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Policy sequencing toward decarbonization

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Many economists have long held that carbon pricing—either through a carbon tax or cap-and-trade—is the most cost-effective way to decarbonize energy systems, along with subsidies for basic research and development. Meanwhile, green innovation and industrial policies aimed at fostering low-carbon energy technologies have proliferated widely. Most of these predate direct carbon pricing. Low-carbon leaders such as California and the European Union (EU) have followed a distinct policy sequence that helps overcome some of the political challenges facing low-carbon policy by building economic interest groups in support of decarbonization and reducing the cost of technologies required for emissions reductions. However, while politically effective, this policy pathway faces significant challenges to environmental and cost effectiveness, including excess rent capture and lock-in. Here we discuss options for addressing these challenges under political constraints. As countries move toward deeper emissions cuts, combining and sequencing policies will prove critical to avoid environmental, economic, and political dead-ends in decarbonizing energy systems.

Economists widely agree that carbon pricing is the most cost-effective strategy for decarbonizing energy systems[1]. Some also suggest that subsidies for basic research are part of optimal policy[2]. Subsidizing the deployment of low-carbon technologies is considered a costly second-best policy by many economists, though not all[3,4]. Yet policies that support technology deployment are the most widely adopted form of actual low-carbon policy; politics favours these policies.

Regulating carbon emissions through direct pricing often faces major political obstacles. The benefits of carbon pricing are diffuse, hard to measure, and lie in the future, while their costs are concentrated and immediate. Meanwhile, green innovation and industrial policies promoting both the development and deployment of low-carbon technologies have proliferated widely. These policies bolster clean-energy industries and reduce the cost of low-carbon technologies[5], thus building political support for regulatory policy such as carbon pricing[6]. In fact, most of these direct deployment subsidies and various other forms of financial support predate direct carbon pricing. Low-carbon leaders such as California and the EU developed low-carbon policy suites through a three-stage sequence: early moves in the form of green innovation and industrial policies; adding direct carbon pricing; and ratcheting up the policy suite over time (Fig. 1).

This suggests a case for deliberate sequencing of policies to enable the low-carbon energy transition. Such steps face their own major challenges, in particular around cost-effectiveness, excessive rent-seeking by those receiving subsidies, and costly lock-in. In this Perspective, we integrate economic and political approaches to low-carbon policy and discuss how policymakers can address the challenges of environmental and cost effectiveness under political constraints.

Sequencing and the politics of decarbonization

In low-carbon policy mixes, green industrial policy has been adopted much more widely than carbon pricing and has mostly predated carbon pricing. In particular, the cases of California and the EU suggest that policymakers initially supplied benefits to clean-energy constituencies before imposing costs on polluters.

From benefits to costs in policy sequencing. There is no one green industrial policy. Instead, such policy often entails a portfolio of different instruments, including support for research and development, subsidies, tax rebates, loan guarantees, and direct mandates for renewable energy[7]. In terms of economic efficiency, such policies are often considered second best compared to carbon pricing[8]. They also vary considerably in their scope and ambition across countries[9]. In the power sector, at least 132 countries and subnational jurisdictions, such as states and provinces, had enacted either a feed-in tariff or a renewable portfolio standard by 2014. In the transport sector, 99 countries and subnational entities had adopted either mandates for biofuels or incentives for electric vehicles by 2014.

Carbon-pricing policy has been spreading globally since 2003, when the EU Emission Trading System (EU ETS) was adopted. In total, 54 carbon-pricing systems have been implemented or are scheduled for implementation, making it much less prevalent than green industrial policies. Prices have been relatively low, with 85% of covered emissions being priced at under US$10 per tonne of CO_2-equivalent emissions in 2014 (ref. [10]). Regulatory climate policy also includes command-and-control regulation such as efficiency standards and outright bans of carbon-intensive fuels such as coal. Anecdotal evidence on greenhouse gas standards for vehicles in the EU and the US suggests a similar policy sequence.

In the electricity sector, green industrial policy precedes carbon pricing in two-thirds of all cases (Table 1). The majority of outliers fall into two categories: countries that joined the EU after it had adopted carbon pricing, or Scandinavian countries that adopted carbon-pricing systems in the early 1990s (ref. [6]). In the transport sector, green industrial policy preceded carbon pricing in 58% of all cases. Only a few countries have started officially to price carbon emitted from transport fuel use. The majority are Scandinavian countries that did so in the early 1990s, building on earlier regulatory efforts related to local air pollution concerns and in response to the 1973 oil embargo and price shock. These and many other European countries also had pre-existing, very high fuel taxes. Out of the countries and states that have started to price

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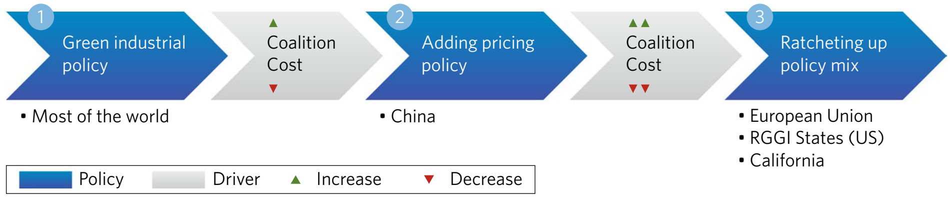

Fig. 1 | California and the EU have moved through three stages in developing low-carbon policies. First, they have adopted green innovation and industrial policies. Most of the world is currently at this stage. These initial policies have helped grow political support coalitions and reduce the cost of low-carbon technologies (green arrows indicate growth, red arrows indicate decline). Second, they have developed carbon-pricing policies. China, for example, is currently at this stage of low-carbon policy development. Third, California and the EU have reformed their pricing policies with an eye toward increasing their environmental effectiveness, responding to growing political support and continuing drops in the cost of low-carbon technologies. Regional Greenhouse Gas Initiative (RGGI) states have also gone through this third stage of ratcheting up.

carbon emissions from transport since 2000, 78% had adopted green industrial policy previously. It is symptomatic that the world leader in carbon taxation, Sweden, has no significant fossil resources or companies that would provide significant lobbying resistance against such taxes.

The EU offers a prime example of this policy sequence. The EU adopted rules on promoting renewable energies in 2001, after eight member states had already implemented renewable-energy support schemes. This occurred in the context of the liberalization of electricity markets across Europe. The EU followed up with industrial policy for renewable fuels in the transport sector in 2003. In a second phase, the EU adopted carbon pricing in 2003, which entered into force in 2005. In a third phase, the EU's decarbonization efforts led to a ratcheting up of all measures in the 2020 Climate and Energy Package of 2009, the 2030 Climate and Energy Package of 2014, and the recent EU winter package of 2016. California followed a path similar to that of the EU[11]. China is on its way to replicate the policy path of climate leaders: in the mid-2000s, it adopted supply-side industrial policy to develop clean-energy industries, followed by feed-in tariffs that fostered domestic demand for renewable energy, leading to a domestic carbon pricing system in the energy sector to be implemented in 2017 (ref. [12]).

Growing low-carbon interests and reducing technology cost. Research on low-carbon policy in Europe and California suggests two drivers for the benefits-to-costs policy sequence in domestic low-carbon policy. One driver is the growth of low-carbon interests that support the decarbonization of the economy. Another is declining technology costs, which can increase the political acceptance of direct carbon regulation.

First, government support for the deployment of low-carbon energy technologies provides economic rents to low-carbon energy providers[13]. This creates economic constituencies that support the expansion of low-carbon policy, including carbon pricing. In particular, high-leverage policy measures such as feed-in tariffs that result in capital investments in clean-energy infrastructure create new interest groups[14]. Economic rents through government support for new technologies then help to create and grow a clean-energy industrial complex[15]. Germany, for example, leveraged its existing industrial technology base to develop renewable energy industries that supported the country's energy transition[16]. The emergence of clean-energy interests is supported by the liberalization of electricity markets, which often goes hand-in-hand with the adoption of renewable energy policies[17]. Liberalization can enable new independent power producers, often younger companies focused on clean energy, to enter the market[18]. Creating such a counterweight helps to resist the lobbying pressure of vested interests locking the energy system into high-carbon technologies[19].

Second, early investments in renewable energy technologies—supported by government incentives—can help technologies travel up the learning curve and down the cost curve, as in the case of solar photovoltaic modules, whose prices have declined by over 80% since 2008 (refs [5,20,21]). Thus, green innovation and industrial policy help reduce the cost of emissions cuts[20]. Importantly, while investments in research and development are crucial to achieve technological innovation and cost reductions, large-scale deployment has been shown to contribute significantly to bringing down costs of renewable energy technologies through economies of scale and active learning-by-doing processes[22,23]. California's solar initiative subsidizing solar photovoltaic deployment was a success precisely because it helped capture the positive learning-by-doing externality, and it was phased down quickly in line with economic theory[23].

Reduced abatement costs may then lower the barrier for policymakers to adopt regulatory policies. In particular, lower mitigation costs may reduce the opposition to carbon policy from energy consumers such as households and energy-intensive manufacturers[24]. Competitiveness in energy-intensive manufacturing has traditionally been one of the largest political hurdles to passing carbon policies, as costs are concentrated among a few industries[25]. Renewable energy support policy also shifts some compliance costs outside the emissions trading scheme[26]. This, in turn, may have helped limit opposition to emissions trading from regulated entities in the EU.

If a benefits-to-costs policy sequence can help overcome major political hurdles in decarbonization given the experience of the EU and California, how can we then address environmental effectiveness and cost-effectiveness within these political constraints?

Green innovation and industrial policy

Initial government support for low-carbon energy technologies faces two enduring challenges: avoiding the lock-in of sub-optimal low-carbon technologies, and maintaining the support for government investment in low-carbon technologies.

First, technology-specific industrial policy creates constituencies that lobby for continuous support, potentially resulting in costly political lock-in that mirrors the lock-in now endemic with fossil fuels[27]. Consider corn ethanol markets: US biofuel mandates have created a market for corn-based biofuels, while the environmental benefits of current biofuel supply chains remain doubtful. Yet vested interests ensure that costly and ineffective subsidies remain in place.

We identify three ways to tie deployment-focused industrial policy to emissions reductions. A first option is to embed any climate policy measures in long-term decarbonization plans, as, for instance, developed by the Deep Decarbonization Pathways Project[28]. These roadmaps provide an outlook on what kinds of technologies we know about today that could lead to deep emissions reductions. A second possibility is to tie government incentives for low-carbon technologies to efficiency improvements or outright

Table 1 | Policy sequencing in power and transport sectors (numbers of jurisdictions)

	Green industrial policy	Carbon pricing	Green industrial policy preceding carbon pricing[a]
Power	132	52	65–86%
Transport	99	12	58–95%

Green industrial policy: in the power sector, this includes renewable portfolio standards or feed-in tariffs; in the transport sector, this includes biofuel mandates or electric vehicle incentives. In terms of carbon pricing, this includes carbon tax or cap-and-trade systems. Data: authors own. [a]Lower bound of range calculates ratio based on existing carbon-pricing systems; upper bound accounts for potential of carbon pricing to appear in jurisdictions that currently have adopted green industrial policies.

emissions reductions. Japan's 'Top Runner' policy, which subsidizes clean technologies by creating automatic market share for the best technology in any particular area, employs this strategy[29]. Policy instruments such as *bonus malus*—an approach involving subsidies for the environmentally preferred technology and fees for the inferior one—can be designed to have similar effects. A final option is to incentivize diversity and experimentation in technological trajectories to mitigate uncertainty in technology development[30]. Tesla's large-scale investment in lithium-ion batteries may help reduce the cost of storage significantly, but could potentially crowd out more advanced competitor technologies. Government procurement policies that require specific niche technologies could create protected markets that would allow for the continued existence of competing—and potentially more advanced—technologies[31].

Second, while in many instances governments expanded renewable energy policy[32], government subsidies run the risk of premature cutbacks or outright reversals, as occurred, for instance, in Australia, Spain, and several US states. The economically optimal approach to technology support is to offer early high subsidies that can be pulled back almost immediately[2,4]. In practice, the timing of that cutback matters. Pulling back subsidies when no longer justified by learning-by-doing externalities is welcome, while pullbacks for solely political reasons are not.

Consumer and industry backlash may drive policy cutbacks. For consumers, green industrial policy can result in rising electricity costs. The cutbacks in Spain's feed-in tariff are largely a result of cost-related consumer pushback, exacerbated by a fiscal and public debt crisis[33]. Incumbent industries may resist low-carbon policies that include regulatory costs and loss of market share, as electric utilities in some US states did when they blocked or reversed expansion of renewable portfolio standards and net metering systems.

Countering politically motivated cutbacks requires communication of the benefits of clean energy, lobbying through political action committees, reform of utility regulators, and progressive electricity payment structures[34]. Cost-effective policy designs are also important. If clean-energy subsidies provide excessive rents to firms, taxpayers bearing the costs may reasonably vote against them. Cost-effective designs of green innovation and industrial policies vary widely across geography and time and across low-carbon technologies[35,36]. European countries, for instance, adjusted their early feed-in tariff systems to provide more flexibility and lower costs via features such as auctioning. Such adjustments may be critical for the political sustainability of clean-energy support schemes.

As renewables expand, maintaining political support needs to extend from subsidies to policies that increase the flexibility of energy systems. The intermittent and decentralized nature of renewable energy requires policy support for new flexibility options, including energy storage, grid interconnection, and demand side response[37].

Adding pricing policies

Policies such as feed-in tariffs and other clean-energy support instruments tend to require high initial costs. Furthermore, they offer little guarantee of emissions cuts[3,38]. Adding pricing policies can improve the environmental and cost-effectiveness of low-carbon policy mixes. This requires managing potential costly and, in part, counterproductive interaction effects with existing subsidies[39,40].

Politically, carbon pricing is a tall order. Failed attempts abound[41,42]. History suggests that early adopters of carbon pricing were countries that introduced high fuel taxes. In those countries, political actors from producers to consumers to treasuries have become accustomed to pricing instruments[43]. Moreover, the balance of power between economic winners and losers plays a particular role. Governments that have introduced carbon-pricing systems promoted green industries prior to pricing carbon, thus fostering a supportive economic constituency[44]. In California, progressive tightening of environmental regulation and early climate policy nurtured a powerful constituency of sunrise industries that successfully opposed Proposition 23 in 2010, a referendum that attempted to suspend the state's landmark Global Warming Solutions Act[11,45]. In fact, while the US federal Waxman–Markey, a proposal for a federal cap-and-trade system, featured fossil-fuel interests that outspent environmental interests by a ratio of 7-to-1 (ref. [46]), Californian environmental interests outspent fossil fuel interests by 3-to-1 (ref. [47]) in battling Proposition 23.

In addition to supporting low-carbon energy constituencies, policymakers have accommodated the demands of emitters to overcome opposition to carbon pricing[48]. Emitters are often large and concentrated players that have the political influence to block regulatory action[49]. Policymakers take various approaches to compensating potential losers, including free allocation of allowances and re-allocation of allowance auction or tax revenue[50]. Free allocation of allowances can be targeted to transfer economic rents to particular industries, while a full auctioning of allowances would reward cleaner sectors. Free allocation, thus, has been a key strategy for mitigating political opposition in the EU and California systems[42,51]. The allowance allocation design of Waxman–Markey reflected a similar influence of emitters[24]. Free allocation shifts interest-group politics from opposition to the policy to a competition over the valuable allowances[52].

Carbon taxes, too, can be designed to accommodate business interests otherwise hostile toward carbon pricing. The revenue neutrality of the British Columbia carbon tax led to a net tax reduction, with reductions in corporate and income taxes for specific sectors[53]. Similarly, the Swedish carbon tax, which has been the highest in the world since its inception in 1991, was coupled with fundamental tax reform and significant reductions in income, wealth, property, and inheritance taxes. The overall tax burden was reduced, and the suite of reforms arguably managed to increase economic efficiency while proving palatable to a majority of the electorate.

Ratcheting up the policy mix

With the prominent exceptions of a few Scandinavian carbon taxes and some EU fuel taxes, most early carbon pricing systems had a limited effect in reducing emissions or inducing innovation[54,55]. They served mainly as backstop measures to avoid a sliding back of emissions reductions earned through clean-energy policies or market forces. The EU ETS, the Regional Greenhouse Gas Initiative (RGGI), and California's emissions trading system (CA ETS) have gone through major internal reforms leading to increased efforts to reduce emissions[54,56] (Fig. 1). How do we ensure that policy suites will lead to greater ambition for carbon mitigation over time?

While cultivating green economic constituencies is politically crucial to strategically tightening regulations, these industries may prefer the continuation and expansion of subsidies over carbon pricing. Subsidies provide more direct and concentrated benefits to low-carbon firms than does carbon pricing. The challenge for smart policy design is, then, to tie the demand of low-carbon energy firms for more subsidies to the expansion of carbon pricing systems. Tying green subsidies to revenues from a carbon tax or auctions in cap-and-trade systems gives low-carbon energy firms direct incentive to support a tightening of carbon prices[41,57,58]. In fact, RGGI's first 23 auctions raised US$1.66 billion, which was largely given out as grants for renewable energy and efficiency measures. This contributed to tightening of the emissions cap and successful reform of the trading system[41].

Institutional strategies also help to lock in a progressive dynamic in tightening emission caps[59]. For instance, institutionalizing a formula that prescribes into carbon-pricing legislation an automatic tightening of the emissions cap or increases in the tax rate could support a ratcheting-up dynamic[60]. Such institutionalization could occur through the inclusion of a formula in the rule-making process or it could be delegated to an independent agency like the California Air Resources Board.

The Paris Agreement and sequencing

A decentralized international climate architecture like the Paris Agreement provides a framework for continuously progressive emissions cuts as governments agreed to five-year review periods. This creates a case for governments to develop policy sequences that allow for continued decarbonization in future rounds of policy commitments and helps avoid political, economic, and environmental dead ends. The three-stage policy sequence of California and the EU offers a heuristic to policymakers (Fig. 1). Here, we highlight key next steps for decarbonization in leaders and followers.

Leverage low-carbon interests for sectoral broadening. In climate leaders such as California and the EU, the three-stage policy sequence has primarily played out in the electricity sector. As these jurisdictions set their eye on deeper emissions cuts, further cuts in the electricity sector and efforts to broaden policies to the transport and other sectors are crucial.

Policy baselines for decarbonization efforts in the transport sector differ significantly across countries. Japan and some countries in Europe have high general fuel taxes that date back half a century or more. Carbon emissions would have been much higher in their absence[61]. Recent efforts to price carbon in the transport sector have been limited. The CA ETS is the only major pricing system that includes transport fuels. However, California failed to implement an emissions reduction target for transportation as part of its 2015 climate legislation. Effective regulatory policy in the transport sector in the future will require stronger political support to embrace target-setting and pricing policies.

Decarbonization in the transport sector typically hinges on electrification[62]. A key political challenge is to leverage low-carbon constituencies, such as electric utilities, that have emerged in the power sector to help drive low-carbon policy in the transport sector. The support of electric utilities would strengthen policymakers as they face opposition from oil and auto companies in moving ahead with emissions cuts in the transport sector. At the same time, transport sector electrification needs to be tied to an expansion of low-carbon sources of power generation to ensure overall emissions cuts. This poses the dual challenge to policymakers of increasing regulatory pressure on power producers to ensure deeper emissions cuts in the electricity sector, while leveraging their support to drive the electrification of the transport sector.

Leverage clean technology for more stringent carbon pricing. The large majority of jurisdictions that have made commitments in the Paris Agreement are followers—they have moved through the first stage of the policy sequence and are considering the second. This includes many emerging economies such as China and Brazil, as well as most US states. Of the 162 Nationally Determined Contributions submitted for the Paris Agreement, more than 90 include proposals for carbon-pricing systems[63]. This suggests a potential wave of new pricing systems in the future. In moving to pricing carbon, followers can reap the benefits from cost reductions of low-carbon technologies. This could enable policymakers in follower jurisdictions to start pricing carbon earlier and at higher levels than they would have done otherwise. In countries like the US, this is particularly important to avoid locking in lower carbon-emitting fuels such as natural gas that must eventually be made obsolete but have long investment cycles. In emerging economies, it is similarly critical to avoid locking in fossil-based infrastructure in the first place.

At the same time, carbon-pricing systems are likely to remain backstop measures for emissions reductions largely achieved through other, more direct means. This suggests that followers need to continue to expand the support for research, development, and deployment of low-carbon technologies. Existing green innovation and industrial policies remain insufficient[9]. This applies in particular to industrialized and emerging economies, as developing countries face broader challenges in deploying green industrial strategies given different institutional and economic capabilities[64]. The International Energy Agency models expanding annual renewables subsidies from US$112 billion in 2014 to US$172 billion in 2040 in its New Policies Scenario[65].

In this Perspective, we propose that careful policy sequencing can help facilitate the progressive decarbonization of energy systems under political constraints, as California and the EU demonstrate. An excessive focus on the need for efficient pricing alone often ignores these constraints. A better integration of economic and political perspectives should help point the way forward on low-carbon policymaking.

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References

1. Tietenberg, T. H. Reflections—carbon pricing in practice. *Rev. Environ. Econ. Policy* **7**, 313–329 (2013).
2. Acemoglu, D., Aghion, P., Bursztyn, L. & Hemous, D. *The Environment and Directed Technical Change* FEEM Working Paper No. 93.2010 https://doi.org/10.2139/ssrn.1668575 (2010).
3. Fischer, C. & Newell, R. G. Environmental and technology policies for climate mitigation. *J. Environ. Econ. Manage.* **55**, 142–162 (2008).
4. Acemoglu, D., Akcigit, U., Hanley, D. & Kerr, W. Transition to clean technology. *J. Polit. Econ.* **124**, 52–104 (2016).
5. Wagner, G. et al. Energy policy: Push renewables to spur carbon pricing. *Nature* **525**, 27–29 (2015).
6. Meckling, J., Kelsey, N., Biber, E. & Zysman, J. Winning coalitions for climate policy: green industrial policy builds support for carbon regulation. *Science* **349**, 1170–1171 (2015).
7. Rodrik, D. Green industrial policy. *Ox. Rev. Econ. Policy* **30**, 469–491 (2014).
8. Jaffe, A. B., Newell, R. G. & Stavins, R. N. Environmental policy and technological change. *Environ. Res. Econ.* **22**, 41–70 (2002).
9. Barbier, E. B. Building the green economy. *Canadian Public Policy* **42**, S1–S9 (2016).
10. *State and Trends of Carbon Pricing 2015* (World Bank, Washington DC, 2015).
11. Biber, E. Cultivating a green political landscape: lessons for climate change policy from the defeat of California's Proposition 23. *Vanderbilt Law Rev.* **66**, 399–462 (2013).
12. Qi, Y. & Wu, T. The politics of climate change in China. *WIREs Clim. Change* **4**, 301–313 (2013).
13. Schmitz, H., Johnson, O. & Altenburg, T. Rent management—the heart of green industrial policy. *New Polit. Econ.* https://doi.org/cdtc (2015).
14. Kelsey, S. M. *The Green Spiral: Policy–Industry Feedback and the Success of International Environmental Negotiation*. PhD Thesis, Univ. California Berkeley (2014).
15. Keohane, R. O. The global politics of climate change: challenge for political science. *PS Polit. Sci. Polit.* **48**, 19–26 (2015).
16. Nahm, J. Renewable futures and industrial legacies: wind and solar sectors in China, Germany, and the United States. *Business Polit.* **19**, 68–106 (2017).

17. Kim, E. S., Yang, J. & Urpelainen, J. Does power sector regulation promote or discourage renewable energy policy? Evidence from the States, 1991–2012. *Rev. Policy Res.* **33**, 22–50 (2015).
18. Borenstein, S. & Bushnell, J. The US electricity industry after 20 years of restructuring. *Ann. Rev. Econ.* **7**, 437–463 (2015).
19. Lockwood, M., Kuzemko, C., Mitchell, C. & Hoggett, R. Historical institutionalism and the politics of sustainable energy transitions: A research agenda. *Environ. Planning C Gov. Policy* **35**, 312–333 (2016).
20. Jenkins, J. D. & Karplus, V. J. *Carbon Pricing Under Binding Political Constraints* (United Nations University, Helsinki, 2016).
21. Schmidt, T. S. & Sewerin, S. Technology as a driver of climate and energy politics. *Nat. Energy* **2**, 17084 (2017).
22. *Revolution Now: The Future Arrives for Five Clean Energy Technologies* (Department of Energy, Washington DC, 2015).
23. van Benthem, A., Gillingham, K. & Sweeney, J. Learning-by-doing and the optimal solar policy in California. *Energy J.* **29**, 131–151 (2008).
24. Jenkins, J. D. Political economy constraints on carbon pricing policies: What are the implications for economic efficiency, environmental efficacy, and climate policy design? *Energy Policy* **69**, 467–477 (2014).
25. Aldy, J. E. & Pizer, W. A. The competitiveness impacts of climate change mitigation policies. *J. Assoc. Environ. Res. Econ.* **2**, 565–595 (2015).
26. Gawel, E., Strunz, S. & Lehmann, P. A public choice view on the climate and energy policy mix in the EU — How do the emissions trading scheme and support for renewable energies interact? *Energy Policy* **64**, 175–182 (2014).
27. Morgan, M. G. Opinion: Climate policy needs more than muddling. *Proc. Natl Acad. Sci. USA* **113**, 2322–2324 (2016).
28. Sachs, J. D. *et al. Why Climate Policy Needs Long-Term Deep Decarbonization Pathways* (United Nations, 2015).
29. Kimura, O. *Japanese Top Runner Approach for Energy Efficiency Standards* (Socio-Economic Research Centre, Central Research Institute of Electric Power Industry, 2010).
30. Cole, D. H. Advantages of a polycentric approach to climate change policy. *Nat. Clim. Change* **5**, 114–118 (2015).
31. Sivaram, V. Ensuring Tesla doesn't out the batteries of the future. *Forbes* (30 April 2015).
32. Zysman, J. & Huberty, M. *Can Green Sustain Growth?* (Stanford Business Books, 2014).
33. del Río, P. & Mir-Artigues, P. Support for solar PV deployment in Spain: Some policy lessons. *Renew. Sust. Energy Rev.* **16**, 5557–5566 (2012).
34. Stokes, L. C. *Power Politics: Renewable Energy Policy Change in US States.* Dissertation, MIT (2015).
35. Callaway, D., Fowlie, M. & McCormick, G. *Location, Location, Location: The Variable Value of Renewable Energy and Demand-Side Efficiency Resources* (UC Berkeley, CA, 2015).
36. Simoes, S., Nijs, W., Ruiz, P., Sgobbi, A. & Thiel, C. Comparing policy routes for low-carbon power technology deployment in EU — an energy system analysis. *Energy Policy* **101**, 353–365 (2017).
37. Mitchell, C. Momentum is increasing towards a flexible electricity system based on renewables. *Nat. Energy* **1**, 15030 (2016).
38. Helm, D. The European framework for energy and climate policies. *Energy Policy* **64**, 29–35 (2014).
39. Böhringer, C. & Rosendahl, K. E. Green promotes the dirtiest: on the interaction between black and green quotas in energy markets. *J. Regulatory Econ* **37**, 316–325 (2010).
40. Fischer, C. & Preonas, L. *Combining Policies for Renewable Energy: Is the Whole Less than the Sum of Its Parts?* Discussion paper 10–19 (2010).
41. Rabe, B. G. The durability of carbon cap-and-trade policy. *Governance* **29**, 103–119 (2016).
42. Houle, D., Lachapelle, E. & Purdon, M. Comparative politics of sub-federal cap-and-trade: Implementing the Western Climate Initiative. *Global Environ. Pol.* **15**, 49–73 (2015).
43. Hammar, H., Löfgren, A. & Sterner, T. Political economy obstacles to fuel taxation. *Energy J.* **25**, 1–17 (2004).
44. Huberty, M. *Energy Systems Transformation and the Political Economy of Climate Change*. PhD Thesis, Univ. California Berkeley (2013).
45. Knox-Hayes, J. Negotiating climate legislation: Policy path dependence and coalition stabilization. *Regulation Gov.* **6**, 545–567 (2012).
46. Mackinder, E. Pro-environment groups outmatched, outspent in battle over climate change legislation. *OpenSecrets* (23 August 2010).
47. Sullivan, C. & Kahn, D. Voters Reject 2-Sided Assault on Climate Law. *ClimateWire* (3 November 2010).
48. Meckling, J. *Carbon Coalitions: Business, Climate Politics, and the Rise of Emissions Trading* (MIT Press, 2011).
49. Ciplet, D., Roberts, J. T. & Khan, M. R. *Power in a Warming World* (MIT Press, 2015).
50. Victor, D. G. *Global Warming Gridlock* (Cambridge Univ. Press, 2011).
51. Markussen, P. & Svendsen, G. T. Industry lobbying and the political economy of GHG trade in the European Union. *Energy Policy* **33**, 245–255 (2005).
52. Cook, B. J. Arenas of power in climate change policymaking. *Policy Studies J.* **38**, 465–486 (2010).
53. Harrison, K. A tale of two taxes: the fate of environmental tax reform in Canada. *Rev. Policy Res.* **29**, 383–407 (2012).
54. Murray, B. C. & Maniloff, P. T. Why have greenhouse emissions in RGGI states declined? An econometric attribution to economic, energy market, and policy factors. *Energy Econ.* **51**, 581–589 (2015).
55. Calel, R. & Dechezleprêtre, A. Environmental policy and directed technological change: Evidence from the European carbon market. *Rev. Econ. Stat.* **98**, 173–191 (2016).
56. Wettestad, J. & Rescuing, E. U. emissions trading: mission impossible? *Global Environ. Pol.* **14**, 64–81 (2014).
57. Duff, D. G. Carbon taxation in British Columbia. *Vermont J. Environ. Law* **10**, 87–107 (2008).
58. Raymond, L. *Reclaiming the Atmospheric Commons: The Regional Greenhouse Gas Initiative and a New Model of Emissions Trading* (MIT Press, 2016).
59. 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).
60. Partnership for Market Readiness and International Carbon Action Partnership. *Emissions Trading in Practice: a Handbook on Design and Implementation* (World Bank, Washington, DC, 2016).
61. Sterner, T. Fuel taxes: An important instrument for climate policy. *Energy Policy* **25**, 3194–3202 (2007).
62. Williams, J. H. et al. The technology path to deep greenhouse gas emissions cuts by 2050: the pivotal role of electricity. *Science* **335**, 53–59 (2012).
63. World Bank, Ecofys *Carbon Pricing Watch 2016* (Washington DC, 2016).
64. Barbier, E. B. Is green growth relevant for poor economies? *Res. Energy Econ.* **45**, 178–191 (2016).
65. *World Energy Outlook* (International Energy Agency, Paris, 2015).

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Competing interests

The authors declare no competing financial interests.

Additional information

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