CHAPTER
9

TRANSFORMATIVE INNOVATION AND SOCIO-TECHNICAL TRANSITIONS TO ADDRESS GRAND CHALLENGES

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Summary

The aim of the chapter is to present the role of transformative innovation as a new paradigm to address many of the most pressing societal challenges we are facing, notably transition to sustainability and combatting climate change. It elaborates on what it means for research and innovation R&I) policy and attempts to 'operationalise' these transitions.

This chapter presents a broader conceptual model to benefit policies for transformative innovation and grand challenges that goes beyond the linear model and innovation system approaches. The new role for R&I is to support socio-economic transformations, but it needs to be complemented with other policies to have a stronger impact. After introducing the socio-technical transitions and potential barriers for the uptake of these niche innovations, the final analytical section gives several examples where these transformations have taken place, in both energy and mobility. The chapter closes with an extensive overview of policy conclusions.

1. Introduction

1.1 Grand challenges in a policy context: climate change, SDGs, and economic growth

Transformative innovation and systemic transitions are attracting increasing attention in the context of three policy problems. First, addressing climate change will require radical innovation and low-carbon transition in many systems, as the Commission's recent climate strategy recognises: 'The transition to a net-zero greenhouse gas emission economy by mid-century will radically transform our energy system, land and agriculture sector, modernise our industrial fabric and our transport systems and cities' (EC, 2018a: 6).

Second, addressing other grand societal challenges (such as ageing, obesity, energy security, urban quality of life, and inequality) and the Sustainable Development Goals (SDGs) will require transformative innovations in health care, agro-food and urban systems, as Vice-Presidents Timmermans and Katainen note in the foreword to the Commission's recent Reflections Paper: 'Sustainable development means that we need to modernise our economy to embrace sustainable consumption and production patterns, to correct the imbalances in our food system, and to our mobility, the way we produce and use energy, and design our buildings on to a sustainable path' (EC, 2019: 3).

Third, low-carbon and sustainability transitions offer attractive growth prospects, as the Commission's expert group on green growth and jobs concludes: 'There is a huge competitive opportunity for Europe to ride this 'green' trajectory and turn environmental problems into solutions for promoting investment and jobs. Such a green direction implies the use of technological capacities (which the EU has) in order to drastically increase the productivity of energy and material resources (which the EU only has in limited quantities). The markets of the future are bound to grow in that direction' (EC, 2016: 11). But to exploit and compete globally in this area, radical innovation should be nurtured: 'Europe is relatively strong in adding or sustaining value for existing products, services and processes, known as incremental innovation. (...) But Europe needs to do better at generating disruptive and breakthrough innovations' (EC, 2018b: 11).

1.2 Analytical challenges for innovation policy

Transformative innovation and systemic transitions pose analytical challenges for innovation policy that come in addition to traditional challenges. Schot and Steinmueller (2018) distinguish three frames for innovation policy, which respectively focus on stimulating R&D, improving knowledge flows in innovation systems, and stimulating transformation (Figure 9-1).

Figure 9-1 Three frames in innovation policy

Framing	Key features	Policy rationale	Policy approaches (examples)
Science and technology for growth (since 1950s)	Linear innovation model, driven by R&D (research and development)	Addressing market failures (firms invest insufficiently in R&D because of public good character of innovation)	State financing of R&D; subsidies or tax incentives for business R&D
National and sectoral systems of innovation for improved competitiveness (since 1980s)	Focus on knowledