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Governing the net-zero transition: Strategy, policy, and politics

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This paper applies insights from the literature on transitions in major consumption–production systems to clarify the nature of the challenge of moving to a net-zero greenhouse gas (GHG) emission society. It highlights critical features of transitions including their multiactor/multicausal logic, phased development, and distributive impacts. Because current systems are so dependent on fossil energy resources, and on GHG-emitting industrial processes and agricultural practices, multiple transitions across a range of distinct consumption–production systems will be required for net zero. The transformation of each system faces different barriers and enabling conditions and is influenced by varied nonclimate-related disruptions. Important policy implications follow, including the need to focus on sector and regional transitions, link climate policy to other societal goals, and adopt policy mixes appropriate to the transition phase. The article discusses recent policy and politics-related findings from the transitions literatures including those dealing with policy mixes, transition intermediaries, and green industrial policy.

transition | net zero | climate change | governance

Since the Paris climate summit in 2015, an increasing number of national governments have explicitly committed to mid-century net-zero climate goals. Achieving this ambition in the short span of a few decades will require a major transformation of existing consumption–production systems and illustrates many of the challenges related to the governance of sustainability transitions.

There is now substantial scholarship on the politics and policy of climate mitigation including work on the evolution of the international climate regime and the orienting logics of climate action (1, 2); political parties, public opinion, and national climate politics (3, 4); policy design, implementation, and assessment (5, 6); resistance by fossil fuel interests (7); grass roots movements and community activism (8); the deployment of renewable energy and other low-carbon technologies (9); and climate justice (10). Contributions have come from many perspectives including political economy, political ecology, new-institutionalism, common pool resource management, socioecological systems thinking, and normative political theory.

This article synthesizes what transition scholarship (11–13) can bring to these discussions, arguing that it can help us better understand the change processes required to reach net zero, provide a bridging framework (14) to draw together insights from across multiple disciplines and perspectives, and offer practical guidance for governance of the net-zero transition. While international institutions have an important role to play in the governance of climate mitigation, the focus here is on politics and policy in the jurisdictions which have formal obligations to deliver on net-zero commitments (essentially national states and the European Union).

Transition studies is a multidisciplinary research tradition with roots in innovation studies (15, 16) and evolutionary economics (17, 18) that is focused on understanding patterns of change in large-scale consumption–production systems (systems that move people and materials, provide food, energy, and so on). While not widely known even a decade ago, transition approaches are now attracting increasing attention across diverse research communities, in international organizations, and from policy practitioners (19). Consider, for example, recent reports from the Brookings Institution (20), the Intergovernmental Panel on Climate Change (IPCC) (21), the European Environment Agency (22), and the European Commission (23).

This article is divided into six parts. It begins by presenting critical characteristics of large-scale transitions in consumption–production systems identified by scholars. These include their multiactor/multicausal logic, pervasive uncertainty, and distributive implications. The following section explores implications of the features of historical transitions for the strategic challenge of moving toward net zero. The third part of the article engages with policy, and the fourth with the politics of low-carbon transitions––drawing in each case from the analysis of contemporary sustainability transitions. This is followed by a short conclusion. In line with the "Perspectives" rubric of PNAS, the goal is to introduce readers to a critical strand of literature while encouraging them to reflect how this might be incorporated into their own thinking on sustainability.

1. Systems, Transitions, and Governance

Change in socioecological systems takes multiple forms across varied dimensions and scales. One way of approaching

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this complexity is through the mesolevel analytical construct of the "sociotechnical system" (24)—which highlights the intertwining of technical and social elements in consumption–production systems. Thus, electrical systems, which provide energy services for industry and households, can be understood as systems (i.e., more than an aggregation of components) that are at once technical (with power plants, transformers, transmission lines, and end-use devices, connected in particular ways) and social (involving financial flows, markets, regulatory standards, and so on). In this schema, ecological dimensions are considered mainly in relation to sociotechnical formations—as resources on which consumption–production regimes depend and as environmental constraints and feedbacks which press on human activities.

Research has shown that for the most part, change in consumption–production systems is incremental, involving piecemeal adjustment of technologies and societal practices (25, 26). Such change can secure substantial advance over time (contrast a modern internal combustion engine automobile with the Model T Ford from which it is descended), while the tight interlinkages that evolve among system components (technologies, business models, regulatory frameworks, consumer expectations) typically resist more basic transformation. Think of the coupling of the automotive industry with oil and steel production, the finance and insurance industries, road building and the layout of cities, vehicle and driver licensing, safety standards, and government budgets (gasoline taxation).

