed a novel mixed-method procedure for the large-scale mapping of the barriers and enablers to climate mitigation policies.

We developed a novel three-step, mixed method procedure, as displayed in Fig 1 (for a more detailed description of the methodological approach, see Supplementaries,): This three-step procedure allows us to inductively derive a typology of enablers and to analyze the evidence on each - such aspects often remain hidden in large-scale maps, despite their important implications for policy-making.

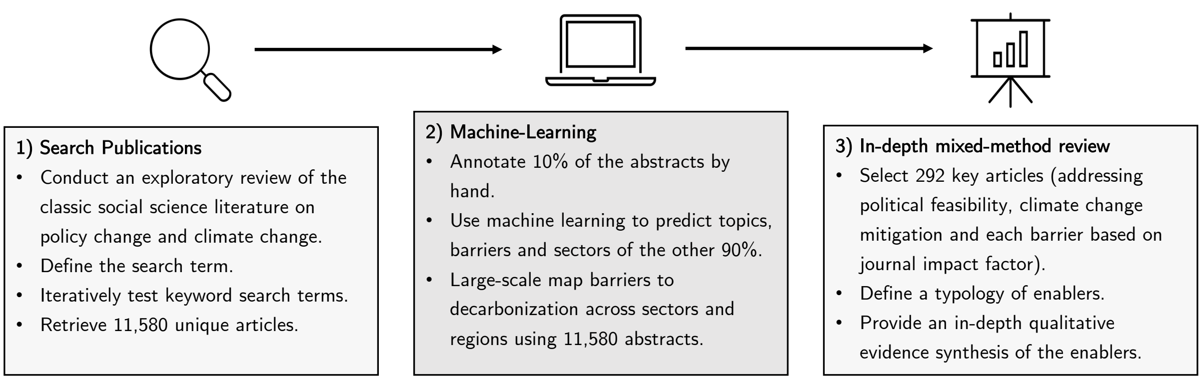

Figure 1. Machine-learning mixed-method review procedure. This diagram illustrates the three-step procedure that we developed. First, based on keywords derived from the relevant literature, we retrieved a large corpus of 11,580 article abstracts from the bibliographic platform Web of Science. Second, we trained a supervised XGBoost machine-learning model to quantify topics (political feasibility, policy impact evaluation, climate, environment, mitigation, adaptation), sectors (energy, transport, buildings, industry, and agriculture forestry and other land use [‘AFOLU’]), and barriers (distributional dynamics, economic cost, institutional capacity, multi-level governance) based on the abstracts of the 11,580 articles. The result is a so-called map of the literature. Third, we review key publications to inductively define a typology of six enablers. We then selected 100 articles from the journals with the highest impact factor that focus on the political feasibility of climate mitigation policies in relation to each barrier. These sum to 294 unique articles, as some treat two or more barriers. Finally, we provide a quantitative overview of the six enablers. We show which barriers, sectors, and evidence types these enablers are frequently associated with. For more detailed reporting on these steps, see the methodology and research protocol in the Supplementaries).

Mapping Research on Barriers to Climate Change Mitigation Policy

Based on our machine-learning analysis of 11,580 article abstracts (see Supplementaries 2), Fig 2 shows publications about barriers over the period from the publication of the IPCC Assessment Reports (AR) 1 to 6. Fig 2 shows that the literature about barriers has grown rapidly. For example, in 2020, barriers to climate mitigation policy were discussed over 550 times in the analysed articles, more than during the entire period from AR1 to AR4.

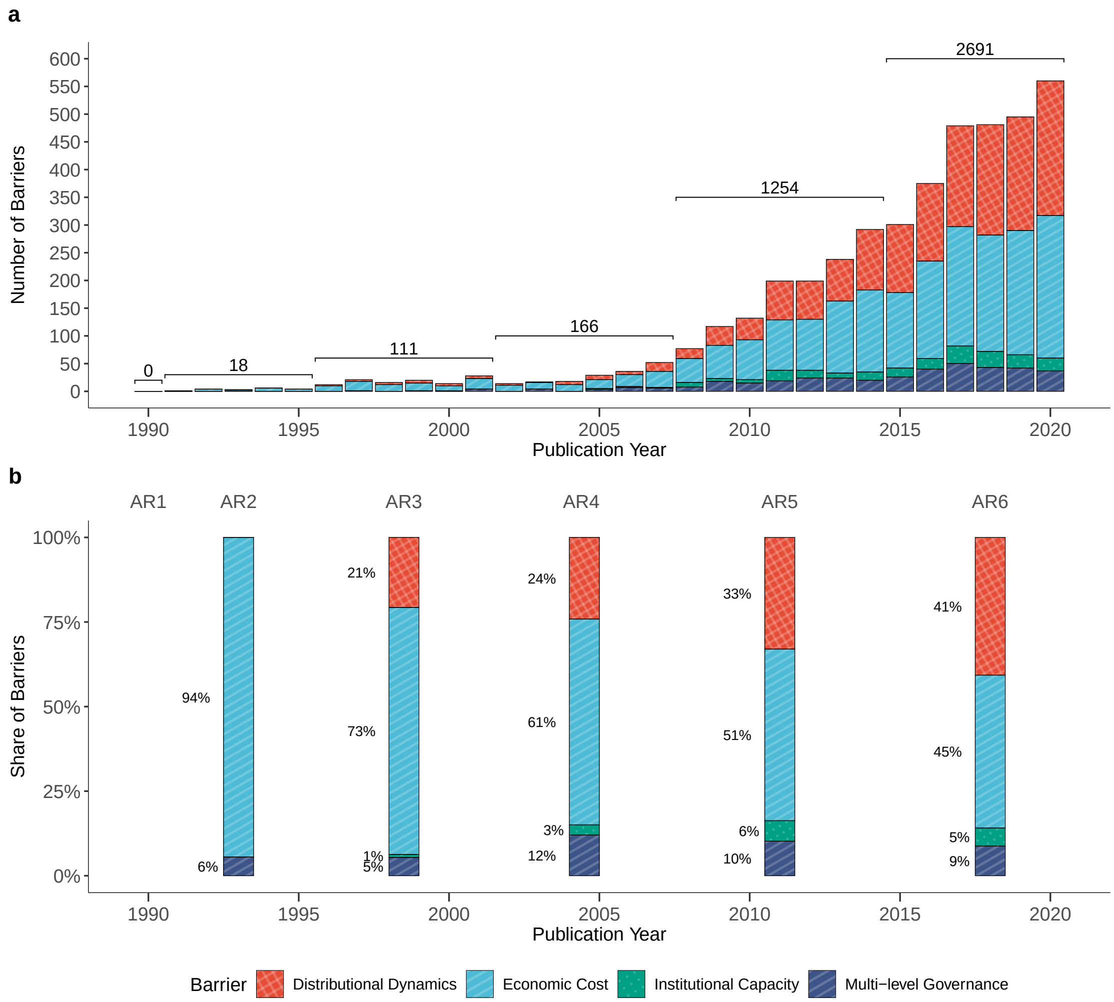

Figure 2. Evolution of research over time. Panel a shows the total number of times that each of the four barriers (for definitions, see Table 1) in the research over time. Panel b displays the relative share of research about barriers for the periods from Assessment Report 2 to Assessment Report 6.

Fig 2 b displays the temporal evolution of research on the barriers (for definitions, see Table 1) in percentages. Research published before AR2 was dominated (share of 94%) by economic cost barriers (cost-of-decarbonization-related factors). In the 1990s, for the period of AR2 (note that our sample does not include articles published before AR1; for details, see Supplementaries), the main questions centred around whether climate change was human-made, the role of technological innovation, and the associated economic costs of climate change mitigation. Little research addressed institutional capacity barriers (e.g., lack of government resources, public trust-related factors, etc.; 1%) or multi-level governance constraints (lack of international enforcement and free-riding-related factors, etc.; 5%). No research during period AR2 on climate change mitigation covered distributional barriers (factors related to the lack of supporting coalitions, etc.). From AR3 to AR6, the share of research on economic cost barriers nearly halved to 45%. Over the period from AR5 to AR6, the dominance of economic cost barriers strongly declined, and research on distributional barriers substantially expanded. This reflects the growing importance of resolving distributional tensions[25] in areas related to public support, elite coalitions, and inequality within countries and between the Global North and South.

Turning to the spatial distribution of these barriers across regions and research on specific countries, Fig 3 a shows the number of articles on a world map. Geoparsing countries' names from the abstracts of articles allows us to summarize which countries are the most researched and which barriers are prominent in each region.

On a general level, the world map in Fig 3 a reveals that over the entire study period, most research focused on China and the US – the countries currently the biggest emitters of GHG emissions in absolute terms[26]. Neither country has implemented sufficient political policies for meeting the emission reduction targets defined in the Paris Agreement[27].

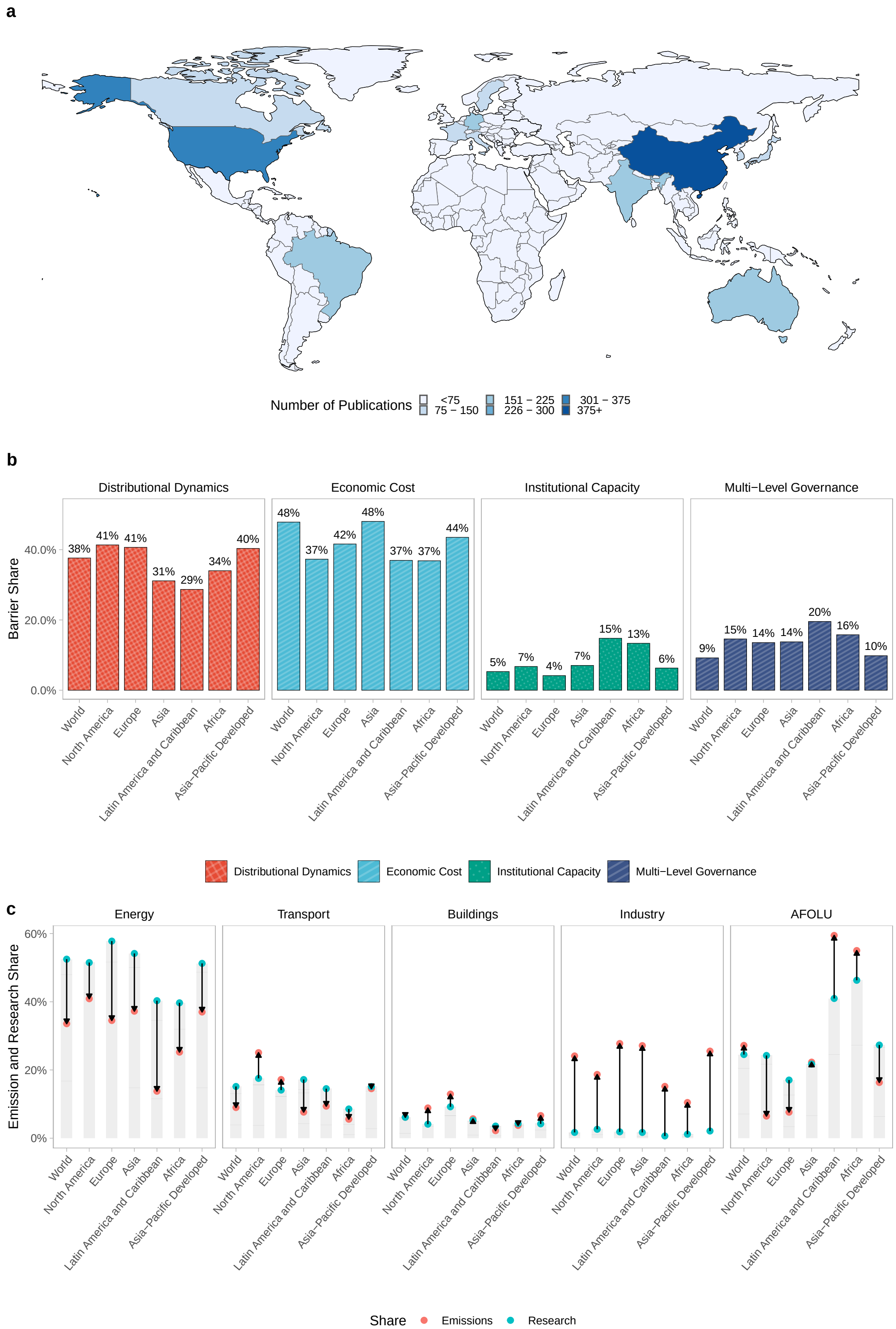

Figure 3. Spatial distribution of research. Panel a shows the number of publications by country, panel b displays the share of each of the four barriers in the research, and panel c contrasts the share of research and emissions according to sector and world region.

Fig 3 b reflects the dominance of research on economic cost barriers in Asia (for the countries in each region, see Supplementaries, Fig 13) where this barrier accounts for the highest share (48%). In contrast, a slightly smaller share of research on economic cost barriers is associated with countries in North America, Latin America, the Caribbean, and Africa. However, the share of research on institutional-capacity-related barriers is greater in less developed countries than in developed regions. Institutional capacity barriers relate to the lack of a supportive institutional environment, trust and shared values[28], or government expertise in managing complex behavioural responses and the inter-connected and cross-sectoral nature of climate policy processes. Although less studied worldwide, our machine-learning-based large-scale map reveals that institutional-capacity-related barriers are rather prominent in climate policy research on Latin America and the Caribbean and Africa, alongside economic cost and distributional barriers.

The greatest regional shares of research on distributional dynamic barriers are found in developed and democratic country regions, specifically North America, Asia-Pacific Developed and Europe. In less democratic regions, which include Asian countries such as China, Russia and India, the share of research on distributional dynamics is slightly less than that on economic cost barriers. Last, there is relatively little variation in the share of research about multi-level governance barriers, ranging from 10% in Asia-Pacific-Developed to 20% in Latin America and the Caribbean.

Barrier	Definition	Example
Distributional Dynamics	Implies struggles between actor coalitions[7], interest group lobbying[29], veto player action[30,31], lack of public support, and ideological clashes based on identity or deep-held beliefs and convictions[8,32,33].	Conflict between pro-ecology and pro-economy coalitions.
Economic Cost	Implies the costs[7] of low-carbon technological and behavioural change for private and public actors.	Technology costs inhibit the adoption of cultivated meat.
Institutional Capacity	Involves the lack of competencies, resources, and expertise[7] of governmental institutions.	Insufficient expertise of administrative staff.
Multi-level Governance	Involves free-riding[7] at the international level and lack of enforcement between vertical governance levels[34–36] (communal, national, regional, and international).	Free-riding incentives for global public good provision.

Table 1. Definition of Barriers

Fig 3 c shows the difference between research on climate change mitigation (light blue) and GHG emissions (red) by world region for each sector. Compared to the respective share of emissions, the energy sector receives more attention in research on climate change mitigation. This is the case across the world and in individual regions. This may be because renewable energies are strategically important in transforming the economy in line with the Paris Agreement and enabling mitigation in other sectors, such as transport and buildings. For transport and buildings, the research share across the world is almost commensurate with the share of emissions. However, in the high-emitting regions of North America and Europe, where distributional barriers loom particularly large, these two sectors are under-researched compared to their relative share of emissions. The share of research associated with the industry sector is again much lower on a global basis, which indicates a key research gap for climate change mitigation research. In the agriculture, forestry and other land use (AFOLU) sector, the global research share is nearly on a p with the share of emissions. Regionally, research is lagging in Latin America, the Caribbean, and Africa – regions with relatively high deforestation rates and emissions from agriculture and land use changes. In contrast, the AFOLU sector receives relatively more attention in North America and Europe.

Typology of Enablers of Climate Mitigation Policy

Since successful decarbonization crucially depends on the adoption of ambitious climate policy, we now zoom in on the enablers of ambitious climate mitigation policies. Our inductive approach yields a typology of six comprehensive enablers of ambitious climate mitigation. These comprise several specific causal mechanisms (see Table 3.3) that, when activated, can relax existing barriers and foster the adoption of more ambitious climate policy[7]. Fig 4 displays this typology of enabler and defines each.

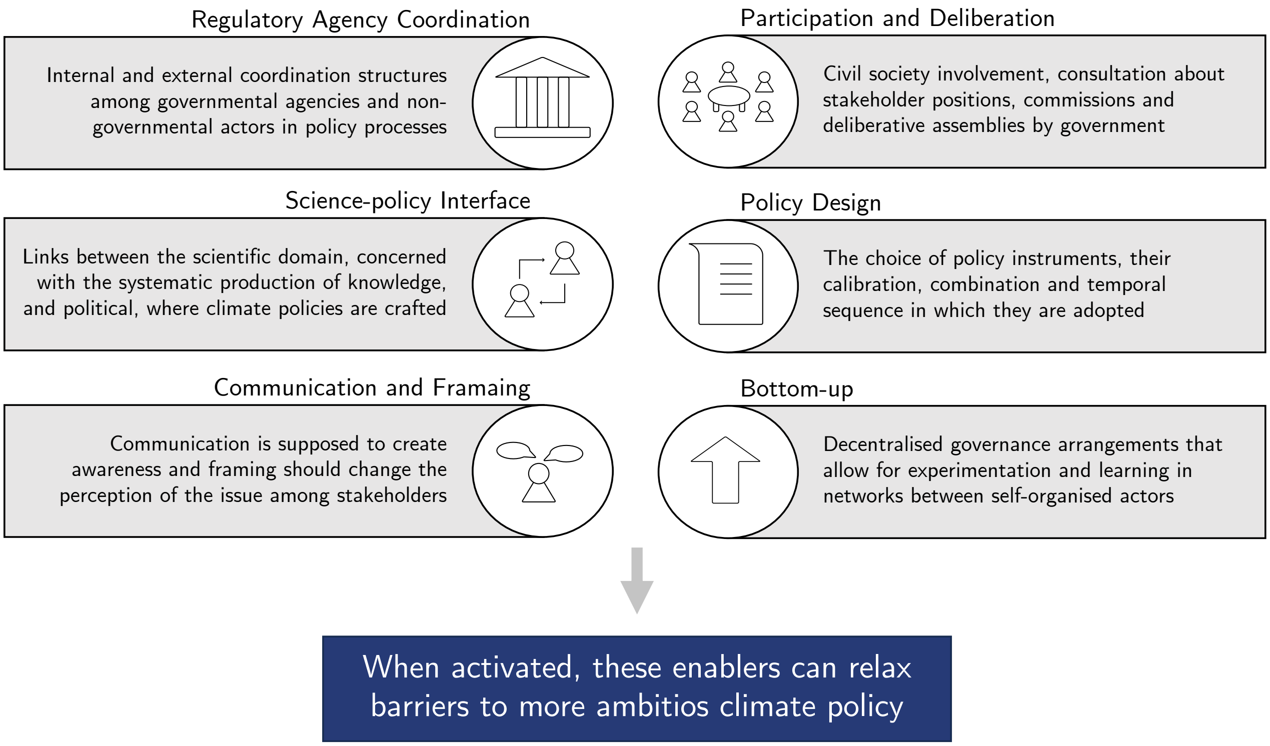

Figure 4. The typology of enablers. This diagram provides a definition for each enabler in the typology that we inductively derived from the literature on barriers.

The six enablers described in Fig 4 involve a range of specific causal mechanisms for overcoming the four barriers to climate mitigation. In contrast to rather stable aspects of political systems, such as voting rules, our typology consists of six comprehensive types of enablers that are relatively amenable to being actively and strategically changed or activated in policy processes. First, to unpack the evidence on these, we systematically grouped the qualitative notes from the quantitative annotations of the six enablers in Fig 5 and summarized this evidence in a comprehensive mind map. This qualitative summary of the research corpus allows us to illustrate the causal mechanisms associated with each of the six enablers. These are shown in Table 2. Below, we introduce these in more detail and provide an in-depth qualitative discussion of the current evidence. Second, we quantitatively map which enablers link to what barriers and sectors and what methodology the researchers used to support the findings for each enabler.

Regulatory Agency Coordination

Definition. Regulatory agency coordination includes internal and external coordination structures among governmental agencies and non-governmental actors in policy processes[37,38].

Mixed-method Evidence Synthesis. Internal coordination includes vertical and horizontal structures that reduce information asymmetry within state institutions. These can broaden the range of available policies by facilitating the cross-sectoral integration of successful policy options[29,39,40] and buttress the implementation capacity of local governments. For instance, de Oliveira (p. 1906) describes how some institutions that addressed air pollution and climate change enriched the portfolio of policy options through cross-sectoral knowledge transfer for policy implementation in the climate change domain[41]. Thus, coordination between government agencies can buttress administrative capacity[41,42], especially when important policy entrepreneurs and leaders can link new policy design ideas[42,43]. Fig 5 shows that 36% of the research on regulatory agency coordination is associated with institutional capacity barriers.

External coordination structures relate to the government's proactive management of policy processes. At the international governance level, the leadership of European countries[44], and specifically the French diplomatic approach that combined leadership and conflict mediation – the so-called "lediator" strategy – was crucial in negotiations before the landmark signing of the Paris Agreement by the national delegations of 194 sovereign nations. The strategy facilitated the organisation of the summit, the structuring of the negotiations, and mediation between conflicting negotiation positions[45,46]. Ambitious international climate negotiations have often been stalled due to free-riding. 36% of the research on regulatory agency coordination addresses such multi-level governance barriers. Besides the international realm, brokerage and conflict mediation by government agencies can also unfold at the national level concerning conflict-resolution coalitions in the policy process. For effective brokerage, other actors must perceive the broker as neutral but influential in policy networks. This actor typically strives for low conflict between opposing positions by coalitions involved in the policy process[47]. These broker roles also require clear leadership[48] to facilitate the assignment of tasks.

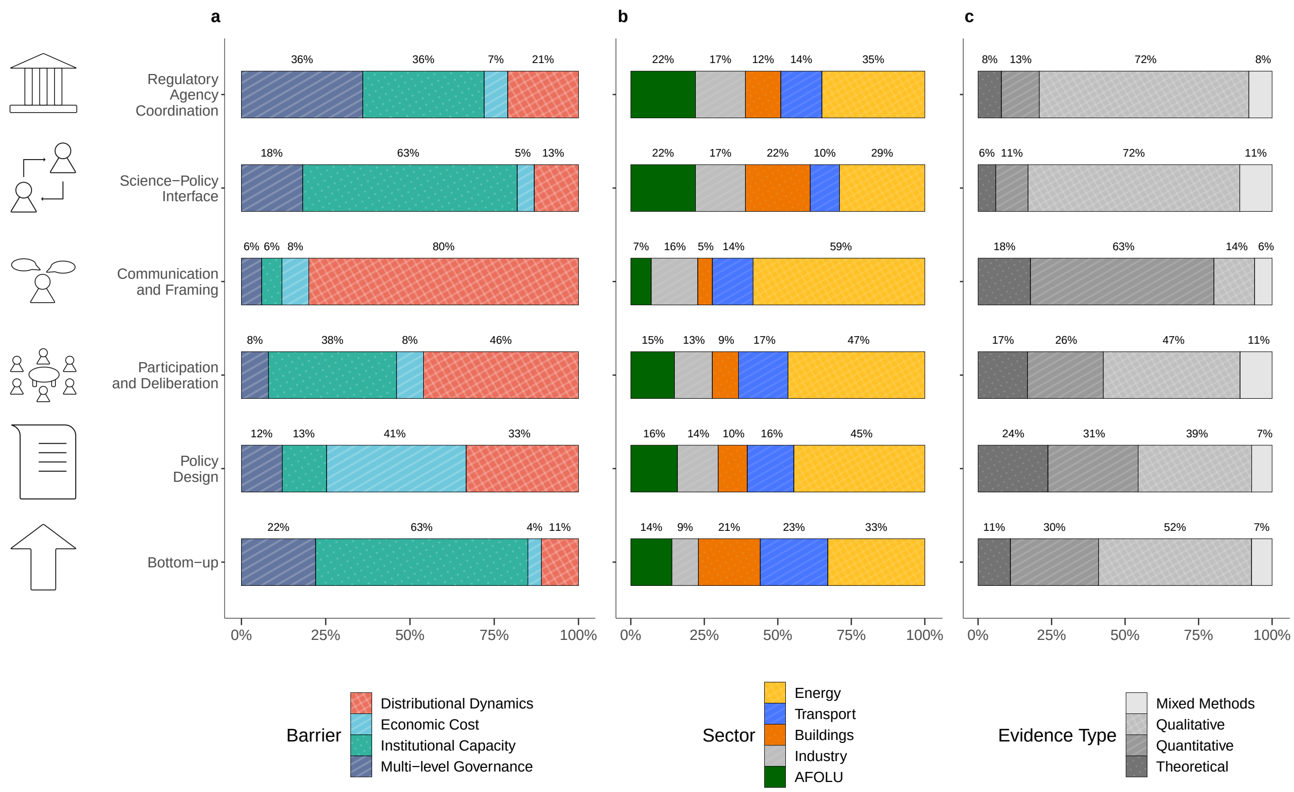

Figure 5. Enablers of barrier relaxation. The figure displays the share of research that associates each enabler with a. one of the four barriers, b. the economic sectors, and c. the research method.

In both internal and external coordination, leadership is also important for empowering the relevant bureaucracies for climate mitigation governance[39]. This may require the establishment of new institutional arrangements and venues that facilitate coordination and leadership. Grosjean et al., for instance, propose establishing independent regulatory institutions to shield the EU Emission Trading System against short-term political pressure. Such independent institutions that facilitate horizontal and vertical coordination can help in long-term oriented policymaking, lessen price fluctuations, and disincentivize politicians from serving industry groups[49]. However, new venues and institutional arrangements may also reduce information asymmetries and foster participation through consultative processes in vertical and horizontal networks among key stakeholders[50].

In total, 72% of research on such coordination between regulatory agencies is supported by qualitative evidence, while only 13% of the current research uses quantitative methods.

Science-Policy Interface

Definition. The science-policy interface links two otherwise separate domains: the scientific and the political[51,52]. Science-policy interfaces can be more or less formalised and often differ substantially in their form, for instance, their initiation, independence, mandate, duration, membership composition, and outputs[53,54].

Mixed-method Evidence Synthesis. Improved science-policy interfaces can have positive effects on the relaxation of institutional capacity barriers because of a reduction in information asymmetry, reduced uncertainty about problem causes and solutions, and more evidence-based decision-making capacity[50,55,56]. This is documented in articles (63%, see Fig 5 a) a majority of which (72%) is qualitative. For example, a comparative case study involving Mexico City and Santiago, Chile, showed that the science-policy interface played an important role in both cases in putting the climate change issue on the agenda. In Mexico City, the Environmental Ministry and the National University established an emission monitoring inventory under the broader umbrella of a dedicated science-policy institution to track cross-sectoral emissions[50]. Also, the UK Climate Change Committee, composed of scientists and experts, has played a crucial role in monitoring and evaluating climate policy progress[29]. By monitoring and evaluating the attainment of policy goals, such science-policy arrangements can decrease institutional capacity constraints[57].

Enabler	Example of a Causal Mechanism for Barrier Relaxation			
	Distributional Dynamics	Economic Cost	Institutional Capacity	Multi-Level Governance
Regulatory Agency Coordination	Conflict mediation	Resource optimisation between government agencies	Reduced information asymmetries between government agencies	Top-down reduction of policy incoherences
Science-policy Interface	Act as honest brokers and policy entrepreneurs in policy networks	Inform about technological learning rates and economic opportunities	Assist with monitoring and evaluation	Advise international climate negotiations
Communication and Framing	Reduced salience of partisan-based opposition	Increased visibility of climate policy benefits	Increased perceived legitimacy of political leaders and agencies	Create norms of reciprocity through communication to avoid free-riding
Participation and Deliberation	Voice options increase social acceptance and deliberation can create novel coalitions	Identification of new potentials to reduce costs of clean technologies	Increases knowledge about coalition preferences	Can increase the willingness to contribute to public goods
Policy Design	Packaging benefit-inducing subsidies with cost-inducing taxes	Policy sequencing can increase acceptance of more ambitious climate policy	Progressive increase of institutional capacities through prior laws	Progressive increase of national harmonisation commitments
Bottom-up Processes	Less preference heterogeneity accelerate decisions and create positive spillovers to higher governance levels	Local regulatory environments can foster economies of scale and local human, social and intellectual capital	Decentralised processes are easier to manage	Up-scaling of locally successful rules and best-practice examples

Table 2. enablers of barrier relaxation. This table provides a definition of each enabler and the causal pathway that enables the relaxation of the four barriers (for a definition, see Table).

Besides monitoring, the science-policy interface can provide direct advice on the operation of policies or technological enablers. Expert panels can, for instance, explain the interaction between emission trading systems and other policies[58]. The involvement of scientists is also crucial in putting climate change[59] and potential mitigation options on governments' agendas and assessing different policy proposals[60]. Scientific communities can create awareness by highlighting the opportunities and risks associated with technological and behavioural mitigation options[9]. Especially in relation to new and rapidly developing technologies and mitigation options, science may operate in so-called epistemic communities – groups of actors acknowledged as experts that share beliefs about the value of specific mitigation options. Such epistemic communities can act as honest brokers and policy entrepreneurs by contributing to the broadening[60] and prioritisation of technologically and politically more feasible policy options[9,28]. This can also reduce economic cost and distributional dynamics barriers to climate mitigation policies.

Thus, the science-policy interface has largely positive effects on the political feasibility of ambitious climate policies. However, the prospects of effectively advising policymakers depend on the exact format of the science-policy interface, which may require tailoring to specific national or local settings, political institutions, traditions and cultures[52]. On a more general level, given the high complexity of the climate problem and the large number of actors needed to resolve it, more inclusive science-policy interfaces are often better equipped to provide advice supported by both the scientific community and policy makers[52].

Communication and Framing

Definition. Communication aims at creating awareness of climate change, political challenges and potential solutions. Framing can aim at increasing support for climate policy by changing the perception of the problem, its causes, and moral and normative conclusions about potential solutions[61,62]. Framing can take different forms, such as emphasising specific arguments in political discourse, modifying the sender of a message (source cue), and changing the perceived (temporal, spatial, social) distance to a problem.

Mixed-method Evidence Synthesis. Communication and framing are inherent to every political campaign. Often, such political campaigns are driven by distributional struggles that are rooted in partisan- and identity-based considerations, especially in two-party majoritarian political systems, such as in the US. Consequently, the literature on communication and framing investigates to what extent such divisions can be overcome[8,33,63–65]. In contrast to most other enablers, communication and framing research centres mostly (80%) around the relaxation of such distributional dynamic barriers. However, the latter is inconclusive about the extent to which framing strategies can overcome such divides. Some argue that decoupling communication from partisan- and identity-based considerations can positively affect support[8] as a salient political identity negatively affects support[33]. Others point out that deep-rooted divisions are unlikely to be overcome only via communication and framing strategies[64].

Closely related to this line of research is the framing literature that investigates how changes in wording, such as speaking of climate change in the present or past tense[66] or with respect to certain health and economic co-benefits, affects public support for climate mitigation policies[65,66]. This research finds, for instance, that framing climate change as an air pollution or energy security problem increases public support in the US among Republicans but not Democrats[65]. This means that framing effects interact with other variables, such as political attitudes or prior knowledge, but tend to have relatively small effects by themselves[67].

Communication that raises awareness or involves talking about benefits rather than costs may potentially increase the feasibility of ambitious climate policy. For instance, consensus in parliamentary debates may emerge when opportunity-oriented discourses, rather than cost-based argumentation, realign positions[68]. Related research on communication with voters shows that the benefits of climate policies should be clearly communicated to increase support. Often, the general population knows little about the benefits of climate-oriented political reforms[69]. For instance, regarding carbon taxation, it is essential to clearly communicate progressive redistributive reimbursement mechanisms so that citizens perceive the policy benefits[70,71].

Research associated with communication and framing covers predominantly the energy sector (59%), with only 5% on buildings but a relatively large share (16%) on the industry sector. There is also little research on framing and communication in the context of the AFOLU sector (7%). The literature on framing and communication employs mostly (63%) quantitative methods. Only 14% of studies are qualitative and 6%use mixed methods. Around 18% of current research is based on theoretical and logical argumentation without empirical analysis.

Participation and Deliberation

Definition. Such participatory processes can take several forms. These include government civil society involvement, consultation about stakeholder positions, commissions and deliberative assemblies where either stakeholders[72] or citizens make proposals to the government[13], for instance, related to policy design.

Mixed-method Evidence Synthesis. Fig 5 illustrates that most research on participation and deliberation links this enabler with distributional- or institutional-capacity-related barriers. First, 46% of the research on participatory and deliberative processes focuses on distributional dynamic barriers. However, the literature is inconclusive concerning whether more inclusive governance increases or decreases the feasibility of ambitious climate policy. Some hold that distributional dynamic barriers can be relaxed through participatory voice options that create access points for diverse actors, including civil society, firms, scientists, and other actors. Including such diverse stakeholders in climate change governance can increase reciprocity[13], trust, and cooperation aimed at solving collective action problems[14]. Different forms of deliberative democracy, such as citizen assemblies[8,13] that allow citizens to participate actively can also reduce polarization and ensure that more diverse opinions are considered in decision-making processes. This can relax distributional barriers by increasing public support[73]. Others, however, highlight that the greater the number of actors with more diverse interests in policy processes, the more veto players who may block decisions, stall progress and prolong decision-making procedures[30,31]. Here, the specific form and design of the participatory, deliberative process are essential for its success.

Second, 38% of the research on participatory and deliberative processes covers institutional capacity barriers. Opening up policy processes creates new forms of peer accountability that allow a more diverse set of actor groups[74] to observe actions, pose questions, and sanction misbehaviour, albeit often informally. This can increase the problem-solving and planning capacity of governments[75,76]. In less democratic countries with lower levels of democratic input legitimacy, civil society involvement has been shown to increase support for climate policy, despite the latter's potential relative lack of independence[77]. Similar results are found for democratic countries[77,78].

Policy Design

Definition. Policy design as an enabler of climate change mitigation involves the specific means of creating laws, rules, and regulations that guide the economy, society, or government. Through the specific choice of policy instruments[70,79–83], the combination[84–86] and calibration of these instruments[9,87], for instance, related to carbon tax revenue recycling[71,88–91], policy design can enhance the political feasibility of ambitious climate policy strategically.

Mixed-method Evidence Synthesis. From the economic efficiency perspective, carbon pricing policies are often favoured over other options, such as low-carbon subsidies[71] or reduced value-added tax rates[81]. However, efficient climate policies such as sufficiently high carbon prices often face high distributional barriers (the systematic map in Fig 2 shows that the latter have become more prominent over time)[71]. Such distributional barriers can be addressed through policy sequencing strategies. Strategic ordering over time in the form of so-called benefit-to-cost sequences that first drive down economic cost using second-best policies, such as low-carbon technology subsidies inducing technological learning, may relax economic cost constraints. This can increase the opportunity to switch technologies, change behaviour, and create new winning coalitions that foster support for more ambitious carbon pricing over time[7,12,92–95]. Policy sequencing can explain why some states, such as California and Germany, have managed to adopt ambitious carbon pricing policies[7,92,93].

Similarly, the literature on policy packaging[96] suggests that non-market-based instruments, such as subsidies, may have complementary effects on the political feasibility of carbon pricing, especially when strong disruption to socio-technical and socioeconomic systems is expected due to job losses and stranded assets[85]. Coupling carbon pricing policies that impose direct costs on carbon emissions with policies that reward low-carbon technologies and behaviour increases the feasibility of more ambitious carbon pricing[84,86,96–98] that would face higher distributional barriers if introduced independently. Research on climate policies in developing countries also increasingly emphasizes the role of co-benefits among development and climate change[88,99–101]. In many developing countries, climate finance is crucial for achieving emission reduction targets since large investments are necessary for transforming the economy and reducing economic cost barriers. One proposal is to make climate finance conditional on the introduction of carbon pricing. Revenues from carbon pricing may then be used to bolster low-carbon economic development. Although this may reduce economic cost barriers, it can lead to distributional trade-offs, for instance, for poor segments of society[88]. Therefore, research highlights that compensation schemes may offset the regressive effects of some climate mitigation policies and enable just transitions. Coupled with clear communication that raises awareness, this can potentially avoid adverse development effects and broaden political support[102]. This is also captured in Fig 5 showing that 43% of research on this enabler links to economic cost and 33% on distributional dynamics barriers. Around 39% of the research uses quantitative methods, while around 31% of studies employ qualitative approaches.

Bottom-up processes

Definition. Bottom-up processes exhibit a relatively low degree of centralisation that allows for experimentation with new governance arrangements and may trigger diffusion processes[103]. These processes include so-called carbon clubs, in which cities or countries create horizontal governance arrangements for knowledge exchange[41,59,104,105] that can relax institutional capacity constraints and involve measures to avoid carbon leakage[1,106].

Mixed-method Evidence Synthesis. Global climate governance is currently lacking enforcement mechanisms. To overcome the deadlock in international negotiations and the barriers associated with free-riding in these multi-level governance systems (17% see Fig 5), political action that addresses climate mitigation has unfolded from the bottom-up in decentralized national and subnational settings[92,103]. A sizeable body of research documents that local climate ambition can surpass national or international policy ambition (see, e.g., refs[104,105,107]). A majority (52%) of this research uses qualitative methods with a relatively large share focusing on the transportation sector (23%).

Such bottom-up processes may not only circumvent multi-level governance barriers but also relax institutional capacity constraints (74% of the research on this enabler, see Fig 5). These constraints often arise due to a lack of information or expertise. This institutional capacity barriers can be relaxed via local experimentation and learning from other successful experiments, which can be diffused via climate action networks, such as the Cities for Climate Protection (CCG) or ICLEI Local Governments for Sustainability[37,104]. This can also create bottom-up pressure[104] that reinforces implementation capacity at the national level[41].

Not only are networks between cities an effective means of information exchange, but they may also operate as so-called carbon clubs. To alleviate the free-riding incentive not to implement ambitious carbon pricing but wait for others to bear the cost of mitigation, governments may form clubs through which they link each other's carbon pricing policies and establish a carbon tariff for non-member states. This could increase the incentive to participate in such clubs and promote carbon-pricing schemes across the globe[1,106]. However, research on such carbon clubs is mainly restricted to theoretical articles.

Conclusion

This paper contributes to the study of the barriers and enablers of ambitious climate mitigation policies. Our large-scale machine-learning-based map of four barriers to climate mitigation policy[7] reveals that distributional barriers have become more prominent in the literature over time. This finding reflects a key challenge for current climate policy processes: a lack of support and conflict among coalitions about the most appropriate political measures for limiting climate change. How to overcome distributional struggles and increase the political feasibility of ambitious climate policy thus remains a relevant question for social science research and policymakers.

Our in-depth mixed method review shows how to enable the adoption of ambitious climate mitigation policies by relaxing the above-mentioned barriers. The typology that we developed based the systematic evidence synthesis includes six such enablers: enhanced regulatory agency coordination, improved science-policy interfaces, tailored communication and framing, use of participatory and deliberative processes, strategic policy design, and bottom-up experimentation.

Our research also shows several avenues for future research. First, we highlight that there is relatively little research on institutional capacity and multilevel governance barriers in all regions compared to that on distributional dynamics and economic cost barriers. Second, in Asia, Africa, Latin America and the Caribbean, distributional dynamic barriers are less often studied than in other regions. Third, compared to the respective emissions share, research on climate change mitigation in the transport sector is lacking in North America and Europe. We also find that, compared to the share of emissions, more research is needed in the industry sector. Moreover, in Latin America, the Caribbean, and Africa – regions with high deforestation rates and emissions from agriculture and land use changes – there is a lack of research on the AFOLU sector. Finally, more research on the enablers rather than the barriers to climate change mitigation is needed. For example, in our in-depth review of research on enablers, we illustrate that it remains an open debate whether more inclusive governance increases the feasibility of ambitious climate policy. Furthermore, the relative importance of different enablers and the potential interactions between them requires more attention. A valuable goal for further research would be creating a more fine-grained understanding of which (combination of) enablers are particularly effective in which context (i.e., region, sector) for overcoming specific types of barriers.

Moreover, our approach creates a novel toolkit for evidence synthesis that can be easily updated and replicated. We combine machine-learning-based mapping with an inductive development of a typology of enablers and an in-depth review of how these enablers are spread across thousands of articles. Despite their potential for evidence synthesis, such mixed-method approaches have thus far rarely been used. Most existing evidence syntheses employ either manual approaches *or* large-scale machine-learning-based maps. To keep up with the rapidly growing climate policy literature and identify broader research trends while not losing track of the specific enablers and mechanisms proposed in the literature, novel mixed-method approaches for evidence synthesis are needed. Climate policymakers rely on global reviews like the IPCC reports and can thus benefit from such novel machine-learning mixed-method procedures. This helps accelerate the adoption and implementation of feasible and effective climate policy solutions.

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Methods and Data

We develop a computer-assisted procedure with supervised machine learning for our mixed-method review. Our three-step procedure allows an investigation of general tendencies in large and fast-growing interdisciplinary fields, such as the social science literature that we analyze, and the selection of relevant articles for in-depth qualitative review based on the predicted topics and barriers. First, we develop the search string. Second, we train the machine learning model. Third, we map large-scale tendencies and perform the in-depth, mixed-method evidence synthesis in which we develop a typology of enablers summarize the evidence on these.

Step 1: Search String

Our broad query allows us to retrieve a large strand of 13'363 research articles from Web of Science (data retrieved on 11.08.21). Although not exhaustive, Web of Science provides a good overview of the literature including article-level meta-data, abstract, title, journal name, and publication year which we use to classify article features.

We develop a search string that captures articles related to policy change that we established through a qualitative analysis of the ten most highly cited articles in related literatures on policy change For articles on climate change, we extend on relevant keywords based on existing evidence synthesis studies on climate change in refs[16,19] that are applicable in our context (see Suppelementaries, Step 1: Search String).

TS=(((("policy" OR "policies") NEAR/5 ("sequenc*" OR "ordering" OR "temporal dynamic*" OR "feedback" OR "design" OR "path depend*" OR "lock-in" OR "spillover" OR "spill-over" OR "network externalit*" OR "external effect*" OR "tipping point*" OR "packag*" OR "adopt*" OR "implement*" OR "feasibil*" OR "integrat*")) OR (("policy" OR "policies" OR "public" OR "political") NEAR/5 ("accept*" OR "support")) OR "instrument constituen*" OR "policy diffusion" OR "policy mix" OR "policy change" OR "policy process" OR "policy output") AND ("climat* chang*" OR "*carbon*" OR "CO2" OR "greenhouse gas" OR "greenhouse effect" OR "changing climat*" OR "global warming"))

Step 2: Machine Learning

Model Selection: XGBoost Model

To select the best-performing algorithm, we compared the model performance of XGBoost, Random Forest, the Support Vector Machine, and Lasso. We found similar performance across these different models. We selected the XGBoost model because it is relatively efficient in terms of computational power, flexible in terms of parameter tuning, and performs well for the prediction of minority categories.

We train separate models for each binary article feature. The XGBoost model is a decision-tree-based algorithm that uses an ensemble of decision trees. Using an ensemble of trees enhances the performance of the classifier. Trees are added until no further improvement can be made regarding model performance. Each tree consists of branches representing observations of the data and end-leaves the outcomes of the classified features. Each branch relies on successive yes-no decisions. The model predicts the classification which is assessed against the training data.

Model Performance

Fig 12 shows the model performance using recall, precision, and the F1 scores as the metrics. Recall measures to what extent we do miss relevant articles while precision captures the amount of noise that we have in the data that our model predicts to be relevant. F1 combines the two scores (see supplementary materials, equation (4)-(6) for the mathematical definition of the performance scores). Our model is optimised on F1 as we would like to avoid missing relevant articles while limiting the noise in our sample. Performance ranges from good to very good (most values are between 0.8 and 1).

To increase the robustness of the classification algorithm when training the model, we use 10-fold cross-validation which involves the creation of ten sub-samples in the training data. Each of these omits ten per cent for out-of-fold model performance assessment. One model is then iteratively trained the model on each fold[108,109]. After tuning model parameters on the training data, we also assess out-of-sample performance on unseen test data. Fig 12 illustrates that our model performs reasonably. We then select the best-performing model and use it to predict the article topics and barriers to map the literature and select articles for in-depth review.

Classifying Article Topics and Barriers Based on Article Abstracts

To train our model to achieve high predictive performance, we manually annotate two dimensions of scientific articles based on 1,202 (close to 10% of 11,580) article abstracts: First, the article topic serves to distinguish between the focus of research on the feasibility of policy change, policy impact evaluation, a focus on climate change or environmental policy more broadly. Second, we predict four barriers for which we extend the definitions of Pahle et al[7]. We code if articles cover distributional dynamics, economic cost, institutional capacity, and multi-level governance barriers (for a detailed code book and reliability checks, see supplementary materials 1, step 2). These data enable the training of a computer algorithm to recognise the features of big data and to analyze a total number of 11,580 research articles.

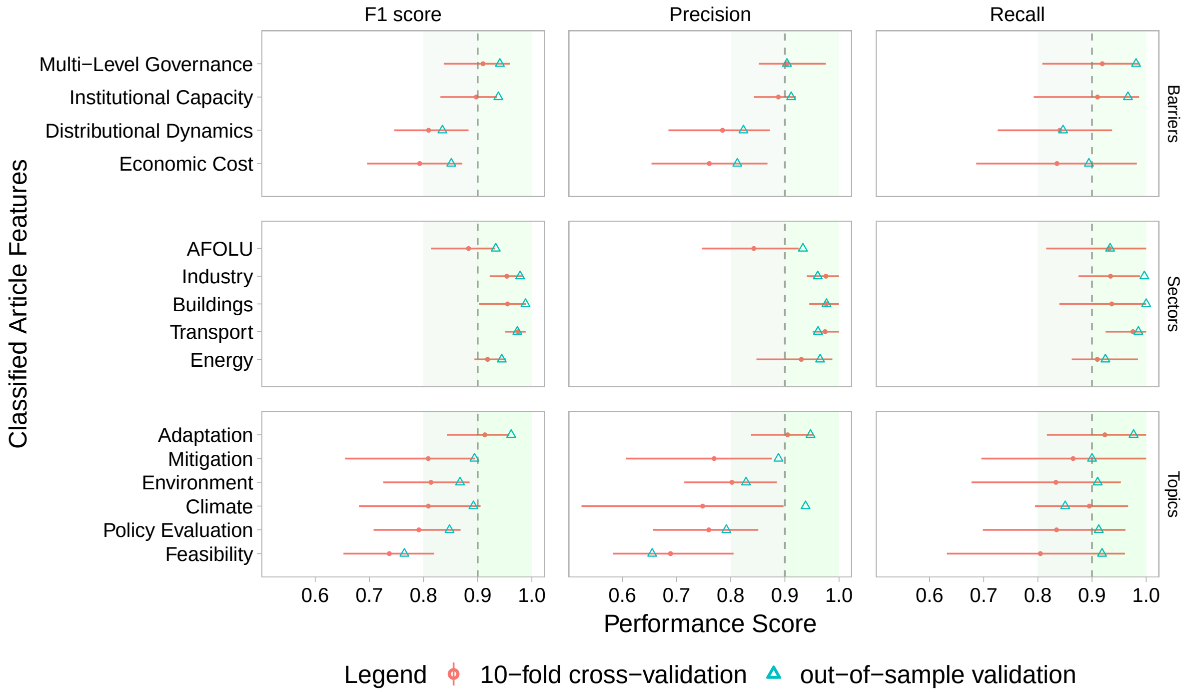


Figure 6. XGBoost Model Performance. 10-fold cross-validation performance on the training set is shown in red with 95% confidence intervals. Out-of-sample performance is shown by the triangle in light blue.

Pre-processing of the Text Data

To prepare for machine learning, we remove stop words, punctuation and numbers, and tokenise the titles, abstracts and keywords using word stems

We then create the term frequency-inverse document frequency (tfidf) of tokens. The tfidf is equal to the term frequency (tf) which measures how many times a token t occurs within document d multiplied by the inverse document frequency (idf) which measures how often the token appears by logarithmically scaling the fraction of documents in the entire corpus D that contain the token t. Highly frequent tokens may not contain much information whereas those that appear in some, contain more relevant information and are therefore given higher weight for the classification task:

$$\begin{aligned} tf(t,d) &= f_{t,d} \\ idf(t,D) &= log\frac{N}{|d \in D : t \in d|} \\ tfidf(t,d,D) &= tf(t,d) \times idf(t,D) \end{aligned} \tag{1}$$

Because we are dealing with unbalanced data, we up-sample the training data. Without re-balancing the data, classification models may over-fit on the majority class which may lead to poor performance when predicting the minority class.

Step 3: Large-scale Map of the Barriers and In-Depth Review of the Solutions

In step three, we quantitatively map the barriers and selected 100 articles from each of the four barriers by sector. We manually read the most-cited article texts to summarise the mechanisms for the relaxation of barriers to policy change. In the first round, we inductively group a set of six mechanisms that relax barriers for more intensive climate policy in group workshops based on the full text of 25 articles from journals with the highest impact factor. We formulate a definition for each enabler and summarise the causal pathways for how each enabler can contribute to the relaxation of the barriers. We use the journal impact factor as an inclusion criterion because high-impact journals represent general tendencies in the field.

In addition, we code the sector (energy, transport, buildings, industry, and AFOLU) and the method that the paper employs to support the finding that a specific solution has on a barrier. This includes theoretical arguments, and quantitative, qualitative or mixed methods empirical evidence. Coding the methods enables us to show which mechanisms are most often discussed together with which barriers and if the evidence was made mainly based on theoretical reasoning or qualitative or quantitative evidence. This approach allows us to provide an in-depth summary of the mechanisms and potential trade-offs for barrier relaxation.

Supplementary Materials: Methodology and Research Protocol

This review employs mixed methods machine-learning procedure for the systematic, large-scale machine-learning-based mapping of the barriers to decarbonization and in-depth reviewing of the enablers to ambitious climate change mitigation policy. Systematic literature reviews qualitatively or quantitatively summarize the evidence for an effect on a particular outcome[110,111] whereas systematic maps provide an overview of how much research has been conducted in specific subjects. This includes the geographical scope, the temporal evolution, the research topics or research methodology of the articles and their documentation, often in the form of a database[22].

For the in-depth qualitative analysis of the enablers, we define a closed-framed research question and its components which facilitates the definition of the studies included for in-depth analysis[110]. Usually, these questions include four components: the population (P), the intervention (I) or the exposure (E), the comparator (C) and the outcome (O) which are usually called PICO or PECO components that can be slightly adapted to the specific focus of the study[22,112]. Since we are particularly interested in advancing the theories on the policy process around increasingly ambitious climate policy and the enablers and specific causal mechanisms to relax existing barriers to the adoption of ambitious climate policy, a systematic review with a slightly adapted PECO question format is the most suitable approach in this context. For our question, we are not interested in the effect of particular exposure (E) but in an explanatory variable (E), we term this element as such in the question below.

Definitions of the Question Components for Systematic map and Review

Research question systematic map: What are the most prominent barriers to climate change mitigation discussed in the social science literature?

Research question systematic literature review: What are the most prominent barriers to climate mitigation policy, and what enablers of overcoming these barriers across sectors are presented in the interdisciplinary social science literature?

PECO components for systematic literature review: Population (P) = social science literature on the adoption process of climate change mitigation policies; Explanatory factor (E) = enabler to overcome barriers to adoption of climate change mitigation policies; Comparator (C) = no enabler to overcome such barriers; Outcome (O) = adoption of climate change mitigation policy.

Objectives

The objectives of this systematic map are the following:

- Summarize the tendencies in the existing knowledge on barriers to decarbonisation and particularly more ambitious climate change mitigation policies.
- Geographically map the research.
- Map the research across sectors

The objectives of this systematic review are the following:

- Inductively define a typology of enablers that relax barriers to ambitious climate policy.
- Provide an in-depth mixed-method review that involves linking the enablers to barriers, sectors and the evidence that the research articles use when addressing the enablers.
- Qualitatively illustrate the causal mechanisms of how each enabler can relax barriers to more ambitious climate policy.

Reviewing and Mapping Process

Fig 7 details the reviewing process outlined in the main text. Our three-step procedure allows an investigation of general tendencies in large and fast-growing interdisciplinary fields, such as the social science literature that we analyze, and the selection of relevant articles for in-depth qualitative reviewing based on the predicted topics and barriers. First, we develop the search string. Second, we train the machine-learning model. Third, we map large-scale tendencies and perform the in-depth, mixed-method evidence synthesis to inductively develop a typology of enablers of the political feasibility of ambitious climate change mitigation policy.

The procedure in Fig 7 is based on the recommended steps for the systematic mapping of literature[22,113] for the development of the search string and systematic reviewing[23]. We extend this literature by using supervised machine-learning for systematic mapping. We are among the first to apply this mixed-method procedure with machine-learning for the systematic mapping of research articles and in-depth qualitative analysis and thereby contribute to an emerging literature[16,19,114] which leverages big data to improve our understanding of climate change enablers. Such mixed-method approaches will become more prominent in the future as the literature is likely to keep growing at an exponential rate making the assessment of the evidence of barriers and enablers to climate change crucial for policy advice in reports, such as the IPCC Assessment Reports. We contribute to the advancement of this field and provide a simple and replicable framework for mixed-method evidence synthesis (see Supplementary Materials for details).

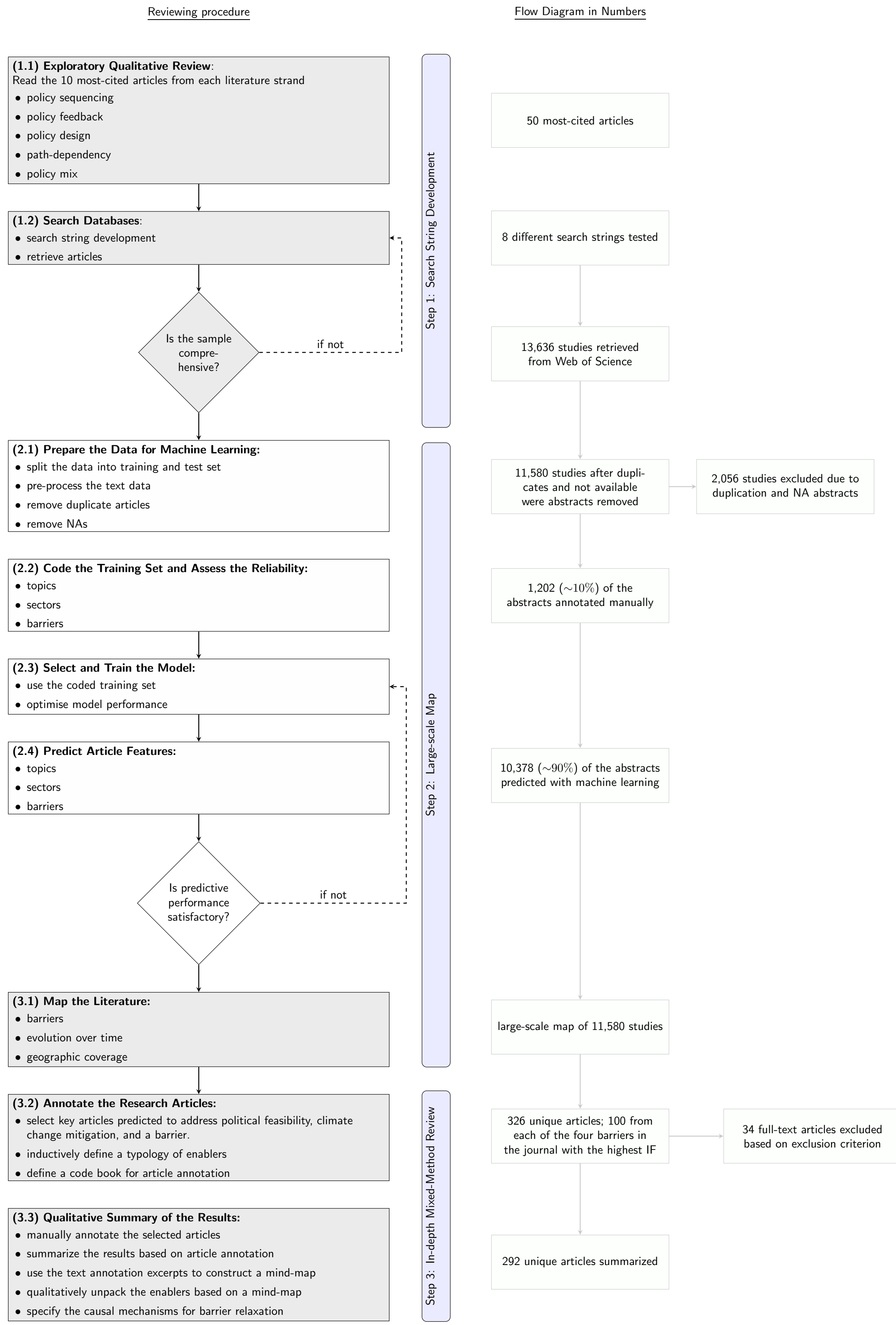


Figure 7. The three main steps of the literature review procedure and the workflow on the number of articles in the review.

1 Search String Development (Step 1)

We develop a query on literature that covers policy changes and climate change which we use to retrieve a large strand of 13'363 research articles from Web of Science (data retrieved on 11.08.21). Although not exhaustive, Web of Science provides a good overview of the literature, including the article abstract, title, journal name, and publication year. We use this data to classify article features (topics, sectors, and barriers).

As we are primarily interested in barriers to decarbonisation and the enablers of ambitious climate change mitigation policies, we develop a search string that captures articles related to climate change policy change. We first explore (see Section 1.1) to what extent we are able to identify barriers from article abstracts (see Table 4) and derive terms for the search string using the ten most-cited articles in the literature on policy sequencing, path dependency, policy mix, policy design and instrument constituencies. For terms related to climate change, we extend existing search strings in refs[16,19]. The final search string that we obtain through an iterative process that involves checking if papers that we know to be relevant (see Section 1.2 and Table 3) are included in the sample is the following:

TS=(((("policy" OR "policies") NEAR/5 ("sequenc*" OR "ordering" OR "temporal dynamic*" OR "feedback" OR "design" OR "path depend*" OR "lock-in" OR "spillover" OR "spill-over" OR "network externalit*" OR "external effect*" OR "tipping point*" OR "packag*" OR "adopt*" OR "implement*" OR "feasibil*" OR "integrat*")) OR (("policy" OR "policies" OR "public" OR "political") NEAR/5 ("accept*" OR "support")) OR "instrument constituen*" OR "policy diffusion" OR "policy mix" OR "policy change" OR "policy process" OR "policy output") AND ("climat* chang*" OR "*carbon*" OR "CO2" OR "greenhouse gas" OR "greenhouse effect" OR "changing climat*" OR "global warming"))

1.1 Exploratory Review (Step 1.1)

In the first exploratory step, we examine to what extent the four barriers to climate change mitigation policy by Pahle et al[7] can be detected from article abstracts and article texts. Exploratory testing and refinement of coding rules are suitable to develop a code book, which has been termed coding in cycles[115], and the development of the search string. To do so, we read the 10 most-cited articles in five large strands of literature related to policy change and to the policy sequencing literature (see e.g. Pahle et al[7]) on which we base the definition of the barriers to climate policy (see 10 key articles in Table 3) .

Authors	Title	Journal
Seto et al[116]	Carbon Lock-In: Types, Causes, and Policy Implications	Annual Review of Environment and Resources
Ingold & Fischer[117]	Drivers of collaboration to mitigate climate change: An illustration of Swiss climate policy over 15 years	Global Environmental Change
Anderson et al[118]	Effects of fairness principles on willingness to pay for climate change mitigation	Climatic Change
Bernauer[78]	Climate Change Politics	Annual Review of Political Science
Howlett[119]	Process Sequencing Policy Dynamics: Beyond Homeostasis and Path Dependency	Journal of Public Policy
Lockwood et al[120]	Historical institutionalism and the politics of sustainable energy transitions: A research agenda	Environment and Planning C: Politics and Space
Geels et al[11]	Bridging analytical approaches for low-carbon transitions	Nature Climate Change
Schmidt & Sewerin[121]	Measuring the temporal dynamics of policy mixes - An empirical analysis of renewable energy policy mixes' balance and design features in nine countries	Research Policy
Levin et al[122]	Overcoming the tragedy of super wicked problems: constraining our future selves to ameliorate global climate change	Policy Sciences
Burton et al[123]	From impacts assessment to adaptation priorities: the shaping of adaptation policy	Climate Policy

Table 3. Analyse these key papers for codebook and search string development

Research on climate policy change and sequencing is situated at the intersection of policy feedback, policy diffusion, and the policy design literature. The policy feedback and diffusion literature emphasizes that policy and political support are co-constitutive[97,124–127] meaning that they mutually influence each other. The policy design literature stresses that the architecture of policies, their means and ends, affect policy feasibility and effectiveness[119,128–132]. The policy change and sequencing literature is also related to path dependency and the literature on policy mix. Path-dependency emphasizes how potentially random historical switch points spark a development of change which is difficult to revers while the concept of policy mixes stresses that policy instruments are rarely crafted in isolation[97,135,136]. To develop the search string and refine the codebook, we thus analyse the entire article of these selected key publications by carefully reading and taking notes on the barriers and enablers to climate mitigation policy. During this process, we extend the definitions of the four barriers to climate mitigation policy proposed by Pahle et al[7]. These results are shown in Table 4. During the process of this exploratory review, we adapt the label of the last barrier, initially termed free-riding. This barrier relates to the interplay between governance levels. Because the interplay between governance levels is more encompassing and because free-riding may occur also taps into economic cost and distributional dynamic barriers, we slightly depart from the definition by Pahle et al[7] and term this last barrier *multi-level governance dynamics* instead of *free-riding*. Additionally, instead of using the term *Capacity Barriers*, we use institutional capacity. Defining mutually exclusive categories not only facilitates manual coding but is also conducive to machine-learning (ML) model performance.

Specific Barrier	Main Barrier(s)	Author(s)	Literature Strand
scientific knowledge access	institutional capacity	Dilling & Lemos et al[137]	policy design
flexibility of decision making rules	institutional capacity	Dilling & Lemos et al[137]	policy design
incumbent interests	institutional capacity	Dilling & Lemos et al[137]	policy design
uncertainty of information	economic cost / institutional capacity / distributional	Dilling & Lemos et al[137]	policy design
lack of material means / capacity	institutional capacity / economic cost	Dilling & Lemos et al[137]	policy design
lack of trust, lack of relevance, lack of skill	institutional capacity	Dilling & Lemos et al[137]	policy design
political power of winners and losers	distributional dynamics	Jack et al[138]	policy design
infrastructural failure;	economic cost	Woolthuis et al[139]	policy design
lock-in / path dependency failure	economic cost / institutional capacity / distributional	Woolthuis et al[139]	policy design
strong network failures (strong ties make weak ties invisible and lead one to overlook innovations from weak ties)	economic cost / institutional capacity / distributional	Woolthuis et al[139]	policy design
Capability failure	economic cost / institutional capacity / distributional	Woolthuis et al[139]	policy design
myopic orientation to long established and trusted relationships	economic cost / institutional capacity / distributional	Woolthuis et al[139]	policy design
dependence on dominant partners; weak network failure (no complementary technologies)	economic cost / institutional capacity / distributional	Woolthuis et al[139]	policy design
issue linkage	distributional dynamics	Maron et al[140]	policy design
bounded rationality	economic cost / institutional capacity / distributional	Bullard & Mitra[141]	policy feedback
learning of political actors,	distributional dynamics / institutional capacity	Bullard & Mitra[141]	policy feedback

social capital	distributional dynamics / institutional capacity	Kumlin & Rothstein[142]	policy feedback
information asymmetry	distributional dynamics	Campbell[143]	policy feedback
media and information asymmetry	distributional dynamics	Soss[144]	policy feedback
low public awareness	distributional dynamics	Beland[145]	policy feedback
lock-in	economic cost / institutional capacity / distributional	Beland[145]	policy feedback
path dependence (lock-in),	economic cost	Pierson[133]	path dependence
technology cost	economic cost	Pierson[133]	path dependence
collective action	distributional dynamics	Pierson[133]	path dependence
powerful veto players;	distributional dynamics	Pierson[133]	path dependence
short term thinking	distributional dynamics	Pierson[133]	path dependence
free-riding	economic cost	Pierson[133]	path dependence
power asymmetry	distributional dynamics	Pierson[133]	path dependence
Complexity and opacity of politics (time horizons, status quo bias)	information asymmetry	Pierson[133]	path dependence
path dependence (lock-in)	distributional dynamics / economic cost / institutional capacity	Mahoney[146]	path dependence
vested interests	distributional dynamics	Geels[14]	path dependence
powerful incumbent actors	distributional dynamics	Geels[14]	path dependence
complementarity between different technologies fosters lock-in	economic cost	Geels[14]	path dependence
uncertainty	economic cost / institutional capacity / distributional	Geels[14]	path dependence
misalignment of policy and technical systems creates tensions and mismatches	economic cost / institutional capacity / distributional	Geels[14]	path dependence
distributional conflict	distributional dynamics	Thelen[147]	path dependence
collective action, norms and beliefs	distributional dynamics	Thelen[147]	path dependence
sunk cost	economic cost	Thelen[147]	path dependence
vested interests	distributional dynamics	Thelen[147]	path dependence
party competition along partisan lines;	distributional dynamics	Thelen[147]	path dependence
identity of interest groups	distributional dynamics	Thelen[147]	path dependence
(functional, technological and political) lock-in / path dependence	distributional dynamics	Martin & Sunley[148]	path dependence
quasi irreversibility of investments, sunk cost, the difficulty of moving capital (mechanisms for path-dependency)	economic cost	Martin & Sunley[148]	path dependence
factors fostering increasing returns –>large fixed initial cost, dynamic learning, coordination effects, self-reinforcing expectations	economic cost / distributional dynamics / institutional capacity	Martin & Sunley[148]	path dependence
sunk cost	economic cost	Martin & Sunley[148]	path dependence
regional technological lock-in	economic cost	Martin & Sunley[148]	path dependence

cultural traditions	economic cost / distributional dynamics / institutional capacity	Martin & Sunley[148]	path dependence
increasing returns	economic cost	Howlett[149]	policy sequenc*
large set up cost;	economic cost	Howlett[149]	policy sequenc*
excessive rent-seeking;	economic cost / institutional capacity	Meckling et al[93]	policy sequenc*
lock-in;	economic cost / distributional dynamics / institutional capacity	Meckling et al[93]	policy sequenc*
creating automatic market share for the best technology in use (e.g in China)	economic cost	Meckling et al[93]	policy sequenc*
Condorcet paradox,	distributional dynamics	Nagel[150]	policy sequenc*
veto players (Tsebelis)	distributional dynamics	Nagel[150]	policy sequenc*
asymmetric info;	information asymmetry	Nagel[150]	policy sequenc*
lock-in;	economic cost	Dhar, S; Pathak, M; Shukla, PR	policy sequenc*
information asymmetry;	information asymmetry	Pahle et al[7]	policy sequenc*
lack of capacity, data, expertise, public trust	institutional capacity	Pahle et al[7]	policy sequenc*
free-riding;	distributional dynamics / economic cost	Pahle et al[7]	policy sequenc*
state capacity / institutional legacy	institutional capacity	Johnson, J	policy sequenc*
path-dependency: positive feedback;	distributional dynamics / economic cost / institutional capacity	Kivimaa, P; Kern, F	policy mix
market niches	economic cost	Kivimaa, P; Kern, F	policy mix
vested interests	distributional dynamics	Kivimaa, P; Kern, F	policy mix
incumbent actors	distributional dynamics	Kivimaa, P; Kern, F	policy mix
technological change	economic cost	Rogge, KS; Reichardt, K	policy mix
vertical division of power between government	institutional capacity /multi-level governance	Borras & Edquist[151]	policy mix
party conflict	distributional dynamics	Borras & Edquist[151]	policy mix
incumbent interests / vested interests	distributional dynamics	Potter, C; Burney, J	policy mix
distributional conflict between land preservation and productivity	distributional dynamics	Potter, C; Burney, J	policy mix
international political dynamics	distributional dynamics	Potter, C; Burney, J	policy mix
abatement cost	economic cost	Veugelers, R	policy mix
fossil fuel prices	economic cost	Veugelers, R	policy mix
lock-in	lock-in	Veugelers, R	policy mix
jurisdictional conflict	distributional dynamics	Sorrell, S; Sijm, J	policy mix
unintended consequences	distributional dynamics / economic cost / institutional capacity	Sorrell, S; Sijm, J	policy mix
lock-in	distributional dynamics / economic cost / institutional capacity	Sorrell, S; Sijm, J	policy mix

tax exemption for ETS participants	economic cost	Sorrell, S; Sijm, J	policy mix
uncertainty	distributional dynamics / economic cost / institutional capacity	Sorrell, S; Sijm, J	policy mix
market-failure	economic cost	Sorrell, S; Sijm, J	policy mix
imperfect information	information asymmetry	Sorrell, S; Sijm, J	policy mix
asymmetric information	information asymmetry	Sorrell, S; Sijm, J	policy mix
transaction cost	economic cost	Sorrell, S; Sijm, J	policy mix
administrative cost	institutional capacity	Sorrell, S; Sijm, J	policy mix
transaction cost	economic cost	Sorrell, S; Sijm, J	policy mix
uncertainty	distributional dynamics / economic cost / institutional capacity / multi-level	Measham, F	policy mix

Table 4. Exploratory Results: Barriers in the highly-cited articles of each of the five relevant literature strands.

1.2 Search Databases (Step 1.2)

The objective of the search string development in Table 5 was to optimize the trade-off between the comprehensiveness of key articles in Table 3 in the sample from which we knew they are relevant before conducting the analysis and the total number of articles included. We first begin with a relatively simple search string and incrementally include more terms to capture the 10 key articles in Table 3. Our string also builds on established search terms to capture climate-related articles used elsewhere for climate literature reviews to capture climate-related literature[16,19]. We are therefore confident that our sample provides a representative overview of the literature on barriers and enablers to ambitious climate policy.

Date	Search String	Searching	Results
07.04.2021	(("policy sequencing" OR "policy feedback" OR "policy design" OR ("policy" AND "path dependence" OR "path dependency") OR "policy spillover" OR "instrument constituency" OR "policy mix" OR " policy diffusion" OR "policy change") AND ("environm*" OR "clima*" OR "biodiv*" OR "renewab*"))	Topic	3,544
08.04.2021	(("policy sequencing" OR "policy feedback" OR "policy design" OR ("policy" AND "path dependence" OR "path dependency") OR "policy spillover" OR "instrument constituency" OR "policy mix" OR " policy diffusion" OR "policy change") AND ("environm*" OR "clima*" OR "biodiv*" OR "renewab*"))	All fields	4,631
10.04.2021	(("policy sequencing" OR "policy feedback" OR "policy design" OR ("policy" AND "path depend*") OR "policy spillover" OR "instrument constituency" OR "policy mix" OR "policy diffusion" OR "policy change" OR "policy adoption" OR "policy implementation" OR "pol* feasibil*" OR "policy support" OR "policy accept*") AND ("environm*" OR "clima*" OR "biodiv*" OR "renewab*"))	Topic	6,637

19.07.2021	((("policy" AND ("sequenc*" OR "ordering" OR "temporal dynamic*")) OR ("policy" AND "feedback") OR ("policy design") OR ("policy" AND ("path depend*" OR "lock in")) OR ("policy" AND ("spillover" OR "network externality" OR "external effect*" OR "tipping point*")) OR ("instrument constituen*") OR "policy mix" OR "policy packag*" OR " policy diffusion" OR (“policy "NEAR/5" chang*”) OR ("policy "NEAR/5" adoption") OR ("policy "NEAR/5" implementation") OR "poli* feasibil*" OR "policy support" OR "policy accept*" OR "policy translation") AND ("climat* chang*" OR "decarbon*" OR "carbon emissions" OR "CO2" OR "greenhouse gas" OR "greenhouse effect" OR “changing climat*” OR "carbon" OR "global warming"))	Topic	6,637
11.08.2021	((((("policy" OR "policies") NEAR/2 ("sequenc*" OR "ordering" OR "temporal dynamic*" OR "feedback" OR "design" OR "path depend*" OR "lock-in" OR "spillover" OR "spill-over" OR "network externalit*" OR "external effect*" OR "tipping point*” OR "packag*" OR "adopt*" OR "implement*" OR "feasibil*" OR "integrat*")) OR (("policy" OR "policies" OR "public" OR "political") NEAR/2 ("accept*" OR "support")) OR "instrument constituen*" OR "policy diffusion" OR "policy mix" OR "policy change" OR "policy process" OR "policy output") AND ("climat* chang*" OR "*carbon*" OR "CO2" OR "greenhouse gas" OR "greenhouse effect" OR "changing climat*" OR "global warming")))	Topic	9,765
11.08.2021	((((("policy" OR "policies") NEAR/3 ("sequenc*" OR "ordering" OR "temporal dynamic*" OR "feedback" OR "design" OR "path depend*" OR "lock-in" OR "spillover" OR "spill-over" OR "network externalit*" OR "external effect*" OR "tipping point*” OR "packag*" OR "adopt*" OR "implement*" OR "feasibil*" OR "integrat*")) OR (("policy" OR "policies" OR "public" OR "political") NEAR/3 ("accept*" OR "support")) OR "instrument constituen*" OR "policy diffusion" OR "policy mix" OR "policy change" OR "policy process" OR "policy output") AND ("climat* chang*" OR "*carbon*" OR "CO2" OR "greenhouse gas" OR "greenhouse effect" OR "changing climat*" OR "global warming")))	Topic	11,490

11.08.2021	((((("policy" OR "policies") NEAR/4 ("sequenc*" OR "ordering" OR "temporal dynamic*" OR "feedback" OR "design" OR "path depend*" OR "lock-in" OR "spillover" OR "spill-over" OR "network externalit*" OR "external effect*" OR "tipping point*" OR "packag*" OR "adopt*" OR "implement*" OR "feasibil*" OR "integrat*")) OR (("policy" OR "policies" OR "public" OR "political") NEAR/4 ("accept*" OR "support")) OR "instrument constituen*" OR "policy diffusion" OR "policy mix" OR "policy change" OR "policy process" OR "policy output") AND ("climat* chang*" OR "*carbon*" OR "CO2" OR "greenhouse gas" OR "greenhouse effect" OR "changing climat*" OR "global warming")))	Topic	12,755
11.08.2021	(((("policy" OR "policies") NEAR/5 ("sequenc*" OR "ordering" OR "temporal dynamic*" OR "feedback" OR "design" OR "path depend*" OR "lock-in" OR "spillover" OR "spill-over" OR "network externalit*" OR "external effect*" OR "tipping point*" OR "packag*" OR "adopt*" OR "implement*" OR "feasibil*" OR "integrat*")) OR (("policy" OR "policies" OR "public" OR "political") NEAR/5 ("accept*" OR "support")) OR "instrument constituen*" OR "policy diffusion" OR "policy mix" OR "policy change" OR "policy process" OR "policy output") AND ("climat* chang*" OR "*carbon*" OR "CO2" OR "greenhouse gas" OR "greenhouse effect" OR "changing climat*" OR "global warming"))	Topic	13,363

Table 5. Search String Development Documentation over Time

2 Large-scale Map with Machine-Learning (Step 2)

Machine-learning allows predicting article features from a large corpus of articles that would otherwise be difficult to achieve manually. Using machine-learning for prediction involves pre-processing data, human annotation of the training set and the assessment of the reliability of the annotation, assessment of the model's predictive performance and the prediction on the entire dataset which we then use to map the literature. These steps are documented below.

2.1 Prepare the Data for Machine-Learning (Step 2.1)

To train our model to achieve high predictive performance, we manually annotate two dimensions of scientific articles based on 1,202 (close to 10% of 11,580) article abstracts: First, the article topic serves to distinguish between the focus of research on the feasibility of policy change, policy impact evaluation, a focus on climate change or environmental policy more broadly. Second, we distinguish between the energy, transport, housing, industry, and the AFOLU sectors. Third, we capture if an article abstract covers one of the four barriers for which we extended the definitions of Pahle et al[7]. We code if articles cover distributional dynamics, economic cost, institutional capacity, and multi-level governance barriers (for a detailed code book and reliability checks, see supplementary materials, step 2). These data enable the training of a computer algorithm to recognize the features of big data and to analyze the abstracts, article titles and keywords of the total number of 11,580 uniquely identified research articles. The 10% of abstracts, article titles and keywords that we annotate manually allow us to train the machine-learning algorithm to predict the article features of the remaining 90%.

For machine-learning, the text data of article titles, abstracts and keywords have to be pre-processed for computer readability. First, we tokenize the texts into word stems because legalisation creates inferior model performance than word stems. We then remove stop words, punctuation and numbers.

We then create the term frequency-inverse document frequency of tokens. The term frequency-inverse document frequency is equal to the term frequency (tf) which measures how many times a token t occurs within document d multiplied by the inverse document frequency (idf) which measures how often the token appears by logarithmically scaling the fraction of documents in the entire corpus D that contain the token t. Highly frequent tokens may not contain much information whereas those that appear in some contain more relevant information and are therefore given higher weight for the classification task:

$$\begin{aligned} tf(t,d) &= f_{t,d} \\ idf(t,D) &= log \frac{N}{|d \in D : t \in d|} \\ tfidf(t,d,D) &= tf(t,d) \times idf(t,D) \end{aligned} \tag{2}$$

Because we are dealing with unbalanced data, here meaning that the shares of the binary outcome categories are not equally distributed, we use smote up-sampling in the training data. Without re-balancing the data, classification models may over-fit on the majority class which may lead to poor performance when predicting the minority class.

2.2 Code the Training Set and Assess the Reliability (Step 2.2)

This code book describes the rules to categorize scientific article features based on article abstracts, article titles and keywords for the machine-learning training set. Topics distinguish between political variables related to political feasibility (adoption, implementation, enactment) and policy evaluation (effectiveness). Environmental variables distinguish if an article covers climate change or general environmental issues such as pollution or Biodiversity. For all variables, we define when the concept is coded as being present (=1) or absent (=0). Each of the variables is coded independently from the others as a binary variable.

Topics

Feasibility. A scientific article is considered to cover political feasibility when the article investigates public policy adoption, enactment or implementation, meaning that the article describes if policy change occurred. This definition includes the articles which present reasons for the adoption, change or implementation of public policy measures but does not include for instance private firm-level policies. Articles that evaluate policy effectiveness or provide scenarios with and without policies are not considered relevant for this variable. For instance, why certain policy types prevail over others, i.e. why they are more popular, will be coded as relevant (=1). An article on agenda-setting in its own right should not be confused with policy adoption and would not be considered relevant (=0).

Policy Evaluation. A scientific article is considered to evaluate policies if the article describes the effects of public policies for instance on behavioural or technological change. This definition is different from the process that leads to the adoption, enactment or implementation of a public policy (see above feasibility). An article that investigates the effectiveness of a policy theoretically or empirically falls into this category (=1). By contrast, an article that only makes a policy recommendation on how to increase policy effectiveness is not sufficient to be considered relevant for this category. Articles that cover environmental management, meaning that they for instance address forest management practices of private actors, are also not considered to be on policy evaluation. Similarly, motivating a study through effectiveness is not sufficient (=0).

Climate. An article that discusses climate change from a social science perspective would fall into this category (=1). A discussion of renewable energy policy or electricity market regulation is insufficient to be considered relevant. For it to fall under climate change it must somehow connect energy or electricity with anthropogenic temperature increase. Articles that only cover environmental problems such as water pollution would not fall into this category (=0). When climate change or GHG emissions are not mentioned it is likely not directly about climate change.

Environment. An article that covers environmental issues such as biodiversity or environmental pollution other than climate change falls into this category (=1). This includes natural disasters which are not directly attributed to climate change. Articles that do not discuss any environmental problems but focus for instance on welfare policy do not cover environmental policy (=0). Articles with sectoral coverage of agriculture, forestry and land use are not automatically environmental issues but only when connected with effects on the ecosystem as opposed to effects on the economic use of natural resources.

Mitigation. The article discusses factors related to climate mitigation (=1). For example, this includes articles that discuss emission reductions from the use of renewable energy, reduced deforestation, bio-energy use or policies such as carbon taxes and emission trading systems. Articles that cover theoretical or empirical work related to climate change relevant to understand climate change mitigation also fall into this category (=1). Articles that do not discuss factors related to GHG emission reduction are not considered to be relevant for mitigation (=0).

Adaptation. An article that discusses potential ways to adapt to climate change falls into this category (=1). For example, this includes flood prevention policies or irrigation management strategies or crop choice in farming. Articles that cover theoretical or empirical work related to climate change relevant to understand climate adaptation also fall into this category (=1). Articles that do not discuss factors related to adaptation are not considered relevant for this variable (=0).

Variable	Coding Question	Anchor Example: Excerpts from Article Abstracts
Feasibility:	Does the article discuss factors that make public policy adoption, change or implementation politically feasible?	"A key challenge is to identify opportunities that facilitate sustainable development by making use of existing technologies and developing policies that enhance the resilience of climate-sensitive sectors"[152].
Policy evaluation:	Does the article discuss the factors that make a public policy effective to reach intended policy outcomes?	"Results show a relative increase in the effectiveness of the provision of soil erosion prevention in Mediterranean Europe between 2001 and 2013"[153].
Climate:	Does the article discuss primarily climate change($\neq$ other environmental problems)?	"The Intergovernmental Panel on Climate Change (IPCC) recently concluded that there is ample evidence to suggest climate change is likely to result in significant impacts on biological diversity"[152].
Environment:	Does the article cover primarily other environmental problems than climate change (e.g. biodiversity)?	"Compounding the impacts on biodiversity from deleterious management practices is climate variability and change."[152]

Table 6. Coding Examples for Topics

<u>Sectors</u>

Energy. Articles that mention the generation, conversion or transportation of various energy sources such as crude oil, coal, natural gas, nuclear energy, hydropower, geothermal, wind, solar and bio-energy are considered to cover the energy sector (=1). The transportation of energy for final use (e.g. car or train) is considered part of the energy sector. For articles that do not mention generation, conversion or transportation the variable energy is coded as not present (=0).

Transport. Articles that mention transportation systems such as cars, railways, aviation, and shipping are considered to cover the transport sector (=1). In abstracts where transportation occurs as part of a different sectoral activity, such as agriculture or industry trading, the variable is coded as not present (=0).

Industry. Articles that mention the production of materials such as chemicals, metal, electronics, textiles, machinery, minerals, cement, lime or glass or other raw or final products cover the industry sector (=1). Industrial production of e.g. transportation modes does not fall under the industry sector (=0) but into the respective other sectors.

AFOLU. Articles that mention agriculture, forestry, and other land use (AFOLU) such as wetland or croplands, livestock and soil management are considered to cover the AFOLU sector (=1). Abstracts on the use of wood in the building sector are not considered to cover the AFOLU sector (=0).

Variable	Coding Question	Anchor Example: Excerpts from Article Abstracts
Energy:	Does the article discuss the production, conversion or transportation of energy?	"In designing policies to promote bioenergy, policymakers face challenges concerning uncertainties about greenhouse gas balances of heterogeneous bioenergy pathways, the sustainability of biomass production, technology and resource costs, or future framework conditions of energy markets."[154]
Transport:	Does the article discuss public or private transportation?	"The spread of Electric Vehicles (EVs) and the diffusion of the digital sharing mobility service are conditions capable of producing significant impacts on the urban environment and mobility practices."[155]

Buildings:	Does the article discuss buildings or housing?	"This includes performance and deployment mandates beyond the electricity industry, including in the transport and building sectors."[156]
Industry:	Does the article discuss industrial production or processes?	"However, this policy has different effects across enterprises of different industries and different types of innovation."[69]
AFOLU:	Does the article discuss agriculture, land use or forestry?	"Liberal trade regimes could help improve food productivity if environmental concerns such as adverse weather conditions that affect agriculture are addressed."[?]

Table 7. Coding Examples for Sectors

<u>*Barriers*</u>

Economic Cost. Articles that mention barriers to policy or behavioural change due to economic cost considerations are considered relevant for this category (=1). Cost considerations related to lobbying are not considered relevant when they are merely concerned with distributional dynamics in the policy process (=0).

Distributional Dynamics. Articles that mention distributional dynamics in the policy process around certain instruments are considered relevant for this variable (=1). The variable includes coalition behaviour, lobbying, public opinion or other factors in the political process that determines who gets what and how much. Distributional dynamics include pressure from international organisations or interest groups, veto players, and parliamentary debates. The capacity of governmental actors is not coded as distributional dynamics but as institutional capacity (=0).

Institutional Capacity. Articles that mention the capacity of governmental actors and institutions in which policies are implemented institutional capacity is coded as present (=1). The variable is not considered to be present when these dynamics refer to other governance levels such as supranational or sub-national governments, where policies are not implemented (=0).

Multi-Level Governance. Articles that mention the political dynamics between levels of governance as a relevant factor for policy implementation, enactment or effectiveness of the variable are present (=1). This means that another governance level such as the sub-national or supranational governments are discussed. If the article only refers to the dynamics of the government that enacted or implemented the policy (i.e. on the governance level), the variable is not present(=0).

Variable	Coding Question	Anchor Example: Excerpts from Article Abstracts
Economic Cost:	Does the abstract discuss economic cost as a factor which influences the feasibility or effectiveness of a policy?	"Despite the progress achieved, the utilization of wind power is still limited by several financial and ecological constraints."[157]
Distributional Dynamics:	Does the abstract discuss factors related to distributional dynamics?	"We find that policy decisions over time, often initiated by powerful water policy entrepreneurs, have fuelled southern Nevada's rapid growth and development."[158]
Institutional Capacity:	Does the abstract cover barriers related to institutional capacity for the feasibility or effectiveness of a policy?	"The complex and overarching nature of climate change issues emphasizes the need for greatly enhanced cooperation between scientists, policymakers, industry and the community to better understand key interactions and identify options for adaptation."[152]
Multi-Level Governance:	Does the abstract cover multi-level institutional dynamics as a factor which influences (or does not influence) the feasibility or effectiveness of a policy?	"Policy implementation at the national level to meet responsibilities arising from the UNFCCC (e.g., the Kyoto Protocol) and the UN Convention on Biological Diversity require greater coordination and integration between economic sectors since many primary drivers of biodiversity loss and vulnerability are influenced at this level."[152]

Table 8. Coding Examples for Barriers

To ensure robust annotation of article features, we asses the replicability and reliability of our code book for categorising article abstracts. We randomly sampled 100 research articles from the training set and calculate reliability scores for each individual article feature. In the process of developing the code book in which we describe the rules for the categorisation of article features, the first author drafted the rules and tested them with a subset of articles. Together with the anchor examples summarized in Tables 6 and 8, the entire team of authors and trained coders then tested the coding scheme and qualitatively assessed the overlap of 10 independently coded articles. This process ensured that the rules are specific enough to replicate the categorisation. The first author then coded 10% of all article abstracts to prepare the training data for machine-learning in subsequent steps. From these, we sampled 100 articles which were independently hand-coded by the other authors. Based on these articles, we calculate the reliability scores with Cohen's κ[159–161] which is calculated as follows[159, p.39–40]:

$$\kappa = \frac{p_0 - p_c}{1 - p_c} \tag{3}$$

where p_0 is the proportion of research articles for which coders are observed to agree and p_c is the expected proportion of research articles by chance. The extent to which the observed agreement by chance exceeds the agreement by chance is then divided by $1 - p_c$ which is the proportion which is not expected to occur by chance. The standard error $\sigma\kappa$ for p-value calculation are approximated by[159, p.43]:

$$\sigma\kappa = \sqrt{\frac{p_0 - p_c}{N(1 - p_c)^2}} \tag{4}$$

where N are the number of observations. Note that this approach, which compares the codings agreement by agreement by chance, is more precise than the simple reliability score in the last column of Table 9. The simple reliability score is simply the share of articles that received the same label from two coders, in other words, the proportion of agreement p_0. Cohen's κ is more conservative than simple reliability. Thus, we use a high standard when comparing our text categorisation and our scores are sufficiently high which indicates that we developed a reliable coding scheme.

Article Feature	Cohens' Kappa	P-value	Simple Reliability
Article Feature	Cohens' Kappa	P-value	Simple Reliability
Feasibility	0.743806	3.71.10E-097	0.873907
Policy Evaluation	0.7268	42.606E-097	0.9057
Climate	0.603906	1.862.40E-079	0.794953
Environment	0.552849	9.631.75E-078	0.79493
Mitigation	0.573755	1.145.51E-067	0.81 84
Adaptation	0.691846	2.3485E-08	0.92153
Energy	0.643782	3.281.50E-07	0.9053
Transport	1	0 1.00E-10	1
Buildings	0.79288	1.00E-1023E-07	0.98477
Industry	0.6521	3.41.00E-108	0.9681
Waste	0.656	4.62E-06	0.977
AFOLU	0.7029	1.13.50E-089	0.87953
Economic Cost	0.768853	7.00E-102.18E-08	0.9053
Distributional Dynamics	0.7237	2.408.15E-097	0.8736
Institutional Capacity	0.581782	3.981.50E-067	0.841907
Multi-Level Governance	0.8385	0 3.43E-08	0.93529

Table 9. Reliability Scores for the manually annotated article abstracts' features in the training set.

2.3 Select and Train the Model (Step 2.3)

To select the best-performing algorithm, we compared the model performance of XGBoost, Random Forest, the Support Vector Machine, and Lasso. We found similar performance across these different models. Of our two best-performing models, we select the XGBoost model because it is relatively efficient in terms of computational power, flexible in terms of parameter tuning, and performs relatively well for the prediction of minority categories.

The XGBoost model is a decision-tree-based algorithm that uses an ensemble of decision trees. Using an ensemble of trees enhances the performance of the classifier. Trees are added until no further improvement can be made in terms of the model performance, where each tree consists of branches representing observations of the data and end-leaves the outcomes of the classified features. Each branch relies on successive yes-no decisions. The model predicts the classification which is assessed against the training data.

The objective of the machine-learning algorithm is to obtain a high out-of-sample performance, which means that a high share of the predictions is correct. Fig 12 shows the model performance for binary classification models (one for each topic, sector, and barrier) using recall, precision, and the F1 scores as performance metrics. Recall measures to what extent we miss relevant articles while precision captures the amount of noise that we have in the articles predicted to fall under the respective feature. F1 combines the two scores (see supplementary materials, equation (4)-(6) for the mathematical definition of the performance scores). Our model is optimised on F1 as we would like to avoid missing relevant articles while limiting the noise in our sample.

Recall measures the extent to which outcomes are missed when they occur and is defined as the true positives (TP) divided by the true positives plus true negatives (TN).

$$Recall = \frac{TP}{TP+TN} \tag{5}$$

Precision measures the extent to which the outcome is correctly guessed and is defined as true positives divided by the sum of true positives and false positives (FP).

$$Precision = \frac{TP}{TP+FP} \tag{6}$$

The F1 score is the harmonic mean between precision and recall, thus combining the previous two measures.

$$F1\ score = 2 \times \frac{Precision \times Recall}{Precision + Recall} = \frac{TP}{TP + \frac{1}{2}(FP+FN)} \tag{7}$$

Performance ranges from good to very good (most values are between 0.8 and 1). To increase the robustness of the classification algorithm when training the model, we use 10-fold cross-validation which involves the creation of ten sub-samples in the training data. Each of these omits ten per cent for out-of-fold model performance assessment to iteratively train the model on each fold[108,109]. After tuning model parameters on the training data, we assess out-of-sample performance on unseen test data. The performance of the models without tuning which we consider for model selection are shown below in Fig 8, 9, 10 and 11.

Overall, the performance metrics in Fig 8, 9, 10, and 11 show similar tendencies across the different model types with reasonable metric scores across F1, precision and recall. Of our two best-performing models, the XGBoost and the random forest model, we select the XGBoost model. We tuned the XGBoost model for the minimal number of data points for a node in the tree to split further, the depth of the tree, meaning the number of node splits, the learning rate that influences the adaptation between the iterations of the XGBoost algorithm, and the required loss reduction for the node to split further for an XGBoost model with 1,000 trees. The tuned model is shown in Fig 8. The performance improves slightly compared to the unturned model.

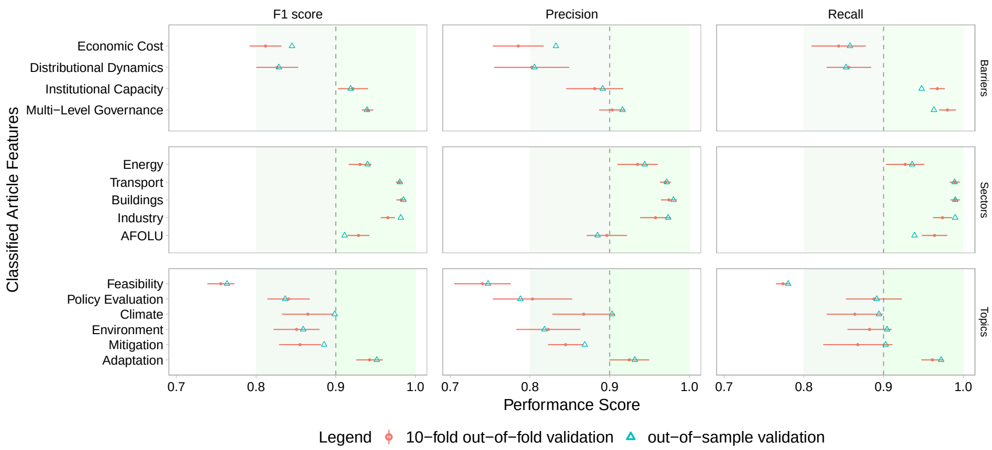


Figure 8. XGBoost Model Performance. 10-fold cross-validation performance on the training set is shown in red with 95% confidence intervals. Out-of-sample performance is shown by the triangle in light blue.

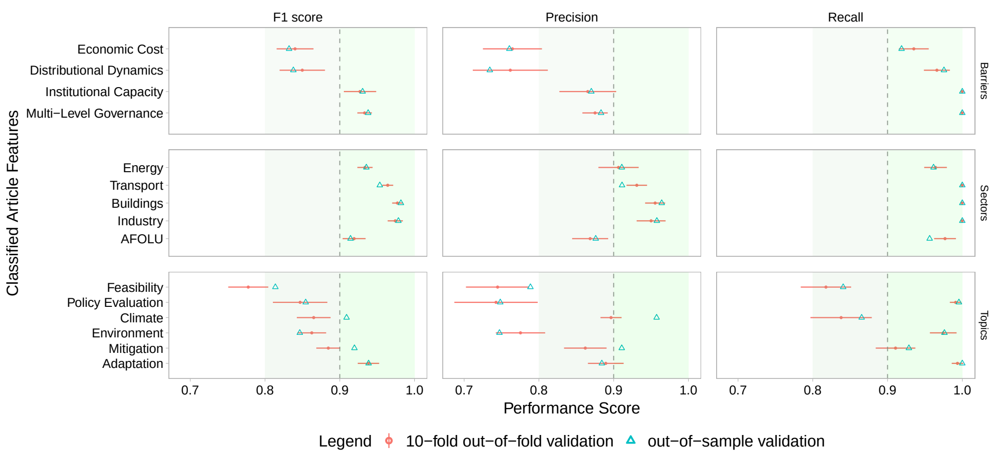


Figure 9. Forest Model Performance. 10-fold cross-validation performance on the training set is shown in red with 95% confidence intervals. Out-of-sample performance is shown by the triangle in light blue.

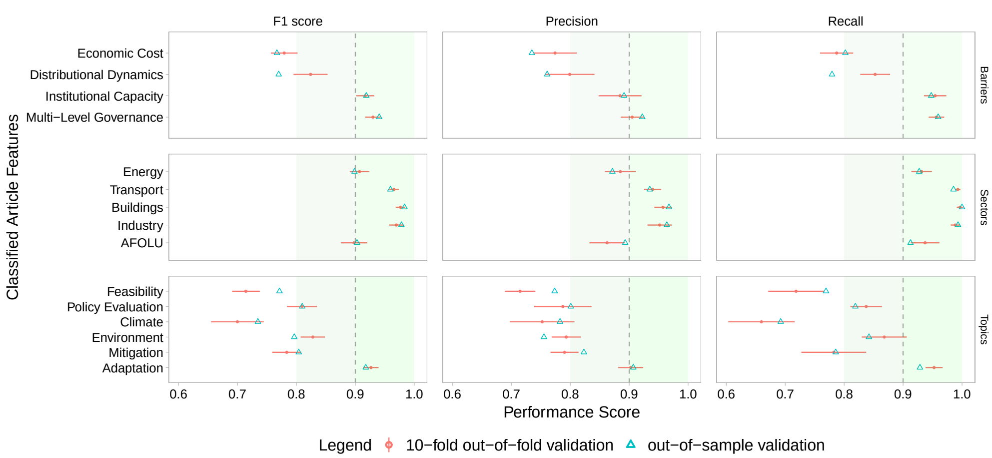


Figure 10. Support Vector Machine Model Performance. 10-fold cross-validation performance on the training set is shown in red with 95% confidence intervals. Out-of-sample performance is shown by the triangle in light blue.

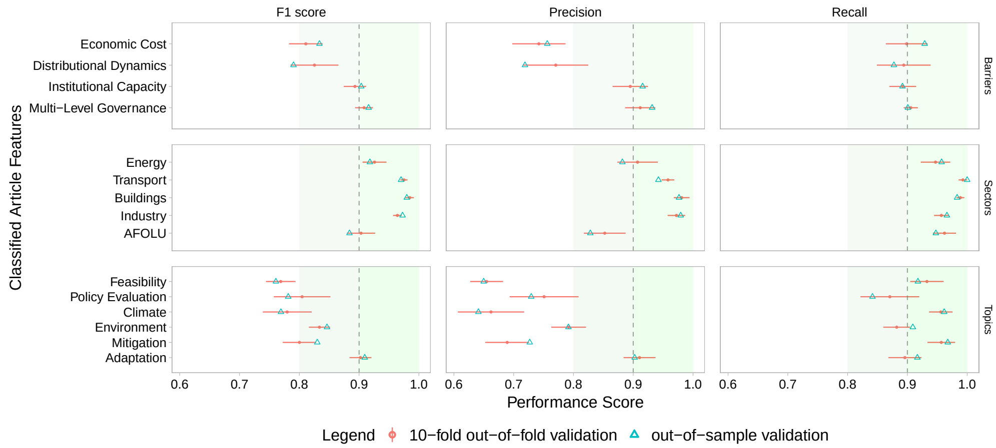


Figure 11. Lasso Model Performance. 10-fold cross-validation performance on the training set is shown in red with 95% confidence intervals. Out-of-sample performance is shown by the triangle in light blue.

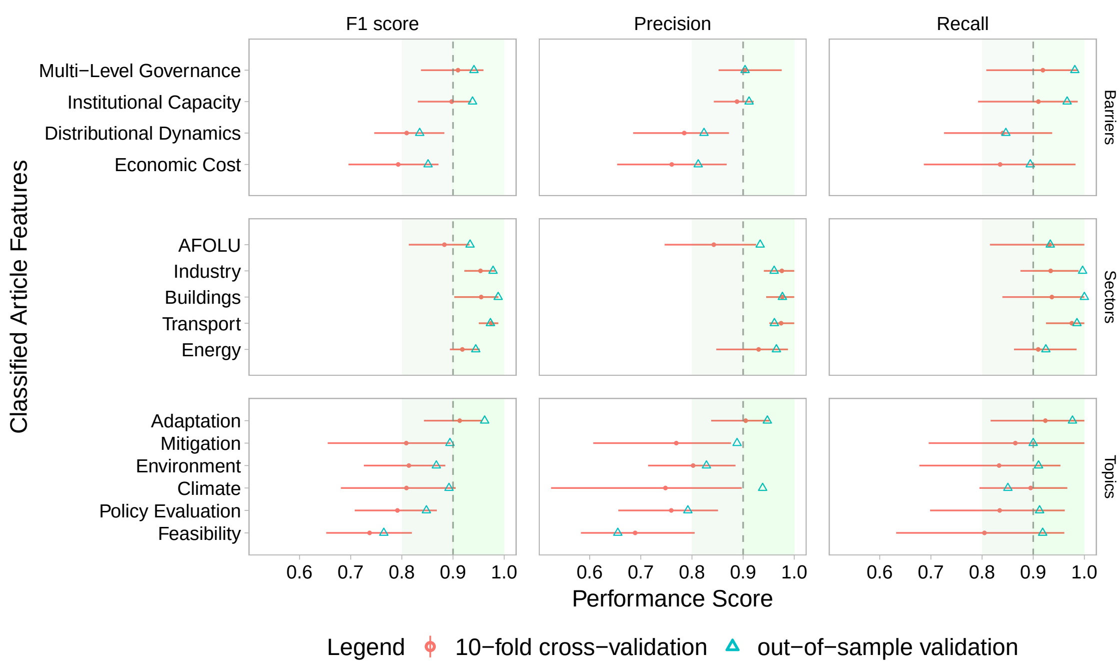


Figure 12. Tuned XGBoost Model Performance. 10-fold cross-validation performance on the training set is shown in red with 95% confidence intervals. Out-of-sample performance is shown by the triangle in light blue.

3 In-depth Review (Step 3)

Based on the predictions of the machine-learning model which is described in Section 2, we zoom into the enablers of politically feasible, ambitious climate change mitigation policies in our in-depth review. To conduct this review, we select articles from the journals with the highest impact factor that cover the following three dimensions: i. political feasibility, ii. climate change mitigation, and iii. the four barriers predicted with supervised machine-learning (see Section 2).

3.1 Map the Literature (Step 3.1)

To understand the geographic focus of the research in our sample, we identify the geographical location of the studies from the article abstracts. We do so by identifying if an article abstract mentions a specific country's name. To obtain the result in Fig 3, panel a on the country-level distribution of climate change mitigation research, we sum the number of times that a country is mentioned in the article abstracts in our sample.

To obtain the regional share in Fig 3, panel b, we combine the geo-information on the country focus with our machine-learning predictions of the topic (climate change mitigation) and each of the barriers (distributional dynamics, economic cost, institutional capacity, and multi-level governance). We compute regional shares that each barrier contributes to the total number of articles that cover any of the four barriers using the definitions for the regions.

Fig 13 displays the countries per region used for the construction of Fig 3 on the regional distribution of the research, the barriers, and the emission and research shares. For better visibility and a lower number of regions, we grouped the Middle East, Asia, South-East Asia and Developing Pacific, Eastern Asia and Eurasia used by Lamb et al[162] into the continent of Asia.

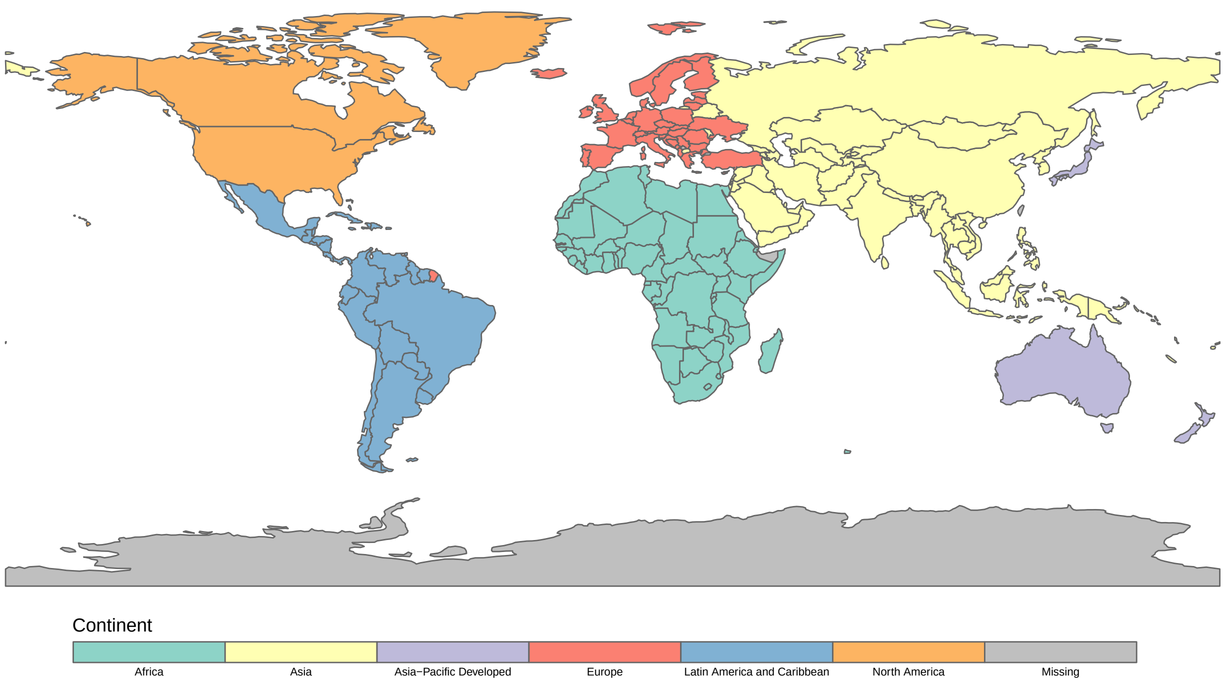


Figure 13. The countries per region.

For sectoral GHG emissions used in Fig 3, panel c showing the share of emissions and the share of research by region, we use data by Lamb et al[162] who constructed their data based on the EDGAR v5.0 database[163]. The database uses International Energy Agency data for emissions from fuel combustion combined with CH4 and N2O emissions from land-use changes from the United Nations Food and Agricultural Organisation[164] based on the Global Fire Emissions Database[165] and separately sourced data from global bookkeeping models[166–168]. For more details on the data, see Lamb et al[162]. This data is suitable for our purpose because it provides emissions by sectors and regions. In comparison to data from the World Resource Institute, we find that the data by Lamb et al[162] more closely aligns with sectoral emission shares across the world provided for instance by the United States Environmental Protection Agency or the European Union estimates submitted to the IPCC. We do not use the data from the IPCC's own inventory because using the data would involve the transformation of a range of different GHGs into CO_2 equivalents and aggregation across sectors. The data by Lamb et al[162] corresponds to the sectoral level of aggregation (energy, transport, buildings, industry, and AFOLU) that we need and are therefore the most suitable data source for our purposes.

To compare the share of emissions and the share of research by region in Fig 3, we aggregate both the research and emissions over our study period from the beginning of 1990 until 2020. For the share of research, we aggregate the number of scientific publications that our machine-learning model predicted to address climate change mitigation over all time periods. For the sectoral and regional emissions data by Lamb et al[162], we conducted a linear interpolation of the emission data available for the data points between each of the years 1990, 2000, 2010, and 2018. We then summed emissions by region and sector over all years and computed the sectoral shares of emissions by region. This approach ensures a commensurate comparison of the regional research and emission shares.

3.2 Annotate the Research Articles (Step 3.2)

We then used a subset of these articles to inductively define a typology of six comprehensive enablers. The typology was developed during four group workshops each of which was based on an in-depth analysis of 25 articles from journals with the highest impact factor. We used the journal impact factor as an inclusion criterion because these represent general tendencies in the field. We formulated a definition for each enabler and summarized the causal pathways for how each mechanism can contribute to the relaxation of the barriers (see Table 13. For the in-depth review, we selected 400 articles, the 100 articles in the journal with the highest impact factor for each of the four barriers. This yields a total number of 326 unique articles because some articles cover two or more barriers. From these, we then excluded 34 articles since the machine-learning predictions may sometimes include false positives (see Section 2.3 for model performance statistics). This corresponds to a ratio of roughly ten per cent which we deem acceptable. Our hands-on review then includes a total number of 292 research articles which we coded using the following code book.

Code Book for Qualitative in-Depth Review

This code book describes the rules to qualitatively categorize scientific articles based on their introduction, discussion and conclusion sections. Based on article abstracts classified in the preceding step of the systematic literature review with supervised machine-learning models, we selected articles on political feasibility for each of the four barriers, namely, i) distributional dynamics, ii) institutional capacity, iii) economic cost, and iv) multi-level governance (for a definition of the barriers, see Table 1). As described above, we then inductively defined a typology of enablers that may relax barriers to adopting climate mitigation policy according to the literature.

Inclusion Criterion

Inclusion Criterion	Variable Coding Question	Anchor Example
Excluded:	Does the article cover the political feasibility of climate change mitigation policies?	ref[169] entitled "Research frontiers for improving our understanding of drought-induced tree and forest mortality"
Reason for Exclusion:	Why was the article excluded?	not on feasibility (note during the coding process)

Table 10. Coding Rules for Inclusion Criterion

Excluded: Research articles that discuss the political feasibility of climate change mitigation policies are not excluded from the sample of articles that we cover in our in-depth review (=0). Articles that only address environmental policy or climate adaptation but do not, at the same time, conduct research on the feasibility of climate change mitigation policies, are not considered relevant. These articles are excluded (=1).

A scientific article is considered to address political feasibility if it addresses public policy adoption, enactment or implementation. This definition includes the articles which present reasons for the adoption, change or implementation of public policy measures but does not include for instance firm-level policies. This means that articles that merely make a policy recommendation on how to increase the political feasibility but primarily deal with a different topic are not sufficient to be considered part of our review. Articles that evaluate policy effectiveness or provide scenarios with and without policies are not considered relevant for this review.

If the research article discusses climate change and its implications for natural or social sciences would fall into this category. A discussion of renewable energy policy or electricity market regulation is insufficient for it to be considered relevant. For it to fall under climate change it must somehow connect energy or electricity with anthropogenic temperature increase. Articles that only cover environmental problems such as water pollution would not fall into this category. When climate change or GHG emissions are not mentioned it is likely not directly about climate change. This variable is independently coded from the variables 'policy' and 'effectiveness' as well as the sectoral variables.

The article discusses climate mitigation, i.e. the reduction of GHG emissions. Articles that only discuss climate adaptation but do not at the same time cover mitigation are not considered relevant.

<u>*Enablers*</u>

Enabler	Variable Coding Question	Anchor Example
Regulatory Agency Coordination:	Does the article discuss regulatory agency coordination as a mechanism to relax any of the four barriers i) distributional dynamics, ii) institutional capacity, iii) economic cost or iv) multi-level governance?	"Empirically, we first establish that the EU indeed achieved its policy objectives to a large extent in Paris. We then argue that this high level of EU goal achievement resulted from [...] effective EU 'leadiator' strategy" ref$^{(p.3)}$,[45]
Science-Policy Interface:	Does the article discuss the science-policy interface as a mechanism to relax any of the four barriers i) distributional dynamics, ii) institutional capacity, iii) economic cost or iv) multi-level governance?	"The presence of scientific groups and multinational networks [ie, World Mayors Council on Climate Change and Climate Adaptation Santiago (CAS)] has been instrumental in putting climate change on the policy agenda in both cities. " ref$^{(p.786)}$,[59]
Communication and Framing:	Does the article discuss communication and framing as a mechanism to relax any of the four barriers i) distributional dynamics, ii) institutional capacity, iii) economic cost or iv) multi-level governance?	"Behavioral acceptance can be boosted via strategic communication, for instance by stressing that emissions trading is both effective (emissions are capped) and fair (those who emit less, pay less)." ref$^{(p.1)}$,[170]
Participation and Deliberation:	Does the article discuss participation and deliberation as a mechanism to relax any of the four barriers i) distributional dynamics, ii) institutional capacity, iii) economic cost or iv) multi-level governance?	"Our findings suggest that – even though few civil society organizations are currently independent from government in China – increased civil society organizations involvement in climate policy-making could contribute to enhancing public support for climate policy" ref$^{(p.1)}$,[77]
Policy Design:	Does the article discuss policy design as a mechanism to relax any of the four barriers i) distributional dynamics, ii) institutional capacity, iii) economic cost or iv) multi-level governance?	"Overall, we conclude that policy-packaging allows to introduce policies that are likely to be unfeasible when implemented in isolation." ref$^{(p.2)}$,[86]
Bottom-up Processes:	Does the article discuss bottom-up processes as a mechanism to relax any of the four barriers i) distributional dynamics, ii) institutional capacity, iii) economic cost or iv) multi-level governance?	"A prominent but contentious policy option for improving the external efficiency is the implementation of carbon tariffs on non-regulating regions. This is thought to reduce carbon leakage and increase domestic production, albeit at the cost of non-regulating countries." ref$^{(p.228)}$,[106]

Table 11. Coding Rules for Sectors

Regulatory Agency Coordination. Regulatory Agency Coordination includes internal, external, horizontal, and vertical coordination of governmental agencies with other governmental or non-governmental actors. This may involve the creation of shared venues, and new bodies (=1). Private actor coordination is not considered to fall under agency coordination(=0).

Science-Policy Interface. The science-policy interface includes interactions between scientists and other actors involved in policy processes and resource governance. These actors create venues that foster the integration of scientific knowledge into decision-making with the aim of improving the foundations for decision-making. For instance, the integration of policy process knowledge includes scientific advice on actor positions, coalitions and voter preferences and questions related to the effectiveness of laws and governance arrangements are covered by ex-post monitoring or ex-ante project evaluation (=1). The science-policy interface does not include general policy-relevant conclusions of the research articles themselves (=0).

Communication and Framing. Communication and framing alter the perceived importance of some elements in communication over others, leading to changes in the perception of the problem, its causes, and the moral and normative conclusions about potential solutions (=1). Policy positions of actors in the policy process are not considered to be part of communication and framing (=0).

Participation and Deliberation. Participation and deliberation ensure that stakeholders can voice their opinions. Such pluralistic and inclusive processes ensure that a larger set of potentially competing interests voice their preferences (=1). Participation and deliberation are different but related to bottom-up approaches in that participation often is but must not necessarily be local and decentralised (=0).

Policy Design. The strategic choice of policies and their design, i.e. the specific rules and calibrations, can mobilize voters and potentially foster support for more ambitious climate policy over time (=1). Private actors policies, e.g. firm-level policy related decisions are not covered under this variable (=0).

Bottom-up Processes. Bottom-up processes exhibit a relatively low degree of centralisation that allows for experimentation with new governance arrangements and may trigger diffusion processes for instance through learning, emulation, and imitation. These processes include so-called carbon clubs, in which cities create governance arrangements for knowledge exchange, and clubs between countries that implement carbon tariffs to avoid carbon leakage or to induce participation in international agreements (=1). Coercion by centralised or supernational institutions does not fall under bottom-up processes (=0).

Sectors

Sector	Variable Coding Question	Anchor Example
Energy:	Does the article mention the production, conversion or transportation of energy?	"Current policies fail to induce the transformation of the energy system to the extent required by long-term climate targets and lead to further lock-in into carbon-intensive infrastructure." ref[(p.2),84]
Transport:	Does the article mention public or private transportation?	"To identify politically feasible and effective policy packages aimed at greening the transportation sector we use choice experiments with representative samples of citizens from China, Germany, and the USA (N = 4876)" ref[(p.2),86]
Buildings:	Does the article mention buildings or housing?	"The climate change debate is shifting from discussing problems towards discussing potential solutions such as low-carbon transitions in buildings" ref[(p.2),11]
Industry:	Does the article mention industrial production or processes?	"Local environmental problems continue in many countries, but the current challenging environmental issues are global problems, such as climate change. In contrast to local industrial pollution, where there is a clear polluter (industries) and potential target of the policy, the polluters and victims of global problems are more dispersed around the globe." ref[(p.1894),41]
AFOLU:	Does the article mention agriculture, land use or forestry?	"We report how the third inventory for the sector of land use, land-use change and forestry (LULUCF) was implemented to address scientific challenges involved in the monitoring of carbon stocks and land-use changes of diverse and complex biomass while addressing international and national policy demands (report and decision support) and transparency to various stakeholders." ref[(p.1),57]

Table 12. Coding Rules for Sectors

Energy. Articles that mention the generation, conversion or transportation of various energy sources such as crude oil, coal, natural gas, nuclear energy, hydropower, geothermal, wind, solar and bio-energy are considered to cover the energy sector (=1). The transportation of energy for final use (e.g. car or train) is considered part of the energy sector but the final use of energy in buildings, transportation, industry or AFOLU is not. For abstracts that do not mention the generation, conversion or transportation the variable energy is not present (=0).

Transport. Articles that mention transportation systems such as cars, railways, aviation, and shipping are considered to cover the transport sector (=1). Articles, where transportation occurs as part of a different sectoral activity, such as agriculture or industry trading, the variable, is not present (=0).

Buildings. Articles that mention the public or private building/housing sector are coded as covering the building sector (=1). For articles that mention buildings that primarily serve any other sector such as power plants, the variable is not present (=0).

Industry. Articles that mention the production of materials such as chemicals, electronics, textiles, machinery, metals, minerals, cement, lime or glass or other raw or final products cover the industry sector (=1). Industrial production of e.g. transportation modes does not cover the industry sector (=0) but falls into the respective other sectors.

AFOLU. Articles that mention agriculture, forestry, and other land use (AFOLU) such as wetland or croplands, livestock and soil management are considered to cover the AFOLU sector (=1). Articles on the use of wood in the building sector are not considered to cover the AFOLU sector (=0).

3.3 Qualitative Summary of the Results (Step 3.3)

Our mixed-method approach allows us to unpack some of the results that otherwise often remain hidden in large-scale machine learning maps. This is an important step to achieve our objectives on the identification of enablers and specific causal mechanisms for barrier relaxation to more ambitious climate change mitigation policy. Such inductive work can contribute to theory-building rooted in existing research.

Fig 14 shows the mind-map based on which we qualitatively unpack the enablers. Purple nodes represent enablers and the branches link specific notes from take during annotation of the articles that may consist of causal mechanisms for barrier relaxation. We use this mind-map to organize the literature qualitatively and to inform the subsection on the causal mechanisms for barrier relaxation below.

