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Climate politics, metaphors and the fractal carbon trap

Steven Bernstein [1] and Matthew Hoffmann [2]

The international community has treated climate change as an emissions reduction challenge, drawing on the analytical metaphor of the global commons, and thus the politics of collective action and international cooperation. So far, these strategies have failed to produce an effective global response. We propose decarbonization as the defining challenge and a new guiding metaphor for the problem structure: the global fractal. This metaphor aptly describes the decarbonization challenge, capturing the multilevel and interdependent nature of carbon lock-in and the fractal carbon trap facing decarbonization efforts. It also provides a means to explore the range of diverse policies and practices that can potentially escape the fractal carbon trap and catalyse deep decarbonization.

Metaphors define and constrain how political actors conceive problems and develop and pursue solutions[1–5]. While not causes of political choices, they can open and close off options because they naturalize particular understandings. Climate change is no exception to this rule[6]. Responses to it have conventionally been built through a 'global commons' metaphor which naturalizes the following logic: states, the actors in the international system with the requisite authority to govern the global commons, must cooperate and overcome collective action problems to reduce their emissions in order to secure the global public good of a stable climate[7,8]. In this world, the 'solution' is to negotiate over who gets how much of a carbon budget[9,10], who is responsible for how much of the emissions reductions, who pays for emissions reductions, how to encourage compliance and identify and discipline cheaters, and what side-bargains will make the distribution of costs to provide the public good feasible (Fig. 1).

Multilateral negotiations essentially pursued this logic from 1990 to 2009. The failure to reach agreement at the 2009 negotiations in Copenhagen after 12 years of post-Kyoto stalemate proved a watershed moment. It revealed the virtual insolubility of climate change framed as a collective action problem and catalysed the search for new thinking for the multilateral process, even as other actors had already begun to experiment with climate governance outside that process[11,12].

The Paris Agreement departed from conventional collective action politics[13]. Its decentralized approach asks states to pledge actions and goals to which they can commit. The international community and bureaucracy's role is to monitor individual commitments and assess the collective effectiveness of nationally determined contributions. Yet, even in the new era of the Paris Agreement, observers and practitioners still rely on old metaphors. The mantra of 'global solutions' still invokes ideas of a treaty that will legally bind states to a collective endeavour[7]. The elements of reciprocity required to make collective action effective still occupy a central place in post-Paris Conferences of the Parties despite mounting evidence that people and states do not necessarily value reciprocity in global climate action[14,15]. Further, much of the discussion about the 'new' realm of non-state and sub-state climate initiatives concerns how they can contribute to filling the Paris gap and change incentives for interstate cooperation and collective action[16,17]. Although attention to these other actors and levels of action highlights increasing recognition of where climate change is being addressed, the global commons metaphor still constrains the thinking of both researchers and policymakers[9].

More productive framings are possible. Changing perspective to consider the challenge of climate change as decarbonization means focusing attention on disrupting carbon lock-in (Box 1)[18,19]. Global carbon lock-in is not a single coherent global system but rather arises because multiple, interdependent systems at local, regional and national levels, as well as the economic activity within and among them, are locked into the use of fossil energy. In other words, carbon lock-in is a multilevel and multisectoral challenge of similar, overlapping and interdependent political, economic, technological and cultural forces that reinforce dependence on fossil fuels in many places simultaneously. A global fractal metaphor better fits the decarbonization challenge, making it apt to guide the development of research and policy.

We argue that this new metaphor can reorient research and action from a dominant focus on the collective action problem of distributing emissions reductions to preserve the global commons, to analysing and deploying strategies that disrupt carbon lock-in at multiple levels and scales, leveraging decarbonization in an interdependent fractal system. Analysing decarbonization through a fractal lens extends climate research beyond theories of collective action to additionally examine the political economy dynamics of the fractal system that lock in carbon, the potential for various purposeful interventions to disrupt those dynamics in specific parts of the fractal, and the leverage points[20,21] through which those interventions catalyse decarbonization more broadly.

Carbon lock-in as a fractal system

Carbon lock-in exhibits three qualities characteristic of fractal systems[22–26]. First, it exhibits repeated patterns — or self-similarity — at different scales of aggregation. Carbon lock-in arises from overlapping political, economic, technological and cultural forces that reinforce fossil energy use. These lock-in dynamics are similar, although not identical, at multiple scales. At any level (both cities and states, for example), transportation and energy infrastructure, cultural

[1]Department of Political Science, University of Toronto, Toronto, Ontario, Canada. [2]Department of Political Science, University of Toronto Scarborough, Toronto, Ontario, Canada. e-mail: steven.bernstein@utoronto.ca; mjhoff@utsc.utoronto.ca

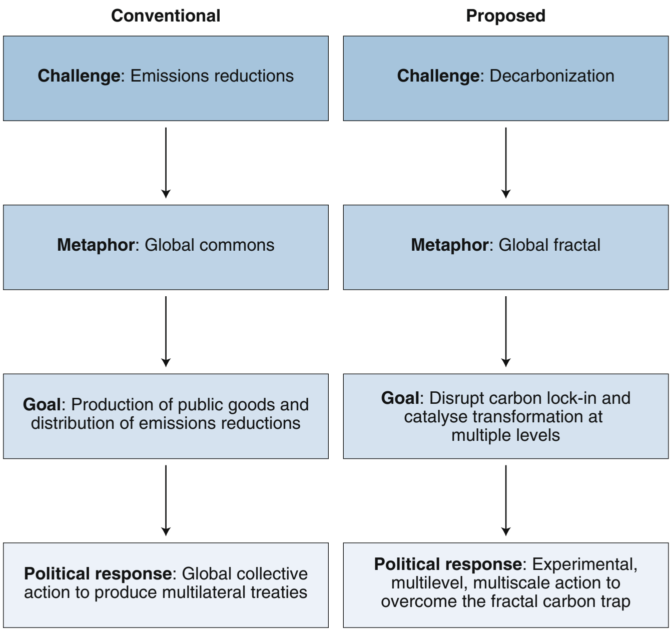

Fig. 1 | Metaphors and climate politics. The conventional logic of the 'global commons' metaphor and the logic of the proposed 'global fractal' metaphor.