Nevertheless, fundamental system realignments do occur, such as the move from horse drawn to motorized road transport (27), societal electrification (28), the build out of sewage and water supply systems (29), or the emergence of digital commerce. Over the past few decades, scholars drawing on multiple analytical traditions have made considerable headway in understanding these large-scale transitions. Although historical transitions display enormous variety, researchers have identified common patterns and features. Among the most important are:

- Their multidimensional, multiactor, and multicausal character (30–32). While popular accounts emphasize individual inventions or entrepreneurs, system change involves multiple adjustments to technologies, business practices, regulatory frameworks, and consumer behavior.
- The centrality of both "building up" and "tearing down" (33–36). Transitions give birth to novelties (technologies, business models, social practices) but they also entail the decline and replacement of older ways of doing things.
- Pervasive uncertainty (37–39). Transitions are messy. Development trajectories cannot fully be known in advance. Innovations may fail to live up to expectations, and shifting economic or political circumstances, societal countercurrents, or contingent events can stall, reverse, or reorient change. "Optimality" is applicable neither to transition processes nor their outcomes, and there are always unintended consequences. History is peppered with examples of technologies that diffused widely not because they were the best but because they benefited from historical contingency and the accumulated allocation of societal resources over time (40).
- Involvement of distinct phases (20, 41–43). These typically include a relatively long "emergence" period where shortcomings with existing arrangements are visible and trials of competing technologies and business models get underway; an expansionist "acceleration" phase with convergence on standardized solutions, and wide-scale adoption; and finally, "stabilization" where new arrangements become dominant and adjustments with adjacent systems are completed.
- The importance of "visions and narratives" for mobilizing resources, coordinating investment, and overcoming resistance (44–48). At the outset, uncertainty is high; alternatives display shortcomings (higher costs, low functionality) and mesh poorly with the established system (49). Visions and narratives help bridge the gap between long-term promise and the less-than-ideal reality of novel solutions (50).
- Distributive consequences (51, 52). Transitions differentially impact businesses, workers, sectors, and regions. While society may gain from new arrangements, the lives of many will be upended. Struggles to redistribute these benefits and costs are ubiquitous (53, 54).
- Politics, policy, and government play a central role (55–58). With its legal authority, regulatory apparatus, and financial resources, governments can influence the pace and direction of change. Appeals to progress and the common good, justice, and entitlement are staples of public debates around transitions.

As complex, uncertain, and contested processes of societal change that unfold over multiple spatial scales and extended periods of time, transitions are not "governed"—if by that one understands being planned and controlled by a single authority (59). And yet it is possible to consider the "governance of transitions" both because formal political institutions (parliaments, public administration, laws, etc.) are inevitably involved, and because governance itself can be understood more broadly to encompass the multiple ways societies are ordered (for example, through markets, networks, and norms) as well as through top-down state-centered mechanisms (52, 60).

If governments cannot typically command transitions, they are nevertheless drawn into these processes because the stakes—especially for energy-related transitions—are so high. Modern states are deeply enmeshed with consumption–production systems: national ambition, political stability, and government revenues ultimately depend on successful economic development; laws and regulations structure consumption–production activities; and political and economic elites are entwined (61). States often see advantage in supporting novel technologies especially in relation to geostrategic goals, and economic and military rivalry (62). Governments facilitated the development of railways (63) and roads (47) for military, strategic, nation building, and economic purposes. Economic and public health ends justified countless public investment programs (water treatment, advanced agriculture practices, gas grids, and the internet). Moreover, novel systems typically require revision of existing regulatory frameworks and property rights. Consider the application of eminent domain for the construction of railroads or ongoing arguments over intellectual property in genetically modified organisms and digital copyright. Finally, both innovators and incumbents turn

to politics and government to protect their interests and block rivals (44).

Such interactions are objects of study for transition research, a diverse field that draws on a variety of methodological approaches from discourse analysis (44) to quantitative modeling (64), involving work that ranges from the detailed examination of everyday consumption practices (65) to the broad sweep of "deep transition" scholarship (66) that tracks the evolution of multiple consumption–production systems over large blocks of historical time. In addition to historically focused analysis, much of the transition literature deals with contemporary "sustainability transitions" (11, 12) driven by the urgency of transforming existing consumption–production systems to accommodate environmental boundaries.

Four analytical and conceptual frameworks with governance implications have been particularly influential in the transition literature to date. "Strategic niche management" (67–69) focuses on the critical role niches play in transitions. Identifying market segments where an emerging technology can mature is a classic function of entrepreneurship, but "strategic niche management" highlights the role policy can play in creating "protected spaces" (70)—where a new technology can gain experience, win consumer confidence, improve functionality, and drive down costs. For example, through public procurement, feed-in tariffs, or portfolio standards, that guarantee a market share to an emerging technology. The "functions of innovation systems" approach (71, 72) starts from understanding the interdependent dimensions of successful innovation systems to identify problematic areas in specific (industry/sector/regional) innovation systems. It goes on to propose specific interventions (that could be adopted by investors or policymakers) to strengthen these systems so that innovations can break out and accelerate transition processes. "Transition management" (73–75) deals explicitly with techniques for orienting sustainability transitions, suggesting a variety of strategies and tools that can network innovators, coordinate programs of societal experimentation, build supportive coalitions, and scale emerging approaches.

By far, the broadest and most influential framework to emerge from transition research is the "multilevel perspective" (31, 76)—a heuristic that integrates the different kinds of factors that drive or retard system change. The schema includes three primary analytical "levels": "the regime," the operative set of arrangements that dominate in a particular sector (the prevailing rules, technologies, actors, and business models); specialized "niches" where emerging alternatives are tested; and the "landscape," the broader economic, social, and political environment within which regimes operate. Typically, system change requires developments at all the three levels, as increasing landscape pressures aggravate difficulties of the prevailing regime, sometimes opening the door for maturing niche arrangements to break through and achieve a more or less significant transformation of existing arrangements (31). Of course, it is all more complicated than this as interactions across the three levels can produce varied patterns of stability or change. While governance implications of the multilevel perspective cannot be read off so directly as from the other three approaches, it nevertheless provides the most comprehensive framework for understanding transition governance processes. Politics and power can be understood as operative within and across all levels of the multilevel perspective (44, 54, 77). And in recent years, partly in response to earlier criticisms that these dimensions were insufficiently explicit in some analyses, many transition scholars have worked to bring these issues to the fore (52, 55).

From this brief introduction to transitions and transition scholarship, we shall now turn to its relevance for governance of net-zero climate goals.

2. Net Zero through a Transition Lens: Strategic Orientation for Governance

Approaching the net-zero greenhouse gas (GHG) emission target (which flows from the 2015 Paris climate agreement) through a transition lens suggests several core strategic considerations. As the IPCC has made clear, net zero will require the profound transformation of existing systems of production and consumption (21). Existing systems—from transport to the built environment, from electricity to agri-food—have been built around fossil energy. Moreover, the foundational materials of industrial society (cement, steel, chemicals, plastics), the agricultural practices currently required to support global populations (forest clearances, nitrogen fertilizers, animal agriculture), and the associated waste streams all have substantial GHG footprints. Driving down emissions, therefore, requires dramatic change across all these areas. To complicate things further, significant uncertainties (viability, cost, and permanence) surround carbon removal technologies—from sequestration in soils to direct air capture—that might ultimately "net out" residual emissions (78). So, we are looking at system change, rather than marginal adjustments, if net emissions are to be eliminated from existing development trajectories.

Although it is fairly common to refer to *the* low-carbon transition or *the* energy transition, achieving a net-zero society actually requires a series of related transitions across multiple consumption–production systems at different scales, including electricity, transport, buildings, and agri-food (79, 80). As experience with earlier transitions suggests, these processes will have different characteristics and are likely to proceed at different rates. Moreover, concern with climate change is not the only (or in some cases even the principal) change driver in these consumption–production systems. Each has its own dynamic, strengths and weaknesses, disruptive currents, and transformative movements (20, 43). Think how personal transport is being upended by new service provision models (Uber, Lyft), changing attitudes toward vehicle ownership, and impending vehicle autonomy. And they can be impacted differentially by contingent events (consider the turn toward teleworking during the COVID-19 pandemic or the energy sector impacts of the war in Ukraine). This suggests that managing transitions requires attention to multiple issues of societal concern. Indeed, transitions research demonstrates that change on a scale required to bring emissions to net zero will necessarily entail other system adjustments to which society will not be indifferent. Thus, climate solutions cannot be divorced from broader

issues related to the operation of these systems and the benefits they provide to society.

Since each of these consumption–production systems is different, with differing barriers and enabling conditions and with varied configurations of actors and potential solutions, transition studies underscore that actions intended to accelerate change are likely to be most effective when targeted at specific contexts (81–83) rather than treating the economy as an undifferentiated whole––as is sometimes the case with purely economic approaches (84). A context-sensitive focus on particular sectors accommodates the varied circumstances and the stage of transition in each system (20, 43). The technologies, infrastructures, business models, social practices, and regulatory frameworks in transport are different from those in agri-food; while low-carbon innovations are rapidly diffusing in transport, they are only now emerging in agri-food. A regional focus allows integration of solutions across multiple adjacent systems in a geographically distinct area (place-based integration), enabling the mobilization of regional actors, resources, and identities (85).

So, if one is interested in accelerating change, transition scholarship suggests that the litmus test for action should not be "will this initiative achieve the lowest cost incremental GHG emission reduction" but rather does it encourage movement toward system adjustment that can deliver net zero and other desirable societal objectives (82). This is important because there are many low-cost measures which reduce GHG emissions but do not advance the large-scale shifts needed to achieve net zero. Think for example of the encouragement of ethanol-based biofuels for light-duty vehicles, which is mandated in many jurisdictions. This achieves marginal short-term emission reductions but is not part of a pathway to net zero, because land-use constraints mean that there cannot be enough ethanol to power our vehicle fleets, and industry is already committed to an electrification option which is scalable. So, investment in such a dead-end pathway is a waste of resources, risking stranded assets (e.g., sunk costs in equipment and infrastructure) and stakeholder demands to perpetuate existing entitlements (e.g., subsidies for corn crops), that could better be applied to accelerate system change.

Taken together, these insights suggest that successful climate mitigation requires movement away from an approach which primarily conceives policy as a pollution control effort and toward one which understands the challenge to be inducing transformative change in critical systems (82, 84). The "pollution control" framing has undoubted advantages––particularly in establishing continuity with the (relatively successful) institutions established to tackle conventional air pollution in developed countries over the past sixty years. And it may be a way to lead reluctant actors (and institutions) to accept incremental steps to reduce GHG emissions. Yet, evidence shows that it fails to capture the magnitude of the changes required to address climate mitigation, or to direct attention to the critical measures that can accelerate system change to deliver net zero (5, 86). Thus, the climate challenge cannot be reduced to an emission-accounting exercise, but instead needs to focus on shifting consumption–production systems toward new configurations.

3. Governing for Net Zero: Policies for Transition

Three decades after climate change emerged as an international policy problem, complex packages of mitigation measures have been adopted in many countries. These include economic instruments (carbon pricing, investment tax credits), subsidies (to consumers or producers), infrastructure investment, regulations, R&D supports for low-carbon technologies, adjustments to land-use planning, and fossil-fuel phase-outs. Discussion of the role and effectiveness of these policy instruments can be found in the numerous case studies of sector and regional transition processes that make up much of the sustainability transitions literature (50). The evaluation of national, regional, sector, and technology innovation policies constitutes another point of entry for transition scholars (85). However, some of the most exciting recent work on sustainability transition deals with the broader analysis of "policy mixes" (87–89). This research starts from an empirical examination of policy measures adopted by governments; considers problems related to policy strategy, processes, and interactions (from overlaps and gaps to coherence and contradictions along with feedbacks and reversals); and explores mechanisms to promote more successful vertical and horizontal policy coordination and the acceleration of change processes (90–92). Such issues are not new to students of public policy, who have long noted disjointed and mutually contradictory government initiatives, the bounded rationality characteristic of decision-making, and the piecemeal layering of new initiatives on the top of preexisting programs (93). This is especially true in an era where multilevel governance continues to rise in complexity (94). Yet these issues are particularly acute in the climate policy space with its global-to-local reach, where obstacles to transformative change are embedded across multiple consumption–production systems (95).

While the policy mix literature is rich with insights, here we emphasize three findings critical to accelerating change: i) adjusting policies to the phase of transition, ii) combining policies that encourage the build out of new arrangements with the destabilization of old ways of doing things, and iii) managing policy feedback processes.

With respect to the first key finding, while transition studies have long attended to the temporal dimensions of system change (31, 41), the more recent turn toward policy mixes has drawn greater attention to the role of interacting policy instruments in propelling transition processes by tuning mixes of interventions to the appropriate stage of the transition (20, 42, 43, 82). Adapting the terminology of Victor et al. and Rotmans et al., it is possible to define three distinct transition phases with implications for policy development (20, 41). The emergence stage involves exploration of novel solution spaces, competition among promising but far-from-perfect alternatives, and increased exposure of the shortcomings of the existing regime. Policy can accelerate these processes by supporting R&D for low-carbon innovation, funding portfolios of experiments, establishing protected niches for potential alternatives, and clearly signaling that existing arrangement cannot continue. Acceleration is about scaling up solutions, driving down costs, and increasing

functionality to allow mass adoption. Here, policy mixes can focus on removing technical and regulatory barriers to deployment, mobilizing capital (by derisking investment), promoting consumer confidence (education, standards), and increasing pressure on (and neutralizing resistance from) existing regimes. Finally, with the stabilization phase, change is carried through at the system level and interlinkages with adjacent systems are stabilized. At this juncture, policy mixes can address lagging dimensions (technical, economic, or social blockages) and stabilize the new institutional context. Importantly, instrument portfolios are also needed to mitigate impacts on communities and households affected by system change while not delaying or reorienting the transition (96).

Some policy instruments are particularly appropriate to specific transition phases (20, 43, 82). Government procurement policies can help to develop early niches for emerging innovations, supporting initial commercial projects (e.g., consider military procurement in this context). Adoption incentives such as feed-in tariffs for renewable electricity supply or purchase rebates for air-source heat pumps make sense in a late emergence/early acceleration context, where alternatives are proven but still expensive. Sales mandates for battery electric vehicles can be critical in the diffusion stage, requiring manufacturers to shift production in order to support wider scale adoption. Other measures, such as carbon pricing or tightening regulations, can extend over multiple phases, with adjustments (e.g., in sector coverage and/or stringency) as change progresses. The above insights are summarized in Fig. 1.

Transition research indicates that a reflective attitude toward transition phases allows forward planning, better communication with stakeholders, and avoidance of policy traps (20, 43). For example, by priming markets for the gradual scaling back of niche protections as emerging technologies acquire momentum. Premature removal of such supports can stall transition but leaving them in place too long can also be counterproductive as firms become overreliant on state support and slow further innovation.

Concerning the second key finding, accelerating the low-carbon transition is not just about encouraging new ways of doing things but also deliberately eroding the innumerable advantages that accrue to dominant fossil-energy systems (34). Research indicates that societal actors and entrepreneurial politicians typically take the lead here as governments initially hesitate to threaten significant financial interests (46). This has proven especially true in countries with major fossil fuel extraction and export industries. Nevertheless, as political conditions permit, governments can introduce measures to erode the advantages of incumbents, removing subsidies and increasing the tax and regulatory burden (carbon pricing, fugitive methane standards), stripping away regulatory advantages (increasing scrutiny of fossil fuel infrastructure projects, adjusting the mandates of regulatory bodies), forcing disclosure of emissions and associated financial risks, divesting public portfolios of fossil-based assets, implementing zero emission mandates (for vehicles, fuels), and announcing phase-outs. In this context, it is difficult to overestimate the significance of phase-outs (even when not yet given legal sanction) for signaling to investors, operators, and consumers that time has been called on a particular practice or technology (97). So far, coal phase-outs for power generation are the most advanced (e.g., the United Kingdom, Canada, and New Zealand), with announcements of end-dates for the sale of gasoline and diesel engine automobiles now following (e.g., the European Union, Canada, and many subnational governments in the United States have set end-dates for 2035).

