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Review

The Socio-Technical Dynamics of Low-Carbon Transitions

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Effective mitigation of climate change will require far-reaching transformations of electricity, heat, agricultural, transport, and other systems. The energy studies and modeling research that so often dominate academic and policy debates provide valuable insights into these transitions, but remain constrained by their focus on rational decision-making and their neglect of non-linear dynamics and broader social processes. This review describes insights from a complementary socio-technical approach that addresses the interdependent social, political, cultural, and technical processes of transitions. Focusing on the "multi-level perspective", the paper conceptualizes transitions as arising from the alignment of processes within and between three analytical levels: niche innovations, socio-technical regimes, and the socio-technical landscape. This analytical framework is illustrated with a case study of the German electricity transition and is used to appraise low-carbon transitions in several other sectors. We end by articulating four lessons for managing low-carbon transitions.

Introduction

Effective mitigation of climate change will require simultaneous transitions toward low-carbon electricity, heat, agricultural, transport, and other systems. The energy studies and modeling approaches that dominate academic and policy debates provide valuable insights into the nature and characteristics of these transitions, but also have several important limitations.[1]

First, such studies have a limited representation of the range of actors involved (mostly firms, consumers, and exogenous policymakers) and the manner in which they make decisions (mostly rational, optimizing). Second, transitions are frequently conceptualized as tame processes, consisting of the steady deployment of low-carbon technologies represented via smooth diffusion curves. Third, techno-economic models tend to optimize on one dimension (social surplus or cost), identifying optimal or "first-best" pathways, even if these include technologies that are socially controversial or not yet feasible, such as bio-energy with carbon capture and storage.[2]

To alleviate these limitations, we suggest that techno-economic models should be complemented with a more realistic understanding of the dynamics of low-carbon transitions. This broader understanding highlights four major challenges:

First, low-carbon transitions do not just involve firms and consumers but also a wider range of actors such as civil society groups, the media, local residents, city authorities, political parties, advisory bodies, and government ministries.[3] The actions of these groups are guided not just by cost-benefit calculations but also by entrenched beliefs, conflicting values, competing interests, unequal resources, and complex social relations.

Context & Scale

Intellectual debates are shifting from assessing the problem of climate change to implementing solutions. One popular approach, integrated assessment modeling, attempts to combine environmental science with policy analysis but struggles to address business strategies, power struggles, cultural meanings, and learning processes relevant for low-carbon innovations. The paper therefore describes a multi-level perspective (MLP) that offers a "big-picture" socio-technical understanding of low-carbon transitions that spans three analytical levels: (1) long-term secular developments; (2) developments in incumbent systems—strategic games, political struggles, and socio-cultural debates; and (3) radical low-carbon niche innovations, including local implementation projects.

We empirically illustrate and apply the MLP and articulate four policy lessons: (1) focus on dynamic policy mixes rather than single, static instruments; (2) analyze politics in addition to policy; (3) broaden the solution space beyond supply-side technology and economics; and (4) actively manage phase-outs in addition to stimulating innovation.

Second, low-carbon transitions are not only about the market diffusion of new technologies but also about changes in user practices, cultural discourses, and broader political struggles. Transitions are therefore not tame, but disruptive, contested, and non-linear processes. Disruptive, because they threaten the economic positions and business models of some of the largest and most powerful industries (e.g., oil, cars, electric utilities, agro-food), which are likely to protect their vested interests.[4] Contested, because actors disagree about the desirability of different low-carbon solutions and often resist their implementation (e.g., onshore wind turbines, carbon capture and storage). Non-linear, because climate change policies and low-carbon innovations can experience setbacks, accelerations, or cycles of hype and disappointment (e.g., current climate policies in the UK, USA, and Australia).[5]

Third, low-carbon transitions require complex negotiations and trade-offs between multiple objectives and constraints, including cost-effectiveness, equity, social acceptance (legitimacy), political feasibility, resilience, and flexibility.[6] The uncertain, long-term benefits of carbon mitigation lack salience and need to be aligned with other objectives to gain stakeholder support.

Fourth, low-carbon transitions are goal-oriented or "purposive" in the sense of addressing the problem of climate change. This makes them different from historical transitions which were largely "emergent," with entrepreneurs exploiting the commercial opportunities offered by new technology.[7,8] Since climate protection is a public good, private actors (e.g., firms, consumers) have limited incentives to address it owing to free-rider problems and prisoner's dilemmas. This means that public policy must play a central role by changing economic frame conditions (via taxes, subsidies, regulations, and standards) and supporting the emergence and deployment of low-carbon innovations. However, substantial policy changes involve political struggles and public debate because: "[w]hatever can be done through the State will depend upon generating widespread political support from citizens within the context of democratic rights and freedoms."[9] These considerations reinforce the point that low-carbon transitions involve interactions between multiple societal groups.

To address these challenges, this paper builds on calls[10,11] to include more social science in climate mitigation research and presents a "socio-technical" framework for understanding and managing low-carbon transitions. This framework has guided work within the Sustainability Transitions Research Network (http://www.transitionsnetwork.org/), which has more than 1,300 members globally. The following section introduces the socio-technical perspective, while the next section illustrates these ideas with a case study of the German electricity transition. The fourth section reflects on the status of low-carbon transitions in different sectors, while the fifth section outlines some lessons for managing these transitions. The last section draws conclusions.