Box 1 | Key terms for understanding the fractal carbon trap

Each system (such as a jurisdiction or market) that makes up the fractal whole faces a dilemma when pursuing decarbonization. We call that dilemma the carbon trap after the poverty trap concept from development economics[23]. The fractal carbon trap has several constitutive elements.

Carbon lock-in. A concept coined by Gregory Unruh[18] that denotes how multiple dynamics (technological, economic, political and social) reinforce the continued and natural use of fossil energy. We assume that carbon lock-in is the initial condition or state for most discrete systems in the fractal whole, and that it is also reinforced in distinct places by fractal interdependence.

Decarbonization. The process toward fossil energy being a vanishingly small part of the energy mix — the hoped-for end state or condition of each system in the fractal whole. Very few systems or sectors have achieved full decarbonization.

Trap. The political-economic dynamics that serve to reinforce an attractor or state space. A system could be 'trapped' in carbon lock-in where the political-economic dynamics tend to dampen or reverse efforts to act on climate change (as one author[102] who uses the term carbon trap implies) or it could be trapped in another state such as decarbonization where reversing efforts to combat climate change would be difficult.

D_{crit}. From Fig. 2, D_{crit} is the threshold point between attractors. Below this point, political-economic factors will tend to drive the system towards carbon lock-in. Above this point, they will tend to drive the system towards decarbonization. Breaching the D_{crit} threshold could potentially result from either a punctuated, revolutionary breakthrough or progressive accumulation of incremental changes[47].

practices, technological options, political coalitions and institutional capacities reinforce the natural use of fossil energy.

Second, patterns of carbon lock-in at each level are interdependent and reinforcing. Not only does "a fractal pattern [repeat] itself at all scales of aggregation" but also in fractal systems "each scale reinforce[s] the pattern at other scales"[23]. Carbon lock-in in cities reinforces state-wide lock-in and global lock-in, just as global lock-in reinforces state-wide lock-in and, in turn, lock-in at the municipal level.

Finally, fractal patterns are self-organized and emerge without central planning or control. The intersection of markets, technological, political and cultural processes produces emergent fractal patterns. A particular system or individual action may be planned, and certainly actors pursue their political interests, reinforcing carbon lock-in. Yet there was no overarching plan to produce global carbon lock-in. It has emerged from multiple interactions at multiple scales.

We are not making an empirical claim that carbon lock-in is mathematically fractal. Rather, treating carbon lock-in as if it has a fractal structure is useful. This perspective highlights the multitude of entry points where action on climate change can and must occur that are easily obscured by a 'commons' metaphor emphasizing a single, inadequate, arena for action. It also suggests that fractal interdependence can potentially be used to spark cascading transformation towards decarbonization across scales. The goal of climate action changes from distributing responsibilities for emissions reduction to disrupting the overlapping and multilevel forces that make the use of fossil energy natural and automatic, and catalysing the spread of disruptions.

We are not the first to propose a shift from a sole focus on collective action to one of disruption or transformation[27,28]. Suggestions to 'keep it in the ground'[29] or 'deep decarbonization'[30] planning reflect a range of such calls that share an understanding of the multilevel problem structure consistent with the fractal metaphor. Nor are we the first to note the multilevel and fragmented nature of climate change politics[31,32]. The fractal metaphor captures and connects these ideas to productive analyses and politics that can break out of or bypass the stalemates, backsliding and political obstacles that continue to slow needed action to disrupt carbon lock-in and generate pathways to decarbonization.

Indeed, the fractal metaphor implies a different kind of politics, focusing on diverse responses[33] and multilevel action. It calls for taking seriously what analysts have variously described as polycentric[32], transnational[31], or experimental[34–37] approaches, recognizing that global collective action efforts are important, but not necessarily dominant, in a robust ecosystem of climate action. The global response to climate change now comprises diverse multilevel policy and governance interventions — intentional efforts to steer actors or change system dynamics in an authoritative way — designed to disrupt carbon lock-in[33]. These efforts include cities enacting carbon action plans and participating in transnational networks[38,39]; states and provinces in North America developing linked emissions trading systems, carbon tax policies and renewable energy targets[40]; corporations and non-governmental organizations joining forces to promote smart grids, carbon accounting and clean technology deployment across national borders[41]; and nation-states developing targets for carbon neutrality, renewable energy industries, or attempts at wholesale transformations such as Germany's Energiewende or calls for a Green New Deal in the United States, in decentralized pursuit of the overarching collective goals set out in the Paris Agreement.

Analytical attention is needed wherever leverage can be potentially maximized, which may be at larger scales such as multilateral cooperation or state policy, but also at other scales and locations.

The research question thus shifts to what is required at each location or scale to disrupt carbon lock-in, and the search for leverage points that take advantage of the opportunities and constraints of the fractal system where decarbonization in one part can influence or catalyse it in others. We understand this as the politics of overcoming the fractal carbon trap.

The fractal carbon trap

Drawing on insights from work on the 'poverty trap'[23,42], we argue that disrupting carbon lock-in requires overcoming a fractal carbon trap (Box 1). The political economy of climate change and the fractal nature of carbon lock-in combine to create a challenging trajectory in each part of the fractal system. Figure 2 represents the trap heuristically as a standard S-curve[43].

The curve represents temporal expectations for the trajectory of a part of the fractal system. The x axis is the current level of decarbonization, and the y axis is the resultant expectation about the future level of decarbonization given the current state. The flat parts of the trajectory represent what are known as attractors in complex systems analysis (carbon lock-in, decarbonization): relatively stable state spaces where the array of factors (political, economic, technological, cultural) are aligned to generate reinforcing dynamics[44–46]. If a system (city, market, nation-state) is currently below (point A) the critical threshold (D_{crit}), the expectation is that the future state of the system will move towards the carbon lock-in attractor (Box 1).

Attempts to disrupt carbon lock-in are interventions that seek to move the system along the trajectory towards greater decarbonization. The D_{crit} threshold could potentially be breached either by a sudden shift such as a technological breakthrough, or through the progressive accumulation of incremental changes over time[47]. Regardless, unless an intervention helps the targeted system to breach the D_{crit} threshold (B), political-economy forces in the system will tend to drive the system back towards the carbon lock-in attractor. The nature of the threshold is determined by the political economy of the targeted system and, because of fractal interdependence, similar factors in the broader systems in which the targeted system is embedded, including: technology and technological practices (the range of choices available and the pace of innovation); economic factors (sunk costs, investment cycles, energy markets, cost structures and so on); cultural inertia (what people want and the practices that they consider normal); and political dynamics (coalitions, norms, institutions and interests that promote or resist change)[48,49]. Cultural and political dynamics are particularly challenging. Interventions must ultimately navigate counter-coalitions supported by incumbent interests and industries, campaigns that appeal to entrenched cultural norms and practices, and institutional arrangements that often favour existing policies in path-dependent ways that can make change difficult[47,50–54].

Consider a municipal policy to install electric charging stations to increase decarbonization in its transportation system. This policy would move the city away from the lock-in attractor and up the decarbonization curve a modest amount (perhaps to point A on Fig. 2). However, once in place, other political-economic factors in the city, and beyond, could drive the city's transportation system back towards the carbon lock-in attractor if the D_{crit} threshold is not breached. These threshold-determining factors could include availability of affordable electric vehicles (EVs), determined by the actions of incumbent industries, government policies and investment decisions; cost and accessibility of charging station technology and places to put them within and outside the city, as well as battery capacity, which are intertwined technological, policy and even psychological (range anxiety) issues; cachet or stigma of driving an EV, which could have both demographic and geographical determinants; and complementary incentives or disincentives at the sub-state or national level for purchasing EVs, which depend on interests and coalitions at broader levels of government.

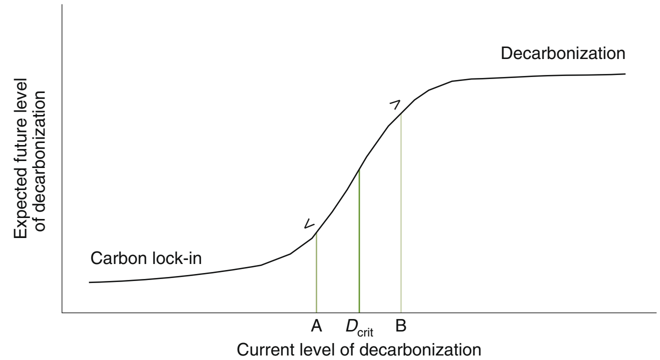

Fig. 2 | The fractal carbon trap. Visual representation of the potential trajectory of a specific targeted system in the fractal with two attractors — carbon lock-in and decarbonization. D_{crit} is the threshold point at the boundary between the two attractors. A and B represent potential interventions in the system below and above that boundary.

Interventions designed to move systems towards decarbonization do not always make it over the threshold. Apropos of this hypothetical example, in Ontario, Canada, the provincially controlled regional public transportation agency recently announced that it would be removing EV charging stations from its parking lots, citing high costs and low demand[55]. In addition, the Ontario government ended a rebate programme for EVs[56], a move that mirrors the US plan to end tax credits for EVs by 2020[57]. Examples like these are, unfortunately, common, for reasons ranging from changes in government to unexpected price shifts or to active opposition because of competing incentives or lack of reinforcement from other parts of the interdependent fractal system.

Several scholarly communities are studying the challenge of transformation, focusing on different aspects of what makes thresholds difficult to overcome. Socio-technical transition studies (STS) scholars examine technological factors and the political power of incumbent industries in assessing whether and how niche technologies can expand to transform technological regimes[27,28,48,58,59]. Economists focus especially on pricing structures and investment decisions as key leverage points[30]. Political scientists study coalitions, normative and institutional change[47,50–53]. All, however, point to similar challenging dynamics captured in our fractal carbon trap. The fractal metaphor is especially helpful because it provides a way to think about the carbon lock-in trap as existing in multiple levels; the threshold for change is determined by both 'local' characteristics and fractal interdependence. Recognition of the fractal nature of lock-in and decarbonization suggests that transformations are not only facilitated or hindered by political-economic factors of the targeted part of the fractal — such as technological change interacting with institutions, incumbent interests, cultures of openness, or price structures that support or hinder market uptake — but also that these factors in one jurisdiction, sector or society interact with similar patterns in other jurisdictions, sectors or societies.

Examples of the fractal carbon trap

Individuals are frequently exhorted to reduce their carbon footprints. However, a growing body of climate politics scholarship demonstrates that individual actions are often overtaken by structural dynamics of other embedded systems[60]. Illustrating micro–macro linkages, for example, Wapner and Willoughby show how banking systems can take money saved when ecologically minded individuals act, such as by switching to LED light bulbs, to generate capital for expansion of ecological destructive activities on a large scale through leveraged lending[61]. When individuals try to move their households over the D_{crit} threshold, they actually make it harder for larger systems to breach that threshold. Meanwhile, a large variety of individual pro-environmental behaviours are overwhelmed by externally driven costs, ranging from relative costs (absent countervailing policies to internalize them) of eco-friendly technologies such as electric cars, to perverse subsidies such as those on fossil fuel extraction, to large distances and time spans that make it hard for individuals to see the connection between their behaviours and environmental consequences[62].

Even large-scale societal commitments to decarbonize under robust national policies encounter fractal trap dynamics. Canada, for example, elected a Liberal government in 2015 with a strong commitment in line with the Paris Agreement, signed shortly after it came to power. It quickly announced a national carbon pricing plan with broad support from an alignment of federal and provincial interests. However, provinces initially on board later pushed back against the tax, with at least three (Ontario, Manitoba and Saskatchewan) launching court challenges. Ontario (the largest province) also cancelled its participation in a cap-and-trade system linked with Quebec and California shortly after the election of a Conservative government in 2018, taking advantage of counter-coalitions against previous energy transition programmes in the province which angered some rural residents opposed to wind power and increased household electricity costs[63,64]. Meanwhile, public support for a national carbon tax hovers around 50%, and fluctuates significantly depending on the province and messaging about policy details such as rebates for households[65]. These political dynamics are typical of the carbon fractal trap in many jurisdictions, where entrenchment and scaling of policies in one location that generate momentum towards the D_{crit} threshold run up against counter-pressures or lack of coordination with other parts of the fractal, absent political conditions to overcome the trap.

Implications for research

The analytical metaphor of the fractal carbon trap suggests that we face two possible worlds. If lock-in is too rigid and interdependent fractal traps too complex, then only a global shock and massive comprehensive response, or simultaneous action across the whole system, can disrupt it and usher in decarbonization. In other words, any efforts to move along the decarbonization trajectory in one part of the fractal would be caught in the trap and stamped out because of the interdependencies and path dependencies in the overarching fractal system. If this condition prevails, then we need to hope for a technological miracle or acknowledge the necessity of unproven engineered planetary responses[66–68].

Our working assumption, however, is that carbon lock-in has enough flexibility for interventions in one part of the fractal system to spread or diffuse[69]. The interdependence that characterizes fractals can be used to spread disruption and create path dependencies around decarbonization more generally. Research and policy should thus be reoriented around questions of how current and future interventions can spur specific target systems to escape the fractal carbon trap and spread transformation through fractal interdependence.

Escaping the fractal carbon trap. Many interventions are making progress towards the D_{crit} threshold, including policies designed to transform the energy mix of entire nation-states, sectoral efforts and non-state initiatives. The following examples illustrate how a fractal lens and attention to the trap can organize research and provide opportunities to test specific explanations for disrupting carbon lock-in and making progress on decarbonization.

Germany's energy transition policy, the Energiewende, is on track to meet ambitious targets for renewables in electricity generation[70–72] and has catalysed much action outside Germany. Whether we consider price of renewable technology or the diffusion of feed-in tariff (FIT) programmes, Germany's intervention has changed the thresholds for decarbonization in multiple parts of the fractal system. For example, the catalytic effects of the 2000 Renewable Energy Sources Act sent strong market signals of increased demand for renewable technologies that created positive policy feedbacks as "renewable energy manufacturers and project developers press[ed] for expanded support policies and international cooperation on market expansion" within and outside Germany[73]. Coalitions of support that started from initial FIT policies in 1990 expanded as benefits accrued from employment growth, public support for active climate policy grew, and large players in the energy market became further incentivized by the 2000 law.

Meanwhile, the FIT model, pioneered by Germany in 1990, diffused from 2 adopters in 1990 to 69 in 2013[74]. Recent empirical studies provide evidence that diffusion occurred owing to emulation, especially within Europe with the adoption of the EU Directive 2001/77/EC, which required member states to set indicative targets for consumption of electricity produced from renewable energy sources.[75] Although the directive only briefly mentions legal and technical support for feeding in new renewable energy sources to grids, emissions reductions achieved by Germany through FIT policies influenced other countries' decisions to adopt FITs[54,73,74].

Or consider Norway's transportation sector. By 2017, following 30 years of aggressive incentives for EVs, 39% of all car sales were electric or hybrid, making Norway the world's most advanced EV market, well ahead of second place Iceland (11.7%) and third place Sweden (6.3%)[76]. This progress towards decarbonization resulted from features of its political economy and cultural circumstances. Since 1988, the government waived EV registration and import taxes, and in 2001 it removed the VAT. Norway also has one of the world's highest fuel taxes, which means considerable savings for non-fossil-operated EVs[77]. Culturally, a series of high-profile events helped to create popular cachet and support for EVs[78]. Government incentive programmes starting in the early 2000s, combined with increased competition from foreign companies from 2009 to 2013, helped to reduce prices, while technological advances in batteries and drive-trains made EVs more energy efficient. Simultaneously, the government began building a network of public charging stations across Norway. In 2017, the government set a non-binding goal of zero sales of fossil-fuel-powered vehicles in Norway by 2025.

Norway's uptake of personal transport EVs is also influencing other parts of the fractal. It actively promotes its policies in forums such as the Nordic EV Summit and is a leader in international initiatives including the transgovernmental Clean Energy Ministerial's Electric Vehicles Initiative[79]. Some of Norway's policies, such as elimination of high vehicle registration taxes and VAT on EVs, are being replicated, for example in Denmark, Iceland and Ukraine, as are incentives such as free charging and discounted road tolls for EVs[80–82]. Meanwhile, existing coalitions in support of EVs and proven benefits to manufacturers and suppliers of batteries within Norway led to national legislation in 2015 requiring all tenders for new passenger ferries to be low- or zero-emission technology. This cross-sector scaling is also evident in aviation, where Avinor, the state-owned operator of Norway's 44 public airports, has pledged that all short-haul flights will be 100% electric by 2040[83].

Moving beyond nation-states, CDP has helped to catalyse normalization of transparency and disclosure around climate risk among corporations. In 2015, CDP had 822 investor signatories, representing US$95 trillion in assets, calling on corporations to disclose and 1,997 respondent corporations, including 70% of the S&P 500 corporations[84]. Although disclosures do not necessarily move these corporations over the D_{crit} threshold, and there is little direct evidence that disclosing firms consistently reduce their emissions[85], a growing normative commitment to carbon disclosure is correlated with climate action for some firms. For instance, in 2010, 19% of Global 500 respondents had made emissions reductions in some or all business activities from specific measures, increasing to

45% of respondents, or 178 companies, in 2011[86]. In 2015, 89% of all respondents had active emissions reduction initiatives, compared with 47% in 2010[84].

CDP's efforts to move corporations towards the D_{crit} threshold contributed to several interdependent effects. Increased disclosure has assisted growth in environmental, social and governance investing. CDP helped develop sustainable finance initiatives including the Portfolio Decarbonization Coalition and supports the work of related initiatives like the Principles for Responsible Investment[87,88]. Further, disclosure facilitated by CDP is connected to the emergence of science-based targets and an increase in corporate carbon pricing[89,90]. Fifteen G20 countries now require public companies to disclose their emissions[91].