Yet, a growing body of research on managed decline indicates that this process is not just about pilling pressure on

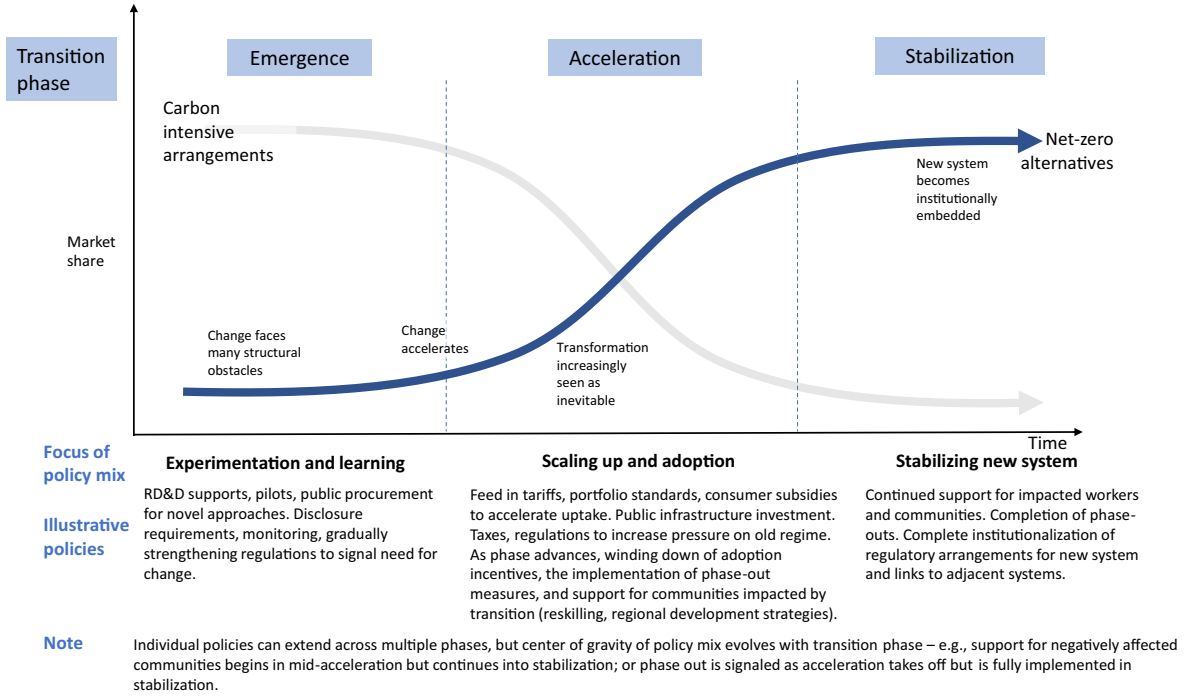

Fig. 1. Tuning policy mixes to transition phases.

incumbents but also about coopting opposition, buying-off fossil fuel interests, and providing support to workers and regions which will be impacted by transition (96, 98). According to this literature, it may be necessary to compensate asset owners for the premature retirement of their facilities, provide retraining for employees in declining industries, and implement regional development strategies in resource-based communities.

Timing plays a particularly important role in the development of policy packages driving innovation and managing decline, with phase-out measures ideally calibrated to the relative maturity (and cost) of alternatives, the robustness of the political commitment to act, the state of public opinion, the strength of incumbents, and the configuration of contingent contextual factors (46). In practice, navigating these policy considerations can be a significant challenge, where authority is split across multiple ministries and overlapping jurisdictional levels, where policymakers are never operating with a clean slate, and where political actors are constantly changing (4).

This brings us to the third key insight, managing policy feedback processes. Drawing from political science literatures on policy processes and feedbacks, transition scholars have examined how policy interventions generate feedbacks which accelerate or set back wider efforts at system reform (56). Instances of policy backlash in the low-carbon transition are well known and range from local opposition to siting wind turbines to broader citizen action such as the French "gilet jaune" movement (53). In Ontario, for example, measures intended to speed up renewable electricity deployment by suspending local planning controls for renewable projects, and favoring large investor-owned projects (rather than community-based initiatives), ultimately eroded public support for wind and solar (28). So how can strategies, processes, and instrument mixes be designed to minimize such effects and instead reinforce transformative currents?

Transition scholars Edmondson, Kern, and Rogge (92) developed a conceptual model of interactions between policy processes and sociotechnical subsystems, noting how resource, interpretive, and institutional effects generated by new policy initiatives effect sociotechnical systems, while sociopolitical, administrative, and fiscal feedbacks from the sociotechnical side can alter developments in the policy subsystem. Feedbacks are articulated by actors and coalitions who support or defect from the original policy orientation, and the whole process is impacted by shifting exogenous conditions.

Their fascinating study of the rise and fall of the UK's "Zero Carbon Homes" strategy (2006 to 2016) illustrates these processes (99). The policy goal—that all new homes built in the United Kingdom would be net zero by 2016—was to be secured by dramatic energy efficiency improvements in new-builds, complemented by small-scale renewable deployment and other permitted offsets. This was to be achieved by a complex mix of policy instruments centered on building codes and financial inducements, but also including reforms to planning law, a code for sustainable homes, tax exemptions, construction of new eco-towns, and investment in research and development. Positive feedbacks initially predominated as new stakeholders were brought to the table, and businesses saw opportunities for investment and reduced planning red tape. But negative feedbacks (including a clearer appreciation of costs, and erosion of support as elements of the package were trimmed back) came to predominate. Changing external circumstances (a new conservative government, economic crisis and fiscal restraint, a shift in priorities to deal with a housing shortage) took their toll. Erosion of credibility about the targets undermined private sector investment and enthusiasm, leading finally to repudiation of the targets by the government. Among the lessons the authors draw from this aborted transition experience are the importance of: formulating an appropriate policy strategy (that realistically maps out how change is to be effected); careful timing (technical approaches need to be tested and pathways for scale up should be identified before mass roll-out is attempted); continually mobilizing innovation coalitions (with targeted incentives to bring them to the table); and close monitoring to track feedbacks and adjust policy goals and instrument mixes as conditions change.

4. Governing for Net Zero: The Politics of Transition

Politics permeates the low-carbon transition from the broadest international forces to decisions affecting local communities (51). Governments have tremendous power to orient, accelerate, or retard transitions (55, 77). And political economic legacies, institutional structures, political culture, and practical struggles shape what can be accomplished by public authorities (28, 37).

Transition scholars have focused particularly on the linkages between political processes and change in consumption–production systems, especially political struggles that determine policies which in turn accelerate or retard change (56). In this regard, the multilevel perspective has proven a useful framework for integrating factors influencing transition dynamics, from broad landscape movements (such as rising geopolitical tensions) to the ways regime and niche players interact with political institutions and processes (100).

Here, we draw out three key themes related to the politics of governing the low-carbon transition that have been the focus of recent transition scholarship and have significant implications for the acceleration of change processes: i) transition intermediaries, ii) industrial policy, and iii) just transition. Each of these link to building the political alliances required to sustain net-zero transition processes.

With respect to the first theme, while governments play a central role in the low-carbon transition, many other kinds of organization influence practical developments. Transition intermediaries, described by Sovacool et al. (101) as "agents who connect diverse groups of actors involved in transition processes and their skills, resources, and expectations," are increasingly understood as important players. Activities of such groups include exchanging information (technical knowledge, business approaches), developing visions and narratives for change, running experiments and popularizing results, developing standards, lobbying for policy change, and educating the public (102–104). They can be funded by government, businesses, civil society groups, or through their own activities. Intermediaries include research organizations,

industry bodies, innovation agencies, green business associations, think tanks, nongovernmental organizations (NGOs), regional development organizations, and enthusiast groups.

Research suggests that a vibrant ecosystem of such bodies can be critical in networking innovators, identifying and overcoming barriers to niche development, popularizing solutions, and bringing pressure to bear on the dominant regime (82). For example, in many countries, electric vehicle clubs were important in the early days of Battery Electric Vehicle (BEV) roll-out, allowing enthusiasts to swap experiences, identify charging station locations, exchange driving tips, and spread the word about electric cars. Community energy cooperatives have similarly played a critical role in driving interest in distributed renewable energy solutions, particularly for individuals without access to property capable of supporting solar or wind installations (105). In Canada, a quasigovernment agency Propulsion Quebec has networked hundreds of businesses and other groups involved in the zero-emission transport supply chains.

Transition processes typically generate intermediary activity as niche actors seek help to overcome barriers, social and political groups attempt to shape change, and regime players explore how to respond to increasing pressures. But, resource constraints (knowledge, time, money) can significantly limit intermediary activity. So, a deliberate strategy to create (or to encourage the self-organization of) low-carbon transition intermediaries, and to support their activities, emerges as a potentially powerful political strategy available to governments to accelerate transition processes. As Kivimaa and collaborators (104) argue: "[t]hus, (political) strategies are needed to guarantee that from a transitions perspective necessary intermediary functions will be carried out."

Analysis of innovation ecosystems and transition context is required to identify missing links, and to establish the forms of intermediary most useful in specific circumstances (102). Transition researchers have suggested various typologies of intermediaries based on their position within the transition ecosystem including the distinction between "systemic," "regime based," "niche based," and "user" intermediaries, which also identifies the kinds of function to which each is best suited (104). While government may support intermediaries, their ability to act at arm's length from governmental bureaucracy (and from the direct influence of individual firms) is often precisely what allows them to play a dynamic and catalytic role with other stakeholder in the transition process (82).

Concerning the second theme, one of the most significant climate-related political developments in recent decades has been the rapid rise of green industrial policy (2, 81, 106, 107). Governments (at the national, regional, and supranational level) are increasingly intervening to develop domestic low-carbon industries seen to include renewable electricity; low-carbon fuels (hydrogen and biofuels); carbon capture, utilization, and storage; battery and BEV production, and mining and critical mineral processing. From China's massive investment in photovoltaics and electric vehicle production to the United Kingdom's support for nuclear power and offshore wind, and the European Union's investment in batteries and the hydrogen economy, states are using a variety of approaches to build out industries that will be of strategic value in a low-carbon world.

Industrial policy can be understood as a deliberate effort by government to orient the path of economic development (108). While the term lost favor in many countries during the heyday of market-centered orthodoxy (roughly the three decades between 1980 and 2008), and it became common to deride the idea that the state can "pick winners" (2), in practice, governments never stopped supporting industries deemed critical to national interests (62). As the scale of the economic transformation required by the low-carbon transition has become clearer, even jurisdictions skeptical about state intervention have expressed enthusiasm for green or low-carbon industrial policy. Terms like "green industrial transformation" or the "next industrial revolution" capture the ambition associated with these initiatives which are presented as both an opportunity (to attract investment, develop new technologies and enterprises, secure jobs, growth, and prosperity) and as a risk—with a failure to secure a place in emerging low-carbon supply chains threatening an erosion of national geostrategic position, a loss of markets, industrial decline, and deteriorating standards of living.

Why is green industrial policy so critical? Economically, these measures can focus investment on low-carbon technologies, firms, and sectors, improving their competitive position and accelerating deployment of climate solutions. But their political significance is at least as important–because it strengthens actors (sometimes described as "countervailing industrial power") with a material interest in deepening low-carbon transition (109). Incumbent firms and sectors (that produce exports, provide jobs, attract investment, and generate tax revenues) have enormous weight in political processes (77). Companies involved in fossil fuel extraction and processing, or heavily dependent on fossil energy consumption, can be powerful obstacles to change. By supporting the development of domestic sectors and firms that materially benefit from transition (green technology developers, manufacturers, finance, and service providers), governments can strengthen political coalitions supporting change (110). Transition scholars have examined these positive, and on occasion negative, feedback processes in multiple jurisdictions including Denmark (wind turbines) (107), the United States (renewables) (111), and Germany (renewables) (112). In a large cross jurisdictional study, Meckling and collaborators (110) showed that governments that stimulated low-carbon industrial development (for example through feed-in tariffs, portfolio standards, and RD&D subsidies) before introducing more punitive measures (such as carbon pricing) were more successful in building coalitions to extend decarbonization.

More generally, transition studies suggest that industrial policies can provide a critical bridge between measures intended to address climate change and those focused on other societal challenges, including geo-strategic positioning, economic development, international competitiveness, and employment generation (113). And they can bring constituencies primarily concerned with these other societal issues to support policies which also favor the low-carbon transition. Put another way, they serve as a critical link tying the net-zero transition to other core state preoccupations including geo-strategic positioning, economic management, and public welfare (81). A case in point is provided by the United States, where the political configuration of interests,

institutions, and ideas were always going to make national climate policy difficult. US geopolitical ascendency in the 20th century was closely tied to fossil fuel interests; the country's constitutional arrangements were designed to make major reform difficult without overwhelming consensus (division of powers, "checks and balances," etc.), and there is a powerful ideological tradition resistant to government interference. Moreover, climate policy has become deeply entangled with wider political cleavages. Yet, while multiple efforts at securing significant climate legislation at the national level over several decades largely failed (for example, efforts to establish a national carbon pricing scheme), and attempts to deploy regulatory tools have been weakened by administration turnover or court challenges, two massive investment programs (the 2021 Infrastructure Investment and Jobs Act and the 2022 Inflation Reduction Act)—largely justified in terms of economic regeneration and geo-strategic competition with China––secured congressional support.

Viewed from a wider international context, low-carbon industrial policies can be seen to harness the dynamics of international economic competition to accelerate the development of alternative technologies, spurring performance and driving down costs, ultimately benefiting decarbonization around the world. Establishing feed-in tariffs for renewable electricity did not allow Germany to dominate the global photovoltaics supply chain, despite hopes by some initial proponents that it would do so. Instead, German consumers helped subsidize the build out of China's (state oriented) photovoltaics industry which drove down international prices (by 85% in the decade to 2020), making electricity from solar cheaper than fossil energy in many contexts (21). And yet the investments in the roll-out of renewables was not a total loss for Germany which not only got cheaper panels, but also developed research competencies and industrial capacities in other parts of renewable power value chains.

While different national approaches to green industrial policy continue to reflect long-term patterns of state/market interactions, research has uncovered significant crossnational learning and borrowing (107). Drawing from the wider literature, a recent paper by Allan and collaborators (108) argues that successful programs require i) clear visions and targets, ii) public–private collaboration, iii) brokers and independent intermediaries, and iv) a portfolio of policies including "supply push" and "demand pull" measures. The first element provides a focus for coordination and a means to assess progress; the second allows meaningful information flows between government and industry; the third allows nimble action to develop the industrial ecosystem, avoiding lock-ins surrounding the state bureaucracy; and the fourth provides the financial and regulatory measures to stimulate action.

Research also identifies a series of risks facing industrial policy approaches. Perhaps most importantly, these include capture and cooptation by rent-seeking firms as well as pervasive uncertainty and the likelihood of failure (114). Nevertheless, green industrial policy can serve as a crucial component for economic development and political alliance building to generate positive feedbacks to spur forward the low-carbon transition and maintain momentum even when climate change is not at the top of the political agenda (81, 106, 108).

A third and final theme relates to the increasing emphasis on equity in transition studies, culminating in a growing body of work on just transition (115). While this concept has been understood differently across scholarly and political debate (116), it emphasizes the importance of attending to issues of inequality and impacts on marginalized groups in defining pathways to a low-carbon future (117). By foregrounding these issues, research on just transitions not only calls attention to redressing historical distributional issues (e.g., in access to energy) but also the distributional implications brought on by deliberately accelerating shifts in sociotechnical systems that are inevitably accompanied by declines in specific industries, regions, and so on (97).

Research points to several practical advantages of emphasizing equity in governing the transition to net-zero, including greater consideration of the costs and benefits accruing to various constituencies (and ensuring that costs are not imposed on already-disadvantaged communities) and the way in which to make transformative processes more inclusive (both in terms of outcomes and processes, perhaps by making decision-making more attentive to historically underrepresented groups) so as to leave no one behind (118). For example, expanding the workforce to build out home energy retrofits can include measures to enhance women's entry into the skilled trades, while renewable energy deployment opens development opportunities for indigenous communities in energy self-sufficiency and leadership. Similarly, policy can be used to soften the impacts on communities affected by the phase out of coal-fired power by offering retraining in industries linked to the transition. From a political perspective, a just transition framing can be seen as an opportunity to activate broader societal considerations (e.g., around racism or poverty) and mobilize diverse constituencies in support of change processes. Research also suggests that such an approach can weaken resistance from incumbents and those communities directly affected by the decline of carbon-intensive arrangements (119). However, care must be taken to avoid the cooptation of just transition strategies by incumbents seeking to impede the pace of change (96).

5. Conclusion

We close our analysis with remarks on some key tendencies, tensions, and takeaways from the transition literature in relation to the governance of net-zero transitions. When approaching the historical literature on transitions, there is sometimes a tendency to dismiss what can be learned from earlier experiences because of the deliberate and collective nature, and dramatic scale, of the societal response required to address climate change. The suggestion is that earlier transitions involved specific sectors and were mainly driven by markets and actors seeking to advance private ends. But, the overall transition to net zero will be composed of many interrelated transitions (across different sectors and regions) each of which will not look so entirely different to historical episodes of change. And contrasts with respect to intentionality are better understood as a matter of degree rather than a fundamental quality. Most large-scale societal transitions have at some

point been deliberately promoted by public authorities, and of course the goals and interventions of private actors are also a key part of the low-carbon transitions. Thus, the fundamental difference lies less in their purposive versus spontaneous character and more in the nature of the goals being pursued, which in the case of sustainability are more fully reflexive, are planetary in scope, span the full range of consumption–production systems, and are directed at finding a development trajectory that allows human flourishing while preserving global ecosystems on which that ultimately depends.

There is also a continuing tension within the transition literature related to the scale of change to be considered an authentic transition and/or required to seriously address sustainability challenges. For example, a switch to BEVs can eliminate GHG emissions (provided electricity production and the full supply chain in mining, steel, and so on are fully decarbonized). It can also relieve ancillary problems such as air pollution from gasoline and diesel combustion. But that will leave unaddressed other sustainability issues related to transportation such as congestion, accidents, equity, and the livability of cities. And it says nothing about the wider socioeconomy within which BEV mobility is embedded that has implications for land use, natural resource extraction, biodiversity loss, and so on. This feeds into wider debates in society about the ultimate fate of the growth economy and the patterns of living compatible with long-term sustainability. Transition theory offers no definitive answers on this front but must turn for insights to the wider disciplines that are being integrated into sustainability science.

The most critical takeaway from the analysis presented here is the importance of shifting from seeing governance of climate mitigation as an economy-wide pollution control venture, focused on incremental emission reduction, to seeing it as about "steering" interrelated transitions in multiple sectors and regions that can together deliver a net-zero society. Of course, climate governance involves international agreements, and high-level policy that coordinates efforts across society. But in a very concrete sense, the transition literature suggests that the real action is at the level of inducing fundamental adjustments in a series of specific consumption–production systems (including interconnections among them).

The argument advanced here is not that successful climate policy can only be undertaken within a transition framework. Many analytical traditions can be fruitfully brought to bear on the challenge of reaching net zero. Moreover, experienced politicians can apply practical wisdom about coalition building, bargaining, maintaining voter support, cooptation of opposition, and so on, to design suitable policy mixes to advance change without a theoretical background in transition thinking. What we are arguing is that a transition framework allows an overview and understanding of change processes, which can help avoid some mistakes and dead ends, and provides a narrative that can be communicated to publics and an analytical frame to help make reasoned judgements. If it were taken up more widely by academics in a range of disciplines concerned with sustainability science, and then linked to practical efforts to secure change through direct engagement with policymakers and innovative stakeholders struggling on the ground to build coalitions for change, it could contribute to accelerating the societal response to climate change.

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