POLICY FORUM

CLIMATE POLICY AND INNOVATION

Sociotechnical transitions for deep decarbonization

Accelerating innovation is as important as climate policy

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Rapid and deep reductions in greenhouse gas emission are needed to avoid dangerous climate change. This will necessitate low-carbon transitions across electricity, transport, heat, industrial, forestry, and agricultural systems. But despite recent rapid growth in renewable electricity generation, the rate of progress toward this wider goal of deep decarbonization remains slow. Moreover, many policy-oriented energy and climate researchers and models remain wedded to disciplinary approaches that focus on a single piece of the low-carbon transition puzzle, yet avoid many crucial real-world elements for accelerated transitions (*1*). We present a "sociotechnical" framework to address the multidimensionality of the deep decarbonization challenge and show how coevolutionary interactions between technologies and societal groups can accelerate low-carbon transitions.

SOCIOTECHNICAL SYSTEMS

Rapid and deep decarbonization requires transformation of sociotechnical systems—the interlinked mix of technologies, infrastructures, organizations, markets, regulations, and user practices that together deliver societal functions such as personal mobility. These systems have developed over many decades, and the alignment and coevolution of their elements make them resistant to change.

The multilevel perspective (MLP) (*2*) sees system transitions as driven by interactions between three analytical levels: (i) the sociotechnical system itself, which is stabilized by lock-in mechanisms (such as sunk investments, core competencies, and institutional commitments) but experiences incremental improvements along path-dependent trajectories; (ii) niche innovations, which differ radically from the dominant existing system but are able to gain a foothold in particular geographical areas or market niches, or with the help of targeted policy support; and (iii) exogenous ("landscape") developments such as slow-changing trends (e.g., demographics and ideologies) or shocks (e.g., elections, economic crises, and wars) that destabilize the system and facilitate the breakthrough of niche innovations. Instead of single drivers or a privileging of techno-economic factors, the MLP's key point is that transitions come about through the alignment of processes within and between these three levels (see the figure).

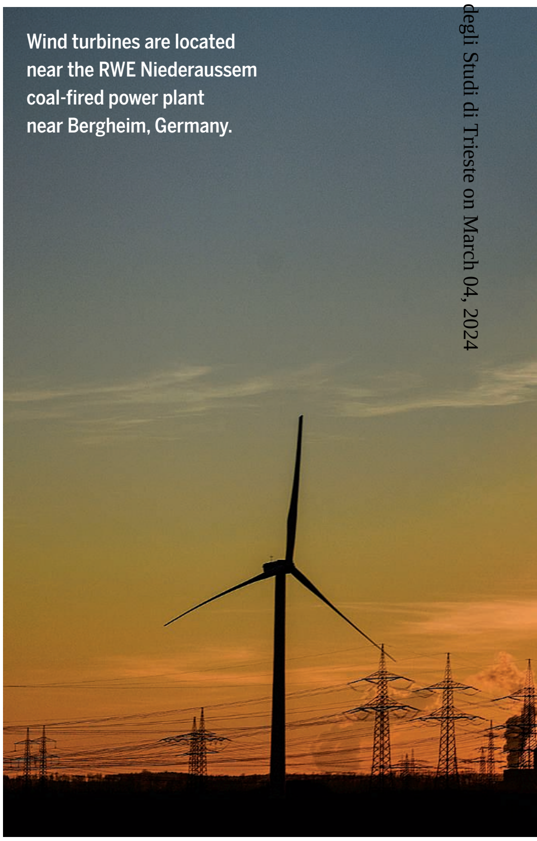
In this framework, acceleration of sociotechnical transitions involves three mutually reinforcing processes: increasing momentum of niche innovations; weakening of existing systems; and strengthening exogenous pressures, which when aligned can create windows of opportunity. The resulting sociotechnical transitions go beyond the adoption of new technologies and include investment in new infrastructures, establishment of new markets, development of new social preferences, and adjustment of user practices.

The unfolding German energy transition, for instance, involved increasing momentum of wind, photovoltaic (PV), and biogas technologies due to price and performance improvements, support from industrial coalitions (e.g., metal and machine-building, turbine manufacturing, and farming), positive cultural framing, and generous policy support (particularly through the 2000 Renewable Energy Act, which established 20-year-long, attractive feed-in-tariffs) (*3*). The existing system, especially nuclear power, also faced long-standing tensions due to a powerful antinuclear movement, negative cultural discourses framing nuclear power as an existential threat and utilities as large monopolists, and political pressure from the Labor/Green Party government coalition (1998 to 2005). The 2011 Fukushima accident was an external, destabilizing shock that triggered the decision to phase out nuclear power and to embrace energy transition as a political goal.

Although the Labor/Green Party coalition could not foresee later fortuitous alignments, the 2000 Renewable Energy Act was deliberately introduced as a long-term transition strategy, which created protected market niches that stimulated technological learning and improvement, the growth of new industries (based on an ecological modernization vision), and the entry of new firms (which were keener to drive renewables than incumbent system actors) (*3*). The case also demonstrates that acceleration depends heavily on country-specific dynamics in political coalitions, industry strategy, cultural discourses, and civil society pressures. There is no "one-size-fits-all" blueprint for accelerating low-carbon transitions.

ALIGN INNOVATIONS AND SYSTEMS

Sociotechnical transitions gain momentum when multiple innovations are linked together, improving the functionality of each and acting in combination to reconfigure systems. The shale gas revolution, for instance, accelerated when seismic imaging, horizontal drilling, and hydraulic fracturing were combined. Likewise, accelerated low-carbon transitions in electricity depend not only on the momentum of renewable energy innovations such as wind, solar PV, and bio-energy (*4*) but also on complementary innovations, including energy storage (e.g., batteries, flywheels, compressed air, and pumped hydro);



Wind turbines are located near the RWE Niederaussem coal-fired power plant near Bergheim, Germany.

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smarter grids (to enhance flexibility and grid management); demand response (e.g., new tariffs, smart meters, and intelligent loads); network expansion (to increase capacity, connect remote renewables, and link to neighboring systems); and new business models and market arrangements (such as energy-only markets and capacity markets to ensure system security).

Linkages between systems may also drive deep decarbonization. Vehicle-to-grid configurations, for instance, in which electric vehicles can modulate their charging rate or even return electricity to the grid, can facilitate diffusion of battery-electric vehicles and mitigate the intermittency problems of wind and solar electricity if car batteries support load balancing (*5*). District heating systems can be coupled with electricity and gas grids, leading to integrated systems in which thermal energy fulfills storage and back-up functions for intermittent electricity (*6*). Urban planning and transport systems can be integrated via transit-oriented development (building mixed-use areas around public transport stops), compact cities, and intermodal transport (which facilitates mode-switching with seamless transfer facilities, smart cards, and aligned timetables) (*7*).

Attention must thus be broadened toward interactions between multiple innovations and sociotechnical systems. "Whole system" models have started to do so but often focus on energy flows and technical linkages, giving limited consideration to consumer acceptance, business models, and sociopolitical drivers.

BUILD SOCIETAL AND BUSINESS SUPPORT

Low-carbon transitions are often seen as a techno-economic implementation challenge, justified by climate science and driven by R&D and carbon pricing. But accelerated transitions also depend upon widespread social acceptance (to create legitimacy and support for strong transition policies) and business support (*8*). Low-carbon transitions in mobility, agrofood, heat, and buildings will involve millions of citizens who need to modify their purchase decisions, user practices, beliefs, cultural conventions, and skills. To motivate citizens, financial incentives and information about climate change threats need to be complemented by positive discourses about economic, social, and cultural benefits of low-carbon innovations.

Business support is essential because development and deployment of low-carbon innovations depend upon the technical skills, organizational capabilities, and financial resources of the private sector. Green industries and supply chains can also solidify political coalitions supporting ambitious climate policies and provide a counterweight to incumbents (*9*). Furthermore, technological progress can drive climate policy by providing solutions or altering economic interests (*10*). Shale gas and solar-PV developments, for instance, altered the U.S. and Chinese positions in the international climate negotiations.

Societal and business support can be built gradually in the first and second phase of transitions (see the figure), through bottom-up learning processes, stakeholder engagement, and polycentric governance (in which multiple independent actors coordinate strategies) (*11*). Business support also depends on low-carbon market opportunities, which can be enhanced by policies (subsidies, tax credits, and standards) or changing consumer preferences. Once in place, societal and business support improves resilience against political setbacks. In the Danish electricity and heat transition, for instance, the weakening of renewable energy policies by a newly elected government (2001) triggered a bottom-up backlash from local energy cooperatives, citizen groups, nongovernmental organizations, manufacturers, and some businesses, which enabled policy restoration several years later (*12*). In the United Kingdom, the low-carbon transition is predominantly a top-down project involving policy-makers and incumbents (*3*). The narrower societal support base creates the risk that the weakened climate policy by the Conservative government since 2015 will derail the unfolding transition.

PHASE OUT EXISTING SYSTEMS

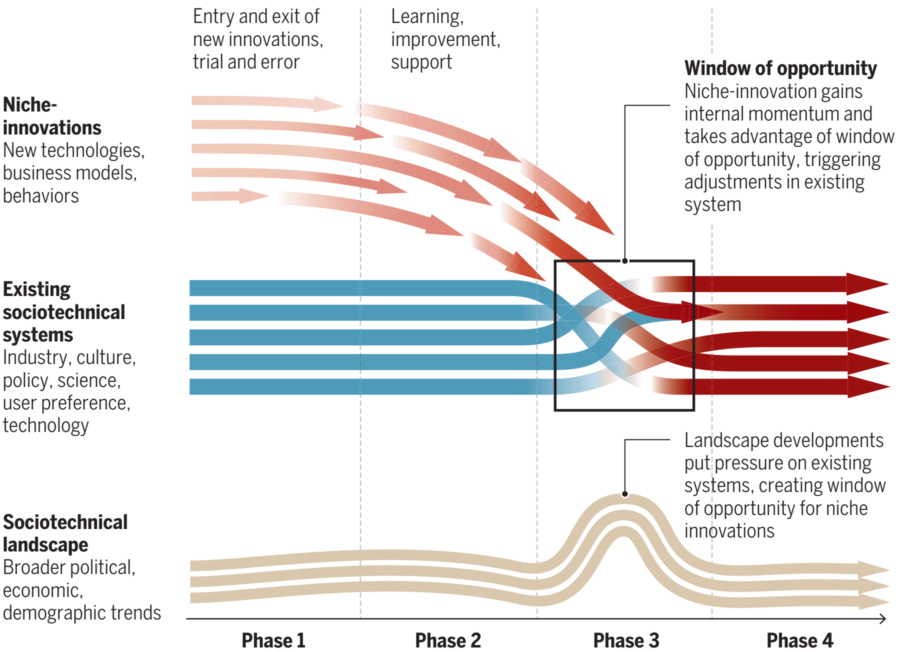
Sociotechnical transitions can be accelerated by actively phasing out existing technologies, supply chains, and systems that lock in emissions for decades (*13*). The UK transition to smokeless solid fuels and gas, for example, was accelerated by the 1956 Clean Air Act, which allowed cities to create smokeless zones where coal use was banned. This drastic policy was introduced after the 1952 Great London Smog (resulting in 4000 excess deaths) created public pressure and the political will for change (*14*). Another example is the 2009 European Commission decision to phase out incandescent light bulbs, which accelerated the shift to compact fluorescents and LEDs. The French and UK governments have announced plans to phase out petrol and diesel cars by 2040. Moreover, the United Kingdom intends to phase out unabated coal-fired power generation by 2025 (if feasible alternatives are available).

Phasing out existing systems accelerates transitions by creating space for niche innovations and removing barriers to their diffusion. The phase-out of carbon-intensive systems is also essential to prevent the bulk of fossil fuel reserves from being burned, which would obliterate the 2°C target. This phase-out will be challenging because it threatens the largest and most powerful global industries (e.g., oil, automobiles, electric utilities, agrofood, and steel), which will fight to protect their vested economic and political interests.

Phase-out policies can take several forms (*15*): bans or regulations that stipulate emission reductions from specific technologies or sectors; targeted financial incentives to encourage decarbonization; or removal of implicit or explicit subsidies for high-carbon systems, which globally range from $1.9 to $5.3 trillion per year (*16*). Whatever policies are used, it is important to consider transitional strategies such as phased tightening of regulations, financial compensation, retraining of personnel, or redevelopment programs for disadvantaged regions (*17*). Such policies may reduce the likelihood of resistance to transitions. Dutch policy-makers, for instance, alleviated the disruption of the 1960s transition from coal to gas by retraining miners and assisting the state-owned company's transformation to a chemicals firm (*18*). Unassisted UK mine closures, in contrast, disrupted entire communities in the 1980s, creating persistent social problems. Similar fears are presently motivating U.S. and German coal mining communities to resist low-carbon transitions, leading to political backlashes.

Foster innovations to take advantage of windows of opportunity

Internal and external forces pressure the existing system, which can realign around maturing innovations



POLICY IMPLICATIONS

General policy implications for accelerated low-carbon transitions can be derived from the above lessons. First, innovation is a crucial accelerator, although not just because it can improve technological price and performance characteristics of low-carbon technologies. Innovation can also open up new markets, disrupt existing systems, galvanize public enthusiasm around positive visions, and build social and business coalitions that in the longer term may support stronger climate policies. Sector-specific innovation policy is therefore at least as important as economy-wide climate policy and may in fact enable it (*9*). Innovation policies (R&D subsidies, feed-in-tariffs, demonstration projects, and adoption subsidies) are also more feasible politically than economy-wide carbon taxes, because the former provide concentrated benefits, whereas the latter impose costs on many voters and industries (*8*).

Second, low-carbon innovation policy should focus not only on R&D and financial incentives but also on experimentation, learning, stakeholder involvement, social acceptance, positive discourses, and opportunities for new entrants. Without sufficient societal and business support, it is difficult to accelerate or sustain low-carbon transitions for long periods.

Third, stronger alignments are necessary between innovation policy and sector-specific policy (in electricity, heat, transport, and urban planning) to explore the potential of interacting technologies and systems, through both foresight methods and on-the-ground demonstration projects. Polycentric efforts in particular, which connect and align scales, actors, and responsibilities, tend to be more effective than efforts contained to one scale.

Fourth, since the emergence of innovations takes time, accelerated low-carbon transitions also involve actively phasing out existing systems. This requires careful political attention to the social and distributional consequences of decarbonization.

Policy-oriented research on deep decarbonization requires complementing model-based analysis with sociotechnical research. Whereas the former analyzes technically feasible least-cost pathways, the latter addresses innovation processes, business strategies, social acceptance, cultural discourses, and political struggles, which are difficult to model but crucial in real-world transitions. Although full integration of both approaches is not possible, bridging strategies may enable iterative interactions in which models provide techno-economic checks of qualitative narratives, while sociotechnical approaches provide wider feasibility checks on model outcomes (*19*). Such analyses may underpin the development and implementation of policy strategies that are both cost-effective and sociopolitically feasible. ■

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