Still work to do. Despite examples of progress and proliferation of policies and initiatives, we do not yet know definitively what makes interventions catalytic in the fractal sense — disrupting carbon lock-in in a way that overcomes the carbon trap in both specific locations and more broadly. There is a dearth of individual cases that have breached the D_{crit} threshold, so scholarship must be forward-looking[47].

The fractal metaphor does not independently prescribe solutions to the carbon trap at different levels, as specific decision-making dynamics in any part of the fractal are likely to have unique characteristics. Furthermore, different approaches, such as STS, decarbonization politics and deep decarbonization economics have different explanations and prescriptions for dynamics in the fractal. The value added here is to conceive of the parameters of transformation as defined by a fractal system and recognize the need to understand how fractal interdependence works. Extant literature recognizes how interdependencies reinforce lock-in through mechanisms such as price, leakage, competitive pressures that limit uptake of new technology without interventions or subsidies, culture, and lack of coordination between local and national policies. We know less about how interdependencies can help to overcome lock-in. Some work has started to look at economic interdependence, for example, in the clean energy sector to see how conditions in different parts of the supply chain foster or limit transitions through mechanisms such as policy feedback or cross-national sequencing[53,73,92]. Other work examines policy diffusion and 'modular scaling', in which similar policies or institutional forms (such as spread of city networks and standards for carbon labelling) are taken up in different parts of the system[39,93].

The global fractal metaphor also opens new avenues of research on some of the biggest practical questions in climate policy, such as the importance of economy-wide policies (for example, carbon pricing) versus sector-specific policies, or how to orchestrate the relationship between local, national and global policies. The fractal perspective suggests reframing the question of economy-wide versus sectoral policies to one that asks about the relationship between them. Similarly, it suggests shifting the focus in multilevel climate policy from one of jurisdictional competencies and interactions to also include questions of scaling and coalition building that expand populations of support across levels[50].

A double trap. No matter the specific direction of research, studies will need to account for a troubling empirical pattern that is revealed by the fractal carbon trap approach. Multiple interventions show evidence of moving systems out of high carbon lock-in to some degree, but well short of functional decarbonization. Although there exists no definitive database of policy interventions, many interventions aim to improve the efficiency of systems without generating full decarbonization, from switching to natural gas as a lower-emission 'bridge fuel' to carbon market schemes with prices much too low to generate real momentum towards decarbonization.

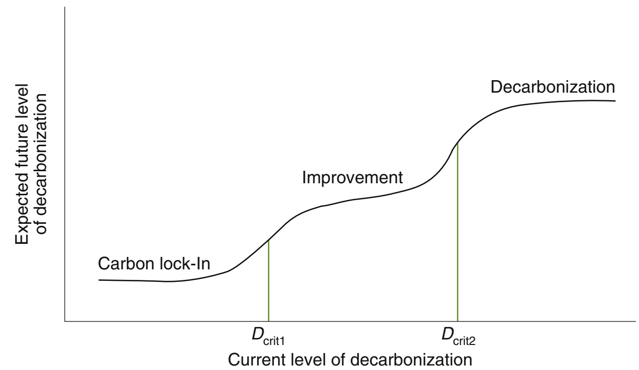

Fig. 3 | The double trap. Visual representation of the potential trajectory of a specific targeted system in the fractal with three attractors — carbon lock-in, improvement and decarbonization. D_{crit1} and D_{crit2} are the threshold points at the boundaries between attractors.

Decarbonization trajectories are probably not fully captured by a two-attractor state space. Rather, the fractal carbon trap frequently exhibits three attractors (Fig. 3): high carbon lock-in, more efficient carbon lock-in or improvement, and decarbonization. Some climate efforts may generate emissions reductions but also generate dynamics that get systems stuck in the improvement attractor. Bridge fuel policies that promote natural gas as an alternative to coal will reduce emissions, assuming methane leakage is addressed. However, they may also entrench industrial interests that oppose moves towards deeper decarbonization, which cannot include natural gas[94]. Similarly, individual nudging efforts have been shown to decrease public support for broader policies such as carbon pricing, as people believe they have done enough[95].

The German case is again instructive. Recent internal and external evaluations highlight that despite progress on its share of renewables, Germany will fall well short of its 2020 emission targets, and 2030 targets will be a considerable challenge[70–72]. The stalling of the Energiewende fits the double trap pattern. The pricing structure of renewable energy — guaranteed under Germany's FIT programme — meant that energy-intensive manufacturers received exemptions from the surcharge on renewable energy costs, shifting high costs to households. Meanwhile, several pricing and policy dynamics, like the shale gas revolution outside Germany and the decision to phase out nuclear power within Germany, led to coal becoming the cheapest source of energy in Germany, thus increasing demand and, subsequently, the extension of coal-fired power plants[72], undermining a deeper transition.

Similarly, the Norwegian EV case shows signs of the double trap. While average emissions for new cars decreased nearly 40% between 2010 and 2016 as the share of EVs grew[96], absolute emissions in the transportation sector as a whole increased by 26% from 1990 to 2018, including a 2.8% increase in 2017–2018, which suggests that the trend is not reversing. Moreover, transportation is the third biggest source of emissions in Norway[97]. Although emissions growth is partly owing to modest population increases and the lag time of changing a country's fleet of vehicles, interactive cultural and political economy factors also may be stalling Norway in the improvement attractor. At the household level, EVs in Norway are typically second vehicles, resulting in greater distances travelled than households with a single fossil-fuel-powered car[98]. Meanwhile, EV policies are expensive, increasing the costs to the state which also relies heavily on rents from offshore oil production. In 2018, the government projected EV-related tax incentives of three billion NOK[99]. Thus, even as cost decreases, infrastructure improves, and increased battery ranges encourage decreases in absolute ground-based emissions, getting to full decarbonization requires greater attention to interactive effects with other parts of the fractal system. Confidence that Norway's transport sector is escaping the double trap requires more evidence that EVs are maintaining momentum to fully replace gas-powered transport rather than becoming a small to medium and stable percentage of transport. Evidence of crossing D_{crit2} would indicate the momentum in the system accelerating towards zero fossil-fuel-powered transport. Future work might develop specific indicators for the thresholds and hypotheses on conditions under which they are crossed.