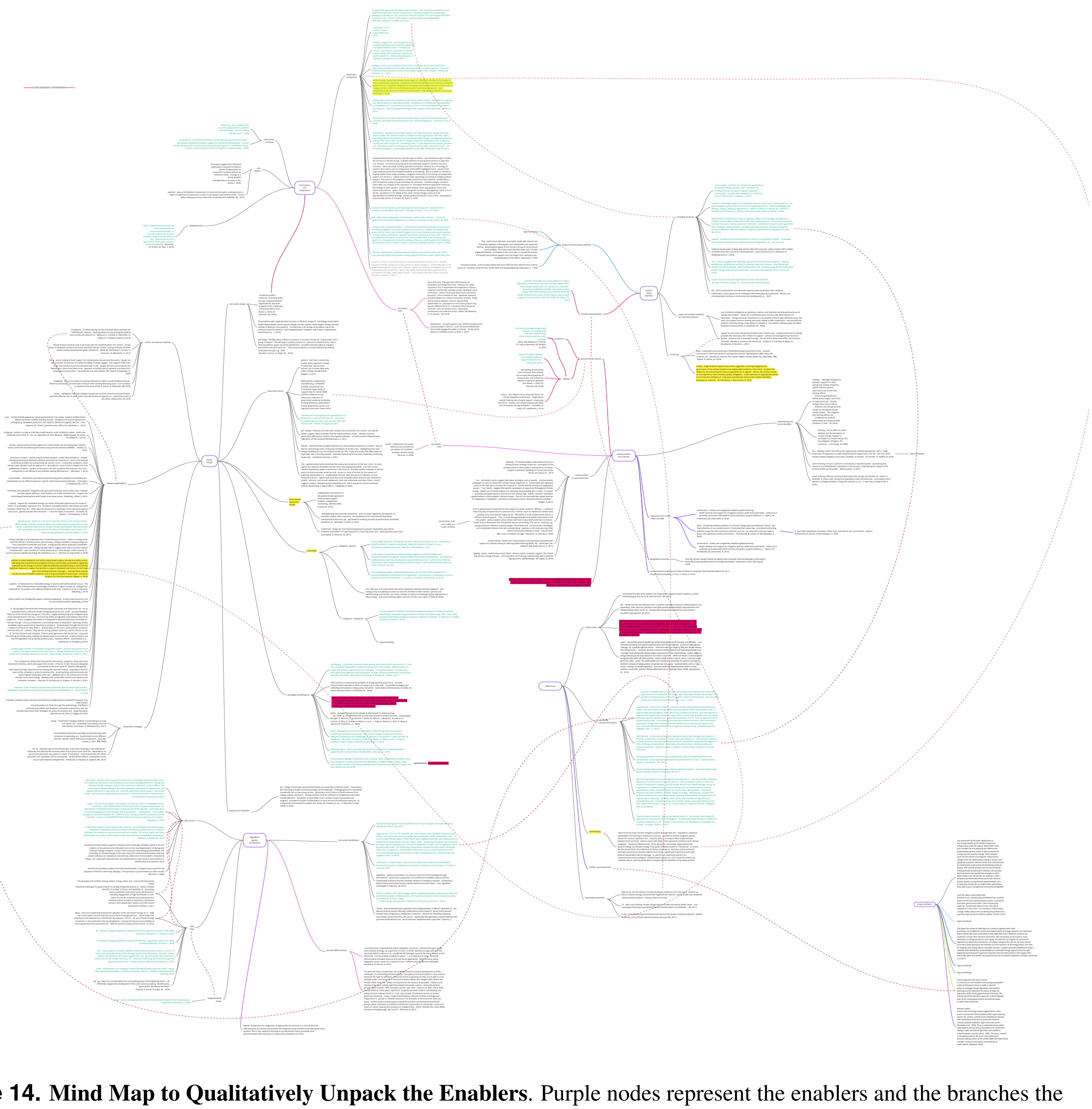


Figure 14. Mind Map to Qualitatively Unpack the Enablers. Purple nodes represent the enablers and the branches the causal mechanisms for barrier relaxation around each enabler. Digital PDFs allow zooming into the elements for for better readability.

Full Description of the Causal Mechanism to Relax each Barrier

Table 13 provides a full description of the causal mechanisms for barrier relaxation. The first column consists of the name of the enabler. The subsequent four columns consist of a summary of the causal mechanism for barrier relaxation, linking the enabler to each of the four barriers. The last column provides an example. Next, we describe these causal mechanisms.

Enabler	Summary of the Causal Mechanism for Barrier Relaxation				Examples
	Distributional Dynamics	Economic Cost	Institutional Capacity	Multi-Level Governance	
Agency Coordination:	Conflict mediation and network brokers	Resource optimisation between government agencies	Reduced information asymmetries between government agencies	Top-down reduction of policy incoherences	Venues for knowledge exchange.
Science-policy Interface:	Inform about actors' policy positions and policies with high acceptance	Inform about technological learning rates	Assist with monitoring and evaluation	Credible scientific information creates harmonisation pressure between governance levels	Scientific taskforces
Communication and Framing:	Reduced salience of partisan-based opposition	Increased visibility of climate policy benefits	Increased perceived legitimacy of political leaders and agencies	-	Emphasising the benefits of climate policy in discourses
Participation and Deliberation:	Increases acceptance and reduces vested interest influence	-	Fosters governance legitimacy	Circumvent dead-lock in international negotiations	Citizen assemblies in the policy making process
Policy Design:	Nurture green identities	Reduce technology costs which increases acceptance of more ambitious climate policy	Formalised progressive increase of institutional capacities through prior laws	Progressive increase of national harmonisation commitments	Concentrated benefits build support for more ambitious climate policy
Bottom-up Processes:	Lower preference heterogeneity makes finding rules easier	Local regulatory environments can foster economies of scale and local human, social and intellectual capital	Decentralised processes are easier to manage	Up-scaling of locally successful rules	decentralised decision-making reduces

Table 13. enablers of barrier relaxation. This table provides a short summary of the enablers and the causal pathways that enable the relaxation of the four barriers (for a definition, see Table 1 in the main text).

Regulatory Agency Coordination. Regulatory agency coordination creates institutional structures that allow the integration of resources between public and public-private actors. Regulatory agencies coordinate internally or externally. Internal coordination operates between agencies of government. External coordination includes non-state actors such as private or public-private partnerships, NGOs[171] or independent advisory bodies. Such coordination structures require clear leadership which facilitates the assignment of tasks, the structuring of conversations, and agenda setting. For instance, the successful negotiation of the Paris Agreement substantially benefited from internal coordination and agenda-setting power by France and leadership by the EU[45,46].

Causal pathway for distributional dynamics: Agency coordination allows the definition of leadership for conflict mediation roles in the policy-making process[45]. Conflict mediation by network brokers with independent positions can reduce conflict, evade policy gridlock and thereby reduce distributional barriers. These in turn enable the formulation of policy proposals that are more likely to receive majority support[45,46].

Causal pathway for economic cost: Agency coordination facilitates the optimisation of the use of government resources between agencies. Coordination with external, non-state actors through the creation of new venues may create new investment opportunities[94]. For instance in South Africa, public-private partnerships disrupted established market dynamics and enabled investments of over 14 billion dollars into renewable energies[94].

Causal pathway for institutional capacity: Regulatory agency coordination can create institutional capacities to manage policy processes and implementation phases[44,101]. Such structures can reduce information asymmetries and foster participation through consultative processes in vertical and horizontal networks among key stakeholders[50]. Agency coordination requires the definition of responsibilities and leadership in government. Clear responsibilities allow for increasing the efficiency and effectiveness of mitigation efforts, especially when coupled with independent institutions tasked with monitoring and science policy interface. Coordination may further serve to foster a common understanding of different ideological and cultural positions between agencies.

Causal pathway for multi-level governance: Agency coordination of actors between governance levels creates learning opportunities from local governance experiments. Decentralised experimentation can result in fragmented governance and geographically incoherent policies. While enabling locally suitable federalist policy solutions, coordination between agencies allows for reducing policy incoherence between local experiments.

Science-Policy Interface. The science-policy interface includes interactions between scientists and other actors[51] in policy processes and resource governance. These actors create venues that foster the integration of scientific knowledge aiming to improve the foundations for decision-making[52]. For instance, the integration of policy impact and process knowledge includes scientific advice on actor positions, coalitions and voter preferences or, related to the effectiveness of laws and governance arrangements, ex-post monitoring and ex-ante project evaluation.

Causal pathway for distributional dynamics: Independent and credible information, such as monitoring by independent bodies operating at the science-policy interface, can increase domestic support for ambitious climate policy at the international level[172]. In addition, the science-policy interface can inform about policy design features that find the largest support among relevant constituencies. The science-policy interface may provide an overview of constellations, discourses, beliefs and interests and options to relax distributional barriers. Thus, tailoring institutions to foster exchange between (social) scientific experts and policymakers can reduce distributional gridlock and increase the feasibility of ambitious climate policy.

Causal pathways for economic cost: Science-policy integration may inform about technological learning rates, upfront investment costs and effective public innovation policies that can lead to cost reductions. Scientists may also inform about the costs and benefits of different climate policies and the specific design of these measures. Thereby they may help balance the efficiency, effectiveness, equity and competitiveness concerns of political and economic actors. Thus, well-operating science-policy integration may relax economic cost barriers and make more ambitious policies feasible.

Causal pathway for institutional capacity: Science-policy integration can reduce information asymmetries and uncertainty for decision-makers[50,56]. Science-policy integration can assist the monitoring and the evaluation of existing policies for instance through scientific advisory panels[57], which reduces information asymmetries across agencies and facilitates the adoption of effective and ambitious policies.

Causal pathway for multi-level governance: Due to the complexity and scope of climate change, science-policy integration allows for credible scientific and coordinated input into policy-making processes. This can lead to harmonization pressure at other governance levels and foster the adoption of more ambitious climate policy.

Communication and Framing. Communication and framing creates awareness and alters the perceived importance of some elements in communication over others, leading to changes in the perception of the problem, its causes, the moral and normative conclusions about potential solutions[61,62]. Framing can take different forms, such as emphasising specific subsets of arguments in political discourse, altering the sender of a message (source cue), and changing the perceived (temporal, spatial, social) distance to a problem.

Causal pathways for distributional dynamics: Communication and framing can contribute to the relaxation of distributional struggles in the policy process by resolving ideological partisan conflict. While partisan-driven argumentation may further amplify conflict and polarisation, communication strategies that are compatible with the ideology of strategically important actors or that frame independent of partisan ideology may reduce ideological clashes and enable crafting majorities for more ambitious climate policy[8,65].

Causal pathways for economic cost: In terms of economic costs and benefits, communication and framing can increase the cognitive importance of benefits relative to the cost of climate policy. Increased benefits can create a supportive environment for ambitious climate policy. Emphasising and communicating tangible and positive welfare and well-being effects can increase their perceived importance. The relative importance of the cost of climate policy is consequently lower[8,65]. Communication is especially important to make the positive effects of climate policy visible which often remain unnoticed because of incomplete information and psychological biases. Risk aversion often draws more attention to the cost of climate policy leaving the benefits unnoticed. Communication and framing can help create knowledge of and shift attention to benefits[173].

Causal pathways institutional capacity: Institutional capacity barriers can be relaxed when communication and framing increase the perceived legitimacy of political leaders and agencies. Perceived legitimacy increases the institutional capacities of political leaders and agencies to adopt and implement ambitious climate policies.

Causal pathways for multi-level governance: -

Participation and Deliberation. Participation and deliberation ensures that a diverse range of stakeholders can voice their opinions and negotiate a common solution. Such pluralistic and inclusive processes enable a larger set of potentially competing interests to voice their preferences. This can enhance the influence of the environment relative to business interests[174,175] and potentially overcome unequal power relations of those actors who favour the status quo. For instance, at the individual level citizen assemblies provide opportunities to condense the preferences of the public. For organisations, including civil society, firms, scientists, and other actors, consultative processes and multi-stakeholder fora form inclusive access points for climate governance.

Causal pathway for distributional dynamics: Policies that incorporate a large range of different positions are more likely to be supported by a winning coalition in the policy-making process. Participation and deliberation ensure the representation of opposing interests in the policy-making process. This reduces the influence of few powerful actors, increases the representation of varying interests and thereby enhances the support among stakeholders and constituents[174,175]. Participatory and deliberative processes can also shift perceptions and create knowledge about climate change[173]. Thus, participatory processes increase the support and provide solutions to dead-lock due to distributional questions in climate policy processes

Causal pathways for institutional capacity: Participation and deliberation can create institutional capacity can foster governance legitimacy to make ambitious climate policy feasible.

Causal Pathway: econ cost not clear

Causal pathway for multi-level governance: participatory and deliberative processes may circumvent deadlock in international negotiations if they enable the crafting of rules that are supported by key constituencies. Especially, when combined with bottom-up processes, decentralised approaches foster experimentation and learning which can in turn facilitate the adoption of more ambitious climate policy.

Policy Design. Policy design shapes politics[143,144,176]. Past policy decisions can feed back into present and future policy processes. The strategic choice of policies and their design and the specific rules and calibrations of policy instruments can mobilize voters and potentially foster support for more ambitious climate policy over time[92,93,177].

Causal pathway for distributional dynamics: The strategic choice of policies can create positive feedback effects that nurture green constituents and facilitate the adoption of more intensive climate policy over time. First, policy design options that reward environmentally friendly technological and behavioural changes can have positive mobilisation effects on green constituents[178] and contribute to the formation of winning coalitions for climate policy. Second, policies that create benefits for relevant voter constituents and elite stake-holders contribute to changes in voter coalition composition[92,93], beliefs and identities that are favourable of more ambitious climate policy. Third, positive policy feedback is more likely to emanate when climate policies are consistent with deep-held identities and convictions. In sum, policy design can contribute to positive feedback effects and a permissive environment for more ambitious climate policy.

Causal pathway for economic cost: Positive policy feedback can be triggered by economic cost reductions of climate friendly technologies. The introduction of innovation-oriented policies, such as research and deployment policies, reduce the cost of specific green technologies[179,180]. These technologies nurture new climate-friendly interests with lower opportunity cost to accept more ambitious climate policy because these constituencies want to maintain or expand on the benefits from green technologies[7,92,93].

Causal pathways for institutional capacity: The strategic design of policy instruments that specify policy design principles can enhance institutional capacities for future policy processes. These include for instance clauses on the successive increase of policy ambition over time or the inclusion of monitoring reports into the policy making process to evaluate success of a specific policy. Such clauses create agency and legitimize policy entrepreneurs to push for more ambitious climate policy (source: my argument). Strategically over-funding environmental policy can entrench pro-environmental interests in government, creating institutional capacities for climate mitigation[181]. However, such tying-hands approaches are questionable from a normative standpoint because they may fail to reflect the preferences of the public[78].

Causal pathway for multi-level governance: Positive policy feedback can also be created by network spillovers across levels of governance. If climate policy leaders can push for more ambitious policies, their experimentation can show feasible pathways that allow laggards to learn from them.

Bottom-up. Bottom-up processes exhibit a relatively low degree of centralisation that allow for experimentation with new governance arrangements and may trigger diffusion processes for instance through learning, emulation, imitation. These processes include so-called carbon clubs, in which cities create governance arrangements for knowledge exchange, clubs between countries that implement carbon tariffs to avoid carbon leakage or to induce participation in international agreements[1].

Causal pathway for distributional dynamics: Bottom-up processes can relax distributional barriers because establishing rules that reflect the preferences decreases with the number of actors involved. Experimentation in decentralised systems can facilitate learning, emulation, and imitation by other jurisdictions.

Causal pathway for economic cost: By creating favourable opportunities for local businesses, bottom-up approaches can facilitate local cost reduction of low-carbon technologies. These can lead to economies of scale in geographically limited spaces due to the accumulation of human capital, and social and intellectual capital. One-fits-all solutions with decentralised rules are less capable to create a regulatory environment that fosters such innovations because the heterogeneity of actors typically increases with the geographic scope and the number of actors in the target group.

Causal pathways for institutional capacity: Bottom-up and decentralised approaches can increase institutional capacities by making policy processes better understandable and easier to manage.

Causal pathway for multi-level governance: Bottom-up processes create opportunities for experimentation and learning. This facilitates the up-scaling of local enablers across levels of governance[103]. For instance, enablers that turned out to be effective at the city level may then be adopted at the national level. Furthermore, individual lead countries may limit free-riding by creating climate clubs[1]. By adopting carbon tariffs that put a top-on price for goods that create high emissions, countries can increase the cost of defection and induce participation in international agreements.

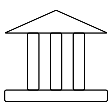
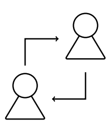
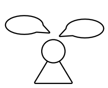
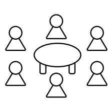
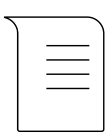
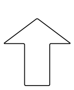
Enabler		Specific Enabling Mechanisms	Example
	Regulatory Agency Coordination	• vertical coordination • leadership • creation of institutional venues	• top-down information exchange[41,42,59,182] • brokers and entrepreneurs[44–46] • specific climate change institutions[29,39,72]
	Science-Policy Interface	• informing about new solutions • monitoring • interface design	• renewable[9] and negative emission technologies[60] • emissions[183] and low-carbon alternatives[57] • inclusive scientific boards[52]
	Communication and Framing	• reducing partisan divisions • emphasizing benefits • reframing	• decoupling identity politics[8] • raising awareness of benefits[69,184] • employing positive wording[67]
	Participation and Deliberation	• democratic processes • new actor motivations • stakeholder involvement	• pluralism promotes low-carbon interests[175] • reciprocity[13], trust, cooperation[14], consent[8] • civil society, consultation[77,78]
	Policy Design	• instrument choice • instrument design • positive policy feedback • policy packaging and co-benefits	• subsidies versus carbon pricing • carbon tax revenue recycling[71] • benefit-inducing policies increase support[7,92,93] • combining taxes and subsidies[85,86,97]
	Bottom-up	• local experimentation • up-scaling • carbon clubs • emission trading linkage	• city-to-city networks[37] • from local to national level[41] • carbon tariffs for non-compliance[106] • unify fragmented markets[185]

Table 14. Unpacking the enablers. Illustration of the typology with specific mechanisms that enable the relaxation of barriers to ambitious climate mitigation policies documented in the literature.