Levels and Phases in Socio-Technical Transitions

The multi-level perspective (MLP) argues that transitions entail major changes in the "socio-technical systems" that provide societal functions such as mobility, heat, housing, and sustenance.[12] These systems consist of an interdependent and co-evolving mix of technologies, supply chains, infrastructures, markets, regulations, user practices, and cultural meanings.[13] Socio-technical systems develop over many decades, and the alignment of these different elements leads to path dependence and resistance to change. Existing systems are maintained,

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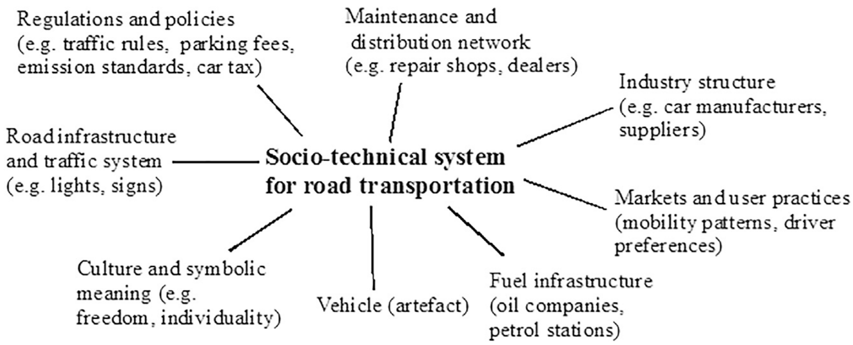

Figure 1. Schematic Figure of Socio-Technical System of Auto-mobility

defended, and incrementally improved by incumbent actors, whose actions are guided by deeply entrenched rules and institutions termed "socio-technical regimes." Figure 1 provides an example of the car-based transportation system, which in most Western countries accounts for 80%–85% of passenger-kilometers. This system is sustained by formal and informal institutions, such as the preferences and habits of car drivers; the cultural associations of car-based mobility with freedom, modernity, and individual identity; the skills and assumptions of transport planners; and the technical capabilities of car manufacturers, suppliers, and repair shops.[14]

The MLP argues that socio-technical transitions involve interactions between the incumbent regime, radical "niche innovations," and the "socio-technical landscape." Niche innovations are emerging social or technical innovations that differ radically from the prevailing socio-technical system and regime, but are able to gain a foothold in particular applications, geographical areas, or markets (e.g., the military), or with the help of targeted policy support. The socio-technical landscape refers to broader contextual developments that influence the socio-technical regime and over which regime actors have little or no influence. Landscape developments comprise both slow-changing trends (e.g., demographics, ideology, spatial structures, geopolitics) and exogenous shocks (e.g., wars, economic crises, major accidents, political upheavals). The MLP's key claim is that transitions come about through the alignment of processes within and between the three levels, as depicted in Figure 2. Hence, to fully explain transitions it is necessary to identify these processes and the complex interactions between them; while to effectively shape the speed and direction of transitions it is necessary to influence several of these processes simultaneously.

The MLP distinguishes four phases in these decades-long transition processes.[15] In the first phase, radical innovations emerge in niches, on the fringe of existing regimes. Innovator networks are unstable, uncertain, experimental, and fragile, propagating different design options, many of which will fail.

In the second phase, the innovation enters small market niches that provide resources for further development and specialization. The innovation develops a trajectory of its own, with a dominant design emerging and with expectations and associated rules beginning to stabilize.

In the third phase the innovation breaks through more widely and begins to compete head-on with the established regime. On the one hand, this process depends upon

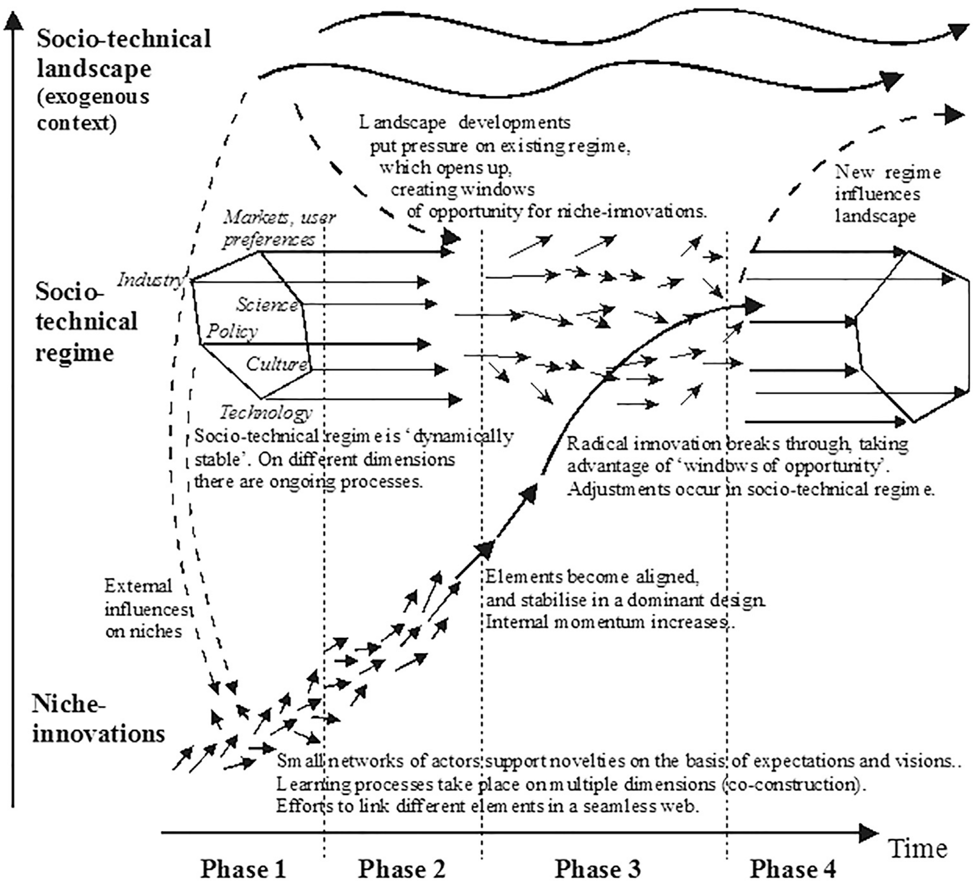

Figure 2. Multi-level Perspective on Socio-Technical Transitions
Modified from Geels and Schot.[13]

drivers internal to the niche such as price/performance improvements, scale and learning economies, the development of complementary technologies and infrastructures, positive cultural discourses, and support from powerful actors. On the other hand, the incumbent regime begins to destabilize as a consequence of persistent internal problems (e.g., urban air quality), landscape pressures (e.g., rising oil prices), or a combination of the two, thereby creating windows of opportunity for niche innovations. Table 1 summarizes some typical drivers of niche momentum, along with typical sources of tension within regimes. Struggles between niche innovations and existing regimes typically play out on multiple dimensions, including: economic competition between old and new technologies; business struggles between new entrants and incumbents; political struggles over adjustments in regulations, standards, subsidies, and taxes; and discursive struggles over problem framings and social acceptance.

The fourth phase is characterized by regime substitution, with the widespread adoption of the new innovations being accompanied by far-reaching adjustments in infrastructures, policies, industrial and market structures, lifestyles, and views on normality. The new regime becomes institutionalized and increasingly taken for granted.

Socio-Technical Analysis of the German Electricity Transition (1990–2016)

To make the socio-technical approach more concrete, we provide an illustrative analysis of the unfolding German electricity transition (Figure 3). Our aim is to

Table 1. Drivers of Niche Momentum and Regime Tensions

	Endogenous Niche Momentum	Regime Tensions
Techno-economic	price/performance improvements as a result of R&D, learning by doing, scale economies, complementary technologies, and network externalities	technical failures, disruption of infrastructures, accumulating negative externalities (e.g., CO_2 emissions)
Business	new entrants or incumbents from other sectors are more likely to drive radical innovation than traditional incumbents. Their success may lead to "innovation races" when other firms follow a first mover	shrinking markets, economic difficulties in incumbent industries, loss of confidence in existing technologies and business models, reorientation toward alternatives
Social	growing support coalitions and constituencies improve available skills, finance, and political clout	disagreement and fracturing of social networks, defection of key social groups from the regime
Political	advocacy coalitions lobby for policy changes that support the niche innovation such as subsidies and supportive regulations	eroding political influence of incumbent industries, declining political support, removal of supportive policies, introduction of disruptive policies
Cultural	positive discourses and visions attract attention, create cultural enthusiasm, and increase socio-political legitimacy	negative cultural discourses undermine the legitimacy of existing regimes (e.g., coal and climate change, diesel cars, and air quality)

R&D, research and development; CO_2, carbon dioxide.

illuminate the multiple economic, social, political, and cultural processes at work, together with the interactions between the three levels illustrated in Figure 2. Our focus is the transition toward renewable energy technologies (RETs) that occurred over the period 1990–2016, which laid the foundation for the official energy transition policy (*Energiewende*) adopted in 2011. Although we focus on electricity generation, further development of the transition could also require complementary innovations, such as energy storage (e.g., batteries, flywheels, compressed air, pumped hydro), 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 capacity markets to ensure system security).

German R&D programs in wind and solar photovoltaics (PV) were stimulated by the 1970s' oil crises, but deployment initially remained limited because of perceived poor performance and high costs.[16] During the 1980s, small wind turbines were adopted to some degree by environmentally motivated citizen groups, farmers, and smaller utilities, which in turn helped to stimulate a positive discourse around green energy.[17] The 1986 Chernobyl accident was a landscape shock that stimulated the engagement of anti-nuclear activists who wanted to demonstrate the feasibility of alternatives.[18] The accident also hardened negative public attitudes toward nuclear power, leading to an institutionalization of views that had been advanced by an active anti-nuclear movement in preceding years.[19] This discursive "crack" in the regime was plastered over by successive Conservative-Liberal governments, who continued to support nuclear power.

The nurturing of RET niches continued in the 1990s, most notably through the 1991 Feed-In Law that obliged utilities to connect RETs to the grid and to purchase renewable electricity at 90% of the retail price. Earlier proposals for RET market support had been defeated in Parliament, but the 1991 proposal succeed "by accident" as the government was preoccupied with German reunification.[20] The Feed-in Tariff (FiT) made onshore wind deployment economically feasible, stimulating significant deployment in the 1990s (Figure 4). The success of German turbine manufacturers (Enercon, Husumer Schiffswerft, Tacke) expanded the RET support coalition and attracted industrial policy support in the peripheral regions of northern Germany. The FiT was too low, however, to

Figure 3. German Electricity Generation by Source, 1990–2016 (%)
Source: AGEnergiebilanzen.

make solar PV and biogas economically feasible. Green NGOs, industrial firms (including Siemens), and the German Biogas Association lobbied for more support, based on the discourse of ecological modernization, but with limited direct success.[18] The green advocacy coalition was successful, however, in defeating a 1997 government proposal to reduce the feed-in tariffs, for which utilities had lobbied. Public protests by environmental groups, solar and wind associations, metal and machine workers, farmers' groups, and church groups led to the rejection of the proposal by the German Parliament.[16]

The election of a "Red-Green" coalition government between the Social Democratic Party and the Green Party (1998–2005) was a landscape shock that disrupted the cozy regime-level relations between utilities and policymakers. In 2002, the government decided to phase out nuclear energy, a move that was opposed by utilities in subsequent years. The government also introduced the Renewable Energy Act (EEG, 2000), which guaranteed fixed, premium payments for renewable electricity over a 20-year period, with the tariffs varying with the maturity of the technology. The Red-Green government also liberalized the electricity sector in 1998. Subsequent mergers and acquisitions resulted in the Big-4 utilities (RWE, E.ON, Vattenfall, and EnBW) capturing 90% of the wholesale market by 2004. By the mid-2000s, instead of focusing on renewables, the Big 4 were investing in new coal- and gas-fired power plants to meet expected demand growth.[21]

Between 2005 and 2011, the share of renewables in total generation doubled from 10.0% to 20.1%, owing to generous FiTs, falling costs (especially for solar PV), positive discourses, and growing societal interest.[22] The very rapid diffusion of solar PV after 2006 (Figure 4) was unforeseen and driven by tariffs that far exceeded the cost of generation. This stimulated strong interest from households who deployed small-scale rooftop PV systems, and from farmers who deployed large-scale roof- and field-mounted systems.[23] Despite having a relatively limited

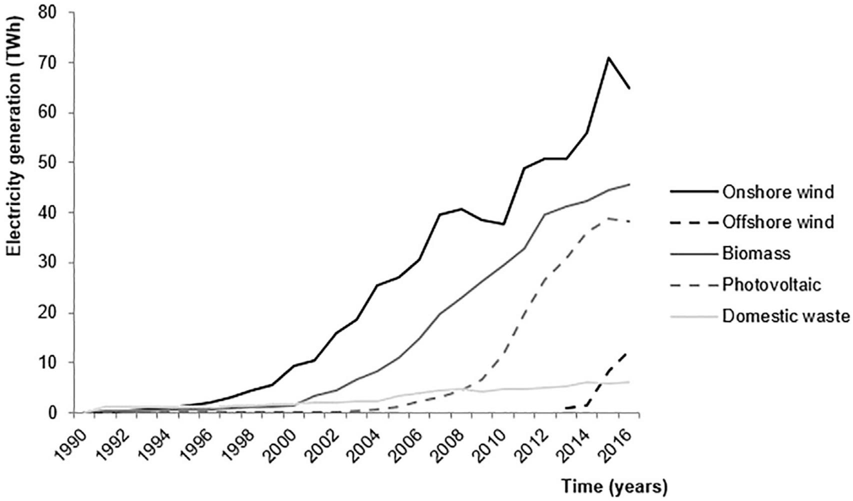

Figure 4. Electricity Generation from German Renewable Energy Technologies, Excluding Hydro, 1990–2016 (TWh)
Source: AGEnergiebilanzen.

solar resource, Germany accounted for almost one-third of global PV capacity by 2011. Solar PV became an industrial success story, as total sales of the German PV industry grew from €201 million in 2000 to €7 billion in 2008. Export sales grew from €273 million in 2004 to approximately €5 billion in 2010.[24] The EEG also enabled a "social opening up" of the electricity sector,[18] with farmers, municipal utilities, households, communities, project developers, and other industries entering the generation market (Table 2). In contrast, incumbent utilities had only limited involvement in RET deployment, producing just 6.5% of non-hydro renewable electricity in 2010 (Table 2).

The Big-4 utilities continued to focus on growth in this period, increasing their stock prices (Figure 5) through European and global expansions.[26] They also enjoyed windfall profits from the European Emissions Trading Scheme (EU ETS), since they were allowed to raise wholesale prices to reflect the opportunity cost of carbon allowances, despite receiving those allowances for free.[27] After years of lobbying, the utilities also scored a political victory when the newly elected (2009) Conservative-Liberal government decided to overturn the earlier nuclear phase-out decision. Their public reputation deteriorated toward the end of the decade, however, because they were increasingly seen as large oligopolists who faced insufficient competition, generated excessive profits, and ignored public concerns. After 2008, the utilities faced growing economic pressures from a global financial crisis (which depressed economic activity and thereby electricity demand), the expansion of renewables (which reduced the market share of fossil plants), and decreasing wholesale electricity prices (because of declining coal prices and low marginal costs of renewables, which means they are dispatched first in power generation). These developments led to a decline in net income from 2011 onward.[26]

The period 2011–2016 saw the destabilization of the electricity regime and further diffusion of RETs, which accounted for 29% of electricity generation in 2016. The Fukushima accident (2011) was a landscape shock that led the government to perform a U-turn and reintroduce the nuclear phase-out, with a target date of 2022. The government also introduced an economy-wide energy transition policy (*Energiewende*) that included ambitious targets for renewable electricity

Table 2. Ownership of Installed Capacity of Different Renewable Electricity Technologies in Germany in 2010

	Households (%)	Farmers (%)	Banks, Funds (%)	Project Developers (%)	Municipal Utilities (%)	Industry (%)	Four Major Utilities (%)	Others (%)
Wind	51.5	1.8	15.5	21.3	3.4	2.3	2.1	2.2
Biogas	0.1	71.5	6.2	13.1	3.1	0.1	0.1	5.7
Biomass	2.0	0	3.0	6.9	24.3	41.5	9.6	12.7
Solar PV	39.3	21.2	8.1	8.3	2.6	19.2	0.2	1.1

Source: Klaus Novy Institut.[25]

(35% by 2020, 40%–45% by 2025, 55%–60% by 2035, and 80% by 2050). Regime destabilization thus created opportunities for the diffusion of renewables, as predicted by the MLP. Diffusion was also driven by endogenous dynamics, such as policy support, positive discourses, and declining RET prices. The price of PV modules, for instance, decreased more than 65% between 2007 and 2011, as a result of scale economies in Chinese production, oversupply, and price dumping.[28] Growing market demand boosted German solar PV generation, which increased from 6.6 TWh in 2009 to 38.2 TWh in 2016 (Figure 4).

Nevertheless, these developments also had unintended negative consequences. For example: (1) many German PV manufacturers went bankrupt because of Chinese competition, which eroded the strength of the green growth discourse; (2) renewables deployment (especially solar PV) increased EEG surcharges from 1.3 eurocent/kWh in 2009 to 6.24 eurocent/kWh in 2014, helping to make German retail electricity prices the highest in Europe[22]; (3) the growing size and regressive nature[29] of these surcharges encouraged political opposition, including from utilities and the Economics Ministry; and (4) the growing proportion of intermittent renewables challenged grid stability and increased wholesale price volatility in both German and neighboring electricity markets, with negative prices on sunny, windy days when supply exceeded demand.

These problems led to government efforts to contain the speed and direction of the electricity transition. Cost-reduction attempts from 2010 onward led to several downward adjustments in the EEG policy.[30] The substantial 2012 adjustment in EEG subsidies sharply slowed solar PV deployment (Figure 4). Another adjustment in 2014 announced that FiTs would be replaced by a bidding system for target capacity by 2017, which is likely to introduce more uncertainty. To facilitate market integration of RETs, the government introduced new policies to stimulate direct marketing of renewable electricity.[31]

Another reason for introducing these containment policies was that the Big-4 utilities were facing substantial economic problems. The immediate shut-down of eight nuclear reactors in 2011, and the closure of the remainder by 2022, threatened major financial losses. Low wholesale prices and competition from RETs undermined the profitability of many conventional power plants, leading to doubts about the viability of traditional business models. In 2012, the CEO of EnBW stated in the annual report that: "… I see a paradigm shift in the energy sector that questions the traditional business model of many power supply companies." A confidential paper titled "RWE's Corporate Story" raised gloomy prospects: "… The massive erosion of the wholesale prices caused by the growth of German photovoltaics constitutes a serious problem for RWE which may even threaten the company's survival."[22] In this volatile context, the Big-4 utilities began strategic reorientation activities, searching for viable business models. In 2014, E.ON decided to split its

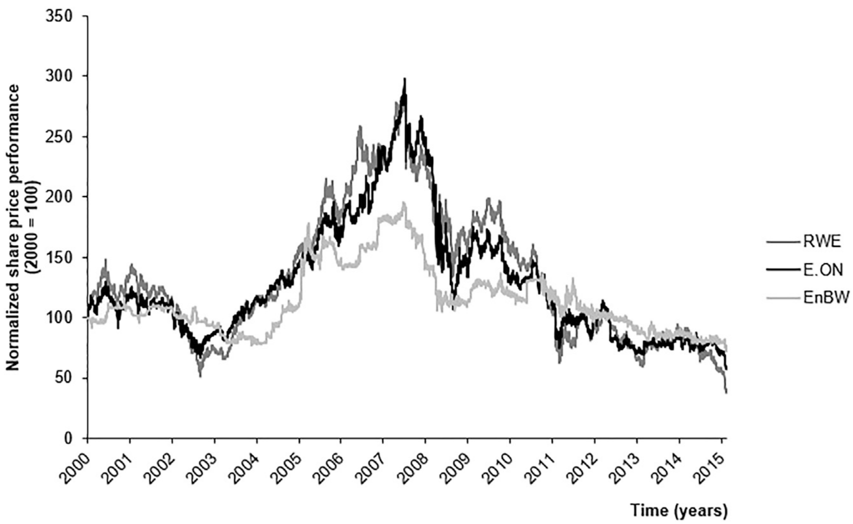

Figure 5. Share Price Performance of German Electricity Companies Normalized by Starting Date
Source: Finanzen.net. Note: Vattenfall is not included because it is a Swedish state-owned company.

business into two separate companies: one would focus on renewables, distribution grids, and service activities while the other would hold conventional assets in large-scale electricity production and trading activities. In 2015, Vattenfall offered its German lignite activities for sale, which represented a major retreat from the German market. In 2015, RWE announced plans to separate its renewables, grid, and retail business in a new subcompany.[26] These problems raised concerns in government, which perceived the utilities as "too big to fail." The government therefore aimed to slow RET expansion and to strengthen support for the utilities. Conventional power plants were increasingly framed as complementary to RETs and as necessary (in the short to medium term) for guaranteeing the stability of the electricity system. Attention also turned to new policies such as demand-side response and "capacity markets," with the latter rewarding generators for providing available capacity rather than electricity generation.[31] The government also stimulated the deployment of offshore wind, which provided an attractive diversification opportunity for incumbent utilities because of size and cost structures.

This brief case study demonstrates several core themes of the socio-technical perspective. First, the German energy transition was clearly a multi-dimensional process, with complex interactions between techno-economic, business, social, political, and cultural dimensions whose relative importance changed over time.

Second, the transition can be fruitfully analyzed as struggles between niche innovations (linked to new entrants) and existing regimes (linked to incumbents). Exogenous landscape pressures (reunification of East and West Germany, Fukushima, financial-economic crisis) played important roles in destabilizing the regime and creating windows of opportunity for the diffusion of niche innovations. The success of niche innovations also depended upon endogenous drivers, such as supportive policies, price/performance improvements, new business creation, positive discourses, and broad advocacy coalitions.

Third, the transition was non-linear and characterized by surprises. For example: (1) the solar PV boom after the mid-2000s was not foreseen; (2) the green growth

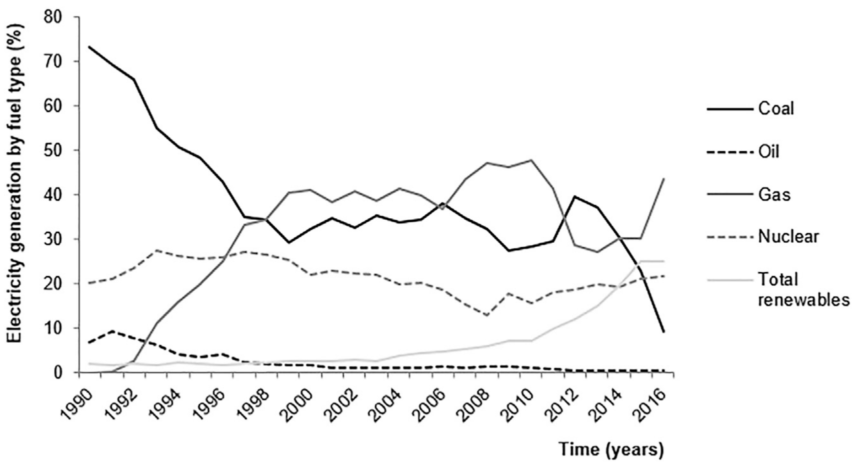

Figure 6. UK Electricity Generation by Fuel Type, 1990–2016 (%)
Source: Digest of UK Energy Statistics.

success story was disrupted by cheaper Chinese imports that bankrupted several German firms; (3) the Fukushima accident was an influential external shock that triggered a policy U-turn; and (4) the expansion of intermittent renewables disrupted normal market functioning, creating the need for fundamental redesign. Such non-linearities and surprises are common in transitions, implying that policymaking needs to be flexible and adaptive.

Fourth, the transition was full of political conflict and struggles. There were continuous struggles, for instance, over nuclear policy. Utilities fought the 2002 phase-out decision, lobbied the Conservative-Social Democrat government (2005–2009) for a roll-back, succeeded in 2009, were faced with a U-turn in 2011, and have since sought financial compensation for the nuclear phase-out via court cases. There were also struggles between Ministries over responsibilities and priorities. In 2002, for instance, the Red-Green government transferred the responsibility for renewable energy policy from the Economics Ministry to the Ministry for Environmental Affairs, which was more positively oriented toward RETs. In 2014, the government transferred this responsibility back to the Economics Ministry. Another battleground was the resistance from German utilities against renewables support policies. In 1995, utilities contested the legality of the Feed-In Law in German courts and the European Court of Justice. They also tried to delegitimize RETs by framing them as expensive and unreliable. Since 2009, this discourse gained traction with Conservative-led government coalitions. Combined with concerns over the economic viability of utilities and the impact of rising prices on electricity consumers, the government started downscaling EEG support. This last point also highlights the importance of dealing with potential "losers" in transitions, something we address further below.

Status of Low-Carbon Transitions in Different Domains

Broadening out from this case study, we use the MLP to briefly appraise the status of low-carbon transitions in different domains. Progress is greatest in electricity systems, where niche innovations such as wind and solar PV are diffusing rapidly,[32] moving from phase 2 to phase 3 in countries such as Denmark, Portugal, Germany (see Figure 3), and the UK (Figure 6). The result is substantial disruption of existing regimes (e.g., economic problems for utilities, perceived threats to supply security) and major adjustments to those regimes (e.g., interconnection, electricity storage,

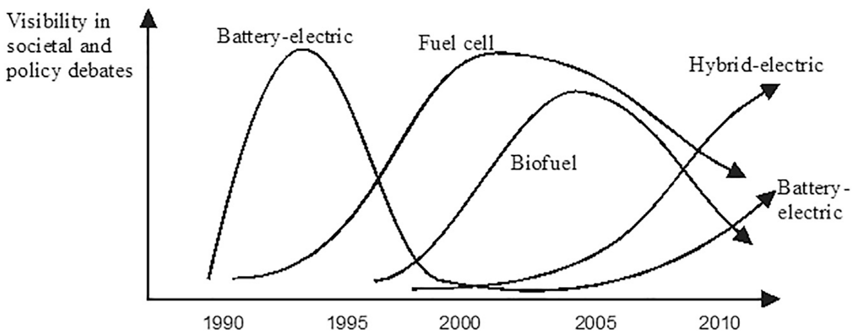

Figure 7. Hype-Disappointment Cycles for Green Car Propulsion Technologies
Source: Geels.[14]

smart grids, demand-side response, and market redesign). However, other low-carbon innovations such as carbon capture and storage and nuclear energy are progressing much slower than anticipated, owing to implementation problems related to public opposition, industry resistance, and lack of political will.[33]

Low-carbon transitions have less momentum in passenger transport, where the petroleum-fueled auto-mobility regime is still deeply entrenched in most Western countries. Some niche innovations are moving from phase 1 to phase 2, particularly hybrid-electric vehicles (HEV), plug-in hybrids (PHEV), and battery-electric vehicles (BEV). In 2015, more than 1.26 million PHEVs and BEVs were on the road globally, and they exceeded 1% of new vehicle sales in five countries (Sweden, Denmark, France, China, and UK) and 5% in two more (Norway and the Netherlands).[34] In 2017 Volvo announced that it will cease production of conventional vehicles by 2019. However, while many analysts extrapolate these positive trends into the future, others are more cautious because low-carbon transport innovations have a history of hype-disappointment cycles (Figure 7).[5] It seems as if BEVs are currently experiencing a second period of recent hype, after an earlier one followed by disappointment in the 1990s. Then again, it is also possible that organizations such as the International Energy Agency will be proved correct and that a genuine breakthrough is taking place that will accelerate in many countries over the next decade.

Low-carbon transitions in agriculture and food are also progressing slowly. Agriculture is a very dispersed regime (geographically and via commodity chains), with supermarkets and food processing occupying powerful positions between consumers and farmers. Low-carbon niche innovations exist (e.g., artificial meat, organic food, manure digestion, farmers' markets, vegetable box schemes), but have limited momentum because of high costs, cultural attachments to existing diets, weak and fragmented policies, and industry reluctance.[35]

Heat and building regimes are also fairly stable owing to the slow turnover of stock, the high cost of low-carbon alternatives, industry lock-in, and entrenched user practices. Incremental innovations (efficient boilers, insulation, and double glazing) have improved the energy performance of buildings, but opportunities for further deployment are declining. In contrast, radical niche innovations, such as whole-house retrofits, passive houses, heat pumps, and district heating networks have relatively little momentum and continue to face multiple obstacles such as high upfront costs, split incentives, limited consumer familiarity, absence of supporting infrastructure, and stunted supply chain skills.[36]

One reason for the more rapid transition in electricity is that the relevant technologies are easy to target and policies such as feed-in tariffs have been highly successful in reducing investment risk. However, this begs the question of why similar policies have not worked as well in other systems. We suggest that the electricity system has three characteristics that facilitate more rapid transition. First, the electricity grid acts as a buffer, making it possible to make radical changes to the generation mix with only limited consumer involvement. Consumers typically pay for low-carbon electricity generation through their electricity bills, but many are unaware of this indirect involvement mechanism. This is different in food, mobility, heat, and buildings, where consumers need to actively decide to purchase low-carbon innovations, which are often seen as costly and have different functional characteristics. Second, electricity is an undifferentiated product, meaning that consumers do not experience changes in functional characteristics with low-carbon electricity and do not need to change their practices. Again this is not the case for mobility, food, and buildings. Third, it is easier for policymakers to interact with a few centralized oligopolistic utilities than with millions of farmers, installers, or small building companies. Nevertheless, despite these differences in system characteristics, meeting ambitious climate targets requires accelerated transitions in all sectors. This in turn requires more differentiated policies, which we address next.

Lessons for Managing Low-Carbon Transitions

Governing low-carbon transitions is complex, because of uncertainties (about the future price and performance of radical innovations, social acceptance, consumer interest, and policy support), disagreements (about desirable solutions, policies, costs, and benefits), and distributed power (policymakers are not all-powerful and depend on other actors).[37] It is therefore insufficient to rely solely upon technically rational criteria for decision-making, whereby experts use computer models to determine an "optimal" transition path which is then implemented by policymakers. Our socio-technical approach to low-carbon transitions highlights at least four important lessons for low-carbon policy.

Focus on Dynamic Policy Mixes, Not Isolated or Static Instruments

Since transitions are multi-dimensional, long-term processes, policymakers should not rely upon a single policy instrument such as carbon pricing, especially when this continues to face major political obstacles.[38] Instead, policymakers should mobilize a range of items such as financial instruments (taxes, subsidies, grants, loans), regulatory instruments (standards, laws, performance targets), and processual instruments[39] (demonstration projects, network management, public debates, consultations, foresight exercises, roadmaps). The appropriate mix is likely to vary over time and between countries and domains, depending on political cultures and stakeholder configurations.[40] Nonetheless, a consistent theme within the energy policy literature has been the necessity of coordinated sets of policies for driving low-carbon innovation and transitions, rather than isolated instruments.[41,42] Such mixes come in different formats: sometimes different instruments carry equal weight, while at other times there is a clear hierarchy with one instrument dominating and others complementary or ancillary.

Consider three examples. To achieve a substantive shift to renewable electricity, California had to complement its mandatory renewable portfolio standard with the removal of excessive utility tariffs, the introduction of tax credits for renewable energy systems, and the use of large consumer awareness programs. In addition, regulators offered streamlined permission for small-scale solar projects, required net metering, and created a rigorous rebate program.[43] Similarly, Denmark was only able to achieve decarbonization of electricity and heat through a mix of carbon pricing, FiTs, government procurement programs, demand-side management, and R&D subsidies.[44]

Even in Germany, "demand-pull" instruments such as the FiT only worked as well as they did because they formed part of a broader policy mix including "supply-push" mechanisms such as R&D subsidies and "systemic measures" such as collaborative research projects and systems of knowledge exchange.[45]

In terms of temporality, the MLP (Figure 2) suggests that policymakers should aim to first nurture low-carbon niche innovations and support coalitions and then gradually increase selection pressures.[38,46] Specifically, in the first two transition phases, policymakers should prioritize network governance and innovation policies (e.g., demonstration projects, foresight and scenario workshops, R&D subsidies, FiTs), aimed at creating "protected spaces" for niche innovations that encourage learning, network building, initial deployment, and articulation of visions and discourses.[47,48] In phase 3, when niche innovations have acquired internal momentum, policymaking should become more selective by increasing pressures on the regime via economic incentives (e.g., carbon pricing) or stricter regulations. The niche-related support coalitions, which were built in phases 1 and 2, may help counter the political resistance and fightback from incumbent actors in phase 3.[38]

Analyze Politics, in Addition to Policy

Because low-carbon transitions are inevitably political, social scientists should provide analysis *of* policy (including its politics) as well as *for* policy.[49,50] Political scientists have developed a number of theoretical models to explain policymaking processes, and these can also provide useful insights for influencing those processes. For example, theories of policy networks see policymaking as a deeply political process involving negotiations, compromises, and the building of coalitions with stakeholders.[38] Acknowledging disagreements and distributed power, politics is the "art of the possible" rather than the "calculation of the optimal." This suggests that more expensive transitions may be preferable if stakeholder support makes their implementation more feasible. To support policymakers, scholars could offer better analyses of the interpretations, interests, resources, and strategies of different actor groups.[51] In other words, policy analysts should focus more on the complex dynamics involved in political struggles, social acceptance, and governance, where factors can serve as both constraints and catalysts for accelerated transition.

Similarly, theories of incrementalism[52] and muddling through[53] see policy implementation as a process of improvisation, experimentation, and learning by doing. This is particularly appropriate for managing the non-linear development of radical innovations, which may lead to surprises and unintended consequences that require flexibility and adjustments. To support policymakers, scholars could offer better analyses of the determinants of success for niche innovations, including the role of demonstration projects, network building, and learning processes.[47,48]

Broaden the Solution Space, beyond Supply-Side Technology and Economics

As noted, low-carbon transitions are proceeding at very different speeds in different parts of the economy. These widely different outcomes are only partly linked to the relative cost of abatement in these different sectors or to the specific characteristics of those sectors. They also reflect blind spots on the part of policymakers and analysts, which in turn are linked to the cognitive constraints imposed by existing regimes (restricting the perceived solution space), the inertia and path dependence of those regimes, and the political influence of the relevant incumbents.

The most obvious example is the bias toward energy supply rather than energy demand technologies that is visible within energy R&D programs, deployment support programs, integrated assessment models, and the overall policy mix.[54] Thirteen of the climate stabilization wedges specified by Pacala and Socolow, for instance, focus on energy supply, while only two wedges address energy demand (reduced use of vehicles and efficient buildings).[55] Reasons for this bias include the facts that energy supply technologies are small in number, similar in configuration, characterized by good data availability (which enables modeling), and provided by a small number of well-organized and politically powerful sectors.[54] Large supply-side investments are also politically salient with straightforward evaluation metrics (e.g., £/kWh), lending themselves to targeted and dedicated policy support. In contrast, end-use technologies (e.g., washing machines, televisions, boilers, internal combustion engines, ICT devices) are large in number, diverse in configuration, focused primarily upon other services, and supplied by a large number of sectors with less political power. The impact of efficiency improvements in those technologies (which have been substantial in some instances, e.g., refrigerators and light bulbs) is largely invisible, and the systems in which they are embedded are more difficult to target through policy intervention. The net result is a relative neglect of demand-side opportunities within climate policy, despite their multiple social benefits[56] and the expectation that they will account for more than half of the total global carbon abatement over the next century.[57]

A second example is the bias toward technological solutions, rather than broader changes in individual routines and social practices, such as more cycling and walking, car sharing, eating less meat, extending product life, and purchasing second-hand or used items. In combination, these have the potential to provide significant emission reductions.[58,59] However, despite this potential it remains difficult for policymakers to deliberately and substantially change user practices in low-carbon directions, for fear of being accused of being an interventionist "nanny state."[60]

From a socio-technical perspective, approaches to stimulate end-use technologies or behavior change should go beyond a dominant individual perspective, which focuses either on changing prices or on providing information (e.g., telling people it would be good for the climate if they adjust thermostat settings, turn off unneeded lights, or operate washing machines at full loads). The literature on technological domestication emphasizes that consumers do not just buy new technologies but also embed and appropriate them in their daily lives, which entails cognitive work (learning about the artifact and developing new competencies), symbolic work (acquiring new interpretive categories and cultural conventions), and practical work (adjusting routines to match the new technology).[61,62] Similarly, the literature on user practices suggests that substantial behavior change usually involves co-evolving changes in skills, meanings, and material components.[63] Pricing and information strategies therefore need to be complemented with polices aimed at encouraging learning (e.g., demonstration projects that address not just technical performance but also users' routines), facilitating public debate, and including trusted intermediary actors such as consumer organizations, NGOs, and community groups.[64]

Actively Manage Phase-Outs, in Addition to Stimulating Innovation

Most analysts and policymakers emphasize the necessity of supporting niche innovations, but this can obscure an equal need to phase out existing carbon-intensive regimes.[42] Such phase-out policies could include: (1) regulations that reduce emissions from specific technologies or sectors; (2) changing market rules for decarbonization through, e.g., a carbon tax or pricing; (3) policies to encourage social discussion and debate, such as the creation of new committees or networks; and (4) reduced support (such as tax breaks or subsidies) for high-carbon technologies.

The political resistance to phase-out is likely to be intense. For example, estimates of global energy subsidies range from \$1.9 to \$5.3 trillion (on a post-tax basis) per year, which mostly benefit coal, oil, and natural gas.[65] At the top end of this range, using an approach that monetizes "full social costs," the International Monetary Fund (IMF) estimate that global fossil fuel subsidies amounted to \$5.3 trillion in 2015, equivalent to 6.5% of global GDP.[66] According to IMF data, coal and petroleum still receive the lion's share of these subsidies, with the largest subsidies in absolute terms being in China (\$2.3 trillion), the USA (\$699 billion), and Russia (\$335 billion). This means that the financial stakes of decarbonization are vast, and the losers significant.

The potential job losses associated with displacing coal, natural gas, and oil may also lead to resistance. Some of these skills and jobs may be transferable to other sectors, such as offshore oil platform engineers putting their expertise into offshore wind turbine foundations, but many will not. A related concern is that higher income groups tend to be the first to adopt niche innovations such as solar panels, electric vehicles, and zero-energy buildings.[67] Hence, subsidizing those technologies could unwittingly exacerbate income inequality, especially if these subsidies are funded by levies on energy bills.

A pragmatic solution to managing, or at least ameliorating, "losses" is to actively plan for them and then provide adjustment packages for those most harmed—an action that may also undercut some of the political opposition against decarbonization (and one that could be funded by carbon pricing). In simple terms, losers need compensation so they will be less likely to hinder transitions. For instance, the German phase-out of coal subsidies involved a savings package for unemployed miners, and subsidy reform packages introduced by Iran, Namibia, the Philippines, Turkey, and the UK provide similar compensating measures to affected groups.[65] Such efforts ensure that what is necessary to protect the climate is also just for some of the most vulnerable in society.

Conclusion

Techno-economic approaches in energy studies are crucial for analyzing and managing low-carbon transitions, but since transitions are disruptive, contested, and non-linear they cannot be reduced to a technical deployment challenge, nor are they driven solely by financial incentives, regulation, and information provision. Low-carbon transitions also involve social, political, and cultural processes, and changes in consumer practices. The multi-level perspective offers a "big-picture" analytical framework that accommodates these broader processes and helps explain both stability and change. Energy and climate policy should not only include finance and regulation, but also stimulate learning and experimentation and the building of coalitions that develop emerging niche innovations and support political struggles. Analysts and policymakers should look beyond single-policy mechanisms such as carbon pricing and consider how a range of instruments can be woven into an effective mix. Analysts should also recognize that disagreement and contestation are central to low-carbon transitions and consider how best to accommodate these conflicts rather than ignore them. This will require aligning climate policy with broader policy objectives, minimizing the impact on low-income groups and providing explicit compensation. To understand and address these issues, techno-economic approaches should be complemented with frameworks that address the socio-technical dynamics of low-carbon transitions.[68,69]

AUTHOR CONTRIBUTIONS

F.W.G. led the drafting of the text with input from B.K.S., T.S., and S.S. All authors contributed to the intellectual content.

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