The double trap may be the most pernicious revelation of a fractal metaphor because things seem better… and they are, but not better enough, as recent research on policy mixes and emissions trajectories suggests[100]. In a political context in which achieving significant climate action can be difficult, scholars have rightly focused on the necessary conditions for initiating action. However, our analysis indicates that they should also give thought to how and under what conditions action can be ramped up following initial improvements, and how fractal interdependence can play a role in so doing. Which improvements — bridge fuels, energy efficiency, renewable portfolios — lead systems to get stuck or lay the foundation for deeper decarbonization is an empirical question. Thus, in addition to political victories around individual policies, more knowledge is needed on which policies provide the greatest leverage points for overcoming the second threshold to decarbonization and how to foster them to support broader transformation.

Implications for climate politics

The fractal metaphor also has implications for action. First, politics matters. In all our examples, technologies of decarbonization such as EVs and renewable energy systems were available but encountered fractal interdependencies that dampened transformation. Consistent with the most recent wave of findings in the STS literature on diffusion and scaling[48], our metaphor facilitates recognition and analysis of how technological interventions must flow through the fractal trap structure where political dynamics loom large.

Second, re-thinking is warranted around which catalytic interventions to incentivize and how to value them. Hypothetical emissions reduction potentials matter less than whether the initiatives scale and entrench and do so in ways that overcome the double trap[16,93]. Valuing emissions reduction potentials in isolation can miss indicators of whether reductions are short term and reversible or likely to be durable, and can also miss the conditions needed to leverage changes that drive systems towards decarbonization. Policymakers should also pay attention to how interventions influence the energy mix trajectory of their targets, assess normative and institutional change, and consider the intended and unintended connections between efforts to disrupt carbon lock-in in different parts of the fractal. The latter means considering how one initiative influences the thresholds and trajectories of other systems when valuing interventions.

Third, fractal interdependencies extend beyond initiatives specifically aimed at addressing climate change. Nearly all policymaking across economic, social and environmental dimensions has implications for a climate-constrained world. This insight resonates with the thinking behind the 2015 Sustainable Development Goals, which not only include a climate change goal, but also are underpinned by the notion that implementation requires integration of the three dimensions of sustainable development[101]. The fractal metaphor implies that mainstreaming and integrating climate efforts across policy areas, and assessing the decarbonization ramifications, both positive and negative, of all policies and activities, are of crucial importance.

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References

1. Shimko, K. L. Metaphors and foreign policy decision making. *Polit. Psychol.* **15**, 655–671 (1994).
2. Hajer, M. A. *The Politics of Environmental Discourse: Ecological Modernization and the Policy Process* (Clarendon, 1995).
3. Schlesinger, M. & Lau, R. R. The meaning and measure of policy metaphors. *Am. Polit. Sci. Rev.* **94**, 611–626 (2000).
4. Lakoff, G. & Johnson, M. *Metaphors We Live By* (Univ. Chicago Press, 1980).
5. Bougher, L. D. The case for metaphor in political reasoning and cognition. *Polit. Psychol.* **33**, 145–163 (2012).
6. Shaw, C. & Nerlich, B. Metaphor as a mechanism of global climate change governance: a study of international policies, 1992–2012. *Ecol. Econ.* **109**, 34–40 (2015).
7. Keohane, R. O. & Victor, D. G. Cooperation and discord in global climate policy. *Nat. Clim. Change* **6**, 570–575 (2016).
8. Barrett, S. *Environment and Statecraft* (Oxford Univ. Press, 2003).
9. Peters, S. Beyond carbon budgets. *Nat. Geosci.* **11**, 378–380 (2018).
10. Geden, O. Politically informed advice for climate action. *Nat. Geosci.* **11**, 380–383 (2018).
11. Victor, D. G. *Global Warming Gridlock: Creating More Effective Strategies for Protecting the Planet* (Cambridge Univ. Press, 2011).
12. Depledge, J. The opposite of learning: ossification in the climate change regime. *Glob. Environ. Polit.* **6**, 1–22 (2006).
13. Falkner, R. The Paris agreement and the new logic of international climate politics. *Int. Aff.* **92**, 1107–1125 (2016).
14. Beiser-McGrath, L. F. & Bernauer, T. Commitment failures are unlikely to undermine public support for the Paris agreement. *Nat. Clim. Change* **9**, 248 (2019).
15. Mildenberger, M. Support for climate unilateralism. *Nat. Clim. Change* **9**, 187–188 (2019).
16. Hsu, A. et al. A Research roadmap for quantifying non-state and subnational climate mitigation action. *Nat. Clim. Change* **9**, 11–17 (2019).
17. Hale, T. *The Role of Sub-State and Nonstate Actors in International Climate Processes* Research Paper (Chatham House, 2018).
18. Unruh, G. C. Understanding carbon lock-in. *Energy Policy* **28**, 817–830 (2000).
19. Seto, K. C. et al. Carbon lock-in: types, causes, and policy implications. *Annu. Rev. Environ. Resour.* **41**, 425–452 (2016).
20. Farmer, J. D. et al. Sensitive intervention points in the post-carbon transition. *Science* **364**, 132–134 (2019).
21. Duit, A. & Galaz, V. Governance and complexity — emerging issues for governance theory. *Governance* **21**, 311–335 (2008).
22. Bak, P. & Creutz, M. in *Fractals in Science* (eds Bunde, A. & Havlin, S.) 27–48 (Springer, 1994).
23. Barrett, C. B. & Swallow, B. M. Fractal poverty traps. *World Dev.* **34**, 1–15 (2006).
24. Chettiparamb, A. Complexity theory and planning: examining 'fractals' for organising policy domains in planning practice. *Plann. Theor.* **13**, 5–25 (2013).
25. De Florio, V. et al. Models and concepts for socio-technical complex systems: towards fractal social organizations. *Syst. Res. Behav. Sci.* **30**, 750–772 (2013).
26. Perey, R. Organizing sustainability and the problem of scale: local, global, or fractal? *Organ. Environ.* **27**, 215–222 (2014).
27. Meadowcroft, J. What about the politics? Sustainable development, transition management, and long term energy transitions. *Policy Sci.* **42**, 323–340 (2009).
28. Geels, F. W. Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective. *Res. Pol.* **39**, 495–510 (2010).
29. Princen, T., Manno, J. P. & Martin, P. L. (eds) *Ending the Fossil Fuel Era* (MIT Press, 2015).
30. *Pathways to Deep Decarbonization* (SDSN, 2014); http://deepdecarbonization.org
31. Bulkeley, H. A. et al. *Transnational Climate Change Governance* (Cambridge Univ. Press, 2014).
32. Jordan, A., Huitema, D., Van Asselt, H. & Forster, J. (eds) *Governing Climate Change: Polycentricity in Action?* (Cambridge Univ. Press 2018).
33. Widerberg, O. & Stripple, J. The expanding field of cooperative initiatives for decarbonization: a review of five databases. *WIREs Clim. Change* **7**, 486–500 (2016).
34. Overdevest, C. & Zeitlin, J. Assembling an experimentalist regime: transnational governance interactions in the forest sector. *J. Gov. Regul.* **8**, 22–48 (2014).
35. De Búrca, G., Keohane, R. O. & Sabel, C. Global experimentalist governance. *Br. J. Polit. Sci.* **44**, 477–486 (2014).
36. Bulkeley, H. & Castán Broto, V. Government by experiment? Global cities and the governing of climate change. *Trans. Inst. Br. Geogr.* **38**, 361–375 (2013).
37. Hoffmann, M. *Climate Governance at the Crossroads: Experimenting with a Global Response after Kyoto* (Oxford Univ. Press, 2011).

38. Romero-Lankao, P. et al. Urban transformative potential in a changing climate. *Nat. Clim. Change* **8**, 754 (2018).
39. Betsill, M. & Bulkeley, H. Looking back and thinking ahead: a decade of cities and climate change research. *Local Environ.* **12**, 447–456 (2007).
40. Rabe, B. G. *Can We Price Carbon?* (MIT Univ. Press, 2018).
41. Webb, M. *Smart 2020: Enabling the Low Carbon Economy in the Information Age* (The Climate Group, 2008).
42. Lade, S., Hader, J., Engström, J. & Schlüter, M. Resilience offers escape from trapped thinking on poverty alleviation. *Sci. Adv.* **3**, e1603043 (2017).
43. Geroski, P. A. Models of technology diffusion. *Res. Policy* **29**, 603–625 (2000).
44. Kauffman, S. *At Home in the Universe: The Search for the Laws of Self-organization and Complexity* (Oxford Univ. Press, 1996).
45. Juarrero, A. Dynamics in action: intentional behavior as a complex system. *Emergence* **2**, 24–57 (2000).
46. Levin, S. et al. Social-ecological systems as complex adaptive systems: modeling and policy implications. *Environ. Dev. Econ.* **18**, 111–132 (2013).
47. Levin, K., Cashore, B., Bernstein, S. & Auld, G. Overcoming the tragedy of super wicked problems: constraining our future selves to ameliorate global climate change. *Policy Sci.* **45**, 123–152 (2012).
48. Newell, P. Trasformismo or transformation? The global political economy of energy transitions. *Rev. Int. Pol. Econ.* **26**, 25–48 (2018).
49. Geels, F. W. Regime resistance against low-carbon transitions: introducing politics and power into the multi-level perspective. *Theory Cult. Soc.* **31**, 21–40 (2014).
50. Bernstein, S. & Hoffmann, M. The politics of decarbonization and the catalytic impact of subnational experiments. *Policy Sci.* **51**, 189–211 (2018).
51. Meckling, J., Kelsey, N., Biber, E. & Zysman, J. Winning coalitions for climate policy. *Science* **349**, 1170–1171 (2015).
52. Breetz, H., Mildenberger, M. & Stokes, L. The political logics of clean energy transitions. *Bus. Polit.* **20**, 492–522 (2018).
53. Green, F. Anti-fossil fuel norms. *Climatic Change* **150**, 103–116 (2018).
54. Buschmann, P. & Oels, A. The overlooked role of discourse in breaking carbon lock-in: the case of the German energy transition. *WIREs Clim. Change* **574**, https://doi.org/10.1002/wcc.574 (2019).
55. Boisvert, N. Metrolinx removes electric vehicle chargers from GO station parking lots. *CBC* go.nature.com/30MeHu7 (10 January 2019).
56. Benzie, R. Tesla wins lawsuit against Ontario government over phase-out of electric vehicle incentives. *The Star* go.nature.com/30WUiCl (27 August 2018).
57. Gorzelaney, J. Here's which automakers will suffer if Trump ends electric car tax credits. *Forbes* go.nature.com/2LSshHP (10 December 2018).
58. Andrews-Speed, P. Applying institutional theory to the low-carbon energy transition. *Energy Res. Soc. Sci.* **13**, 216–225 (2016).
59. Lockwood, M., Kuzemko, C., Mitchell, C. & Hoggett, R. Historical institutionalism and the politics of sustainable energy transitions: a research agenda. Environ. *Plann. C* **35**, 312–333 (2017).
60. Maniates, M. F. Individualization: plant a tree, buy a bike, save the world? *Glob. Environ. Polit.* **1**, 31–52 (2001).
61. Wapner, P. & Willoughby, J. The irony of environmentalism: the ecological futility but political necessity of lifestyle change. *Ethics Int. Aff.* **19**, 77–89 (2005).
62. DeSombre, E. *Why Do Good People Do Bad Environmental Things?* (Oxford Univ Press, 2018).
63. Stokes, L. C. The politics of renewable energy policies: the case of feed-in tariffs in Ontario, Canada. *Energy Policy* **56**, 490–500 (2013).
64. Miner, J. The Mainstreet Research survey suggests an even split in public opinion about Ontario's embrace of wind energy. *The London Free Press* go.nature.com/2Mixloc (8 June 2016).
65. Carbon pricing: rebate announcement tips opinion in favour of federal plan, slim majority now support it. *Angus Reid Institute* go.nature.com/2MlVIB7 (1 November 2018).
66. Keith, D. W. Geoengineering. *Nature* **409**, 420 (2001).
67. Keith, D. W., Wagner, G. & Zabel, C. L. Solar geoengineering reduces atmospheric carbon burden. *Nat. Clim. Change* **7**, 617 (2017).
68. Givens, J. E. Geoengineering in context. *Nat. Sustain.* **1**, 459 (2018).
69. Bennett, E. M. et al. Bright spots: seeds of a good Anthropocene. *Front. Ecol. Environ.* **14**, 441–448 (2016).
70. Wettengel, J. Climate goal failure warrants high Energiewende priority — gov advisors. *Clean Energy Wire* go.nature.com/2nnS5Cj (27 June 2018).
71. *Sixth 'Energy Transition' Monitoring Report: The Energy of the Future. Reporting Year 2016 — Summary* (German Federal Ministry of Economic Affairs and Energy, 2018); go.nature.com/30ZlJfa
72. Cunningham, T., Hedberg, A., Nazakat, S. & Yao, L. *Assessing the Energiewende: An International Expert Review* (Konrad Adenaeur Stiftung, 2018); go.nature.com/2LVgGru
73. Meckling, J. (2019). Governing renewables: policy feedback in a global energy transition. *Environ. Plann. C.* **37**, 317–338 (2018).
74. Alizada, K. Rethinking the diffusion of renewable energy policies: a global assessment of feed-in tariffs and renewable portfolio standards. *Energy Res. Soc. Sci.* **44**, 346–361 (2018).
75. Boasson, E. Constitutionalization and entrepreneurship: explaining increased EU steering of renewables support schemes. *Polit. Gov.* **7**, 70–80 (2019).
76. *Global EV Outlook 2018* (IEA, 2018); https://www.iea.org/topics/transport/evi/
77. Figenbaum, E. & Kolbenstvedt, M. *Electromobility in Norway — Experiences and Opportunities with Electric Vehicles* (Transportøkonomisk Institutt, 2013).
78. Charles, D. A small spark from Bellona fuels Norway's eco-friendly car explosion. *Bellona Foundation* go.nature.com/2IucEEy (8 January 2018).
79. Clean Energy Ministerial *EV30@30 Campaign* (IEA, 2017).
80. *Danish Motor Vehicle Taxes* (Danish Ecological Council, no date).
81. Electric vehicles summit 2019 in Norway: Ukraine is learning from the leaders. *NUCC* go.nature.com/2IrqS91 (22 March 2019).
82. Wappelhorst, S. & Tietge, U. Iceland is one of the world's most interesting electric vehicle markets. *ICCT* https://www.theicct.org/blog/staff/iceland-ev-market-201807 (9 July 2019).
83. Lemphers, N. *Rolling the Snowball: Norway's Efforts to Electrify Transportation* Working Paper 19-2 (EGL, 2019).
84. *Global Climate Change Report 2015* (CDP, 2015); go.nature.com/30Pbr13
85. Tang, S. & Demeritt, D. Climate change and mandatory carbon reporting: Impacts on business process and performance. *Bus. Strategy Environ.* **27**, 437–455 (2017).
86. *Global 500 Report 2011* (CDP, 2011); go.nature.com/2AM24o6
87. PRI, ICGN launch discussion paper on corporate ESG reporting. *PRI* go.nature.com/2pSAhAh (18 October 2018).
88. Portfolio Decarbonization Coalition *United Nations Environment Program* https://www.unepfi.org/climate-change/pdc/ (no date).
89. Commit to adopt a science-based emissions reduction target to generate the innovations needed to transition to a low-carbon, sustainable economy. *CDP* https://www.cdp.net/en/campaigns/commit-to-action/science-based-targets (no date).
90. *Putting a Price on Carbon* (CDP, 2017); go.nature.com/2Me2RDu
91. *Climate Change Disclosure in G20 Countries* (OECD, 2015); go.nature.com/2ViSoLp
92. Pahle, M. et al. Sequencing to ratchet up climate policy stringency. *Nat. Clim. Change* **8**, 861–867 (2018).
93. van der Ven, H. et al. Valuing the contributions of nonstate and subnational actors to climate governance. *Glob. Environ. Polit.* **17**, 1–20 (2017).
94. Betsill, M. & Stevis, D. The politics and dynamics of energy transitions: lessons from Colorado's 'new energy economy'. *Environ. Plann. C* **24**, 381–396 (2016).
95. Hagmann, D., Ho, E. H. & Loewenstein, G. Nudging out support for a carbon tax. *Nat. Clim. Change* **9**, 484–489 (2019).
96. Johnsen, T. J. *Norway's Electric Vehicle Policies* (Environment Oslo, 2017).
97. *Emissions to Air* (Statistisk sentralbyrå, 2018); https://www.ssb.no/en/klimagassn
98. Klöckner, C. A., Nayum, A. & Mehmetoglu, M. Positive and negative spillover effects from electric car purchase to car use. *Transp. Res. D* **21**, 32–38 (2013).
99. Knudsen, C., Doyle, A. Norway powers ahead (electrically): over half new car sales now electric or hybrid. *Reuters* (3 January 2018).
100. Le Quere, C. et al. Drivers of declining CO_2 emissions in 18 developed economies. *Nat. Clim. Change* **9**, 213–217 (2019).
101. Stafford-Smith, M. et al. Integration: the key to implementing the Sustainable Development Goals. *Sustain. Sci.* **12**, 911–919 (2017).
102. Haley, B. From staples trap to carbon trap: Canada's peculiar form of carbon lock-in. *Stud. Polit. Econ.* **88**, 97–132 (2011).

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Additional information
Correspondence should be addressed to S.B. or M.H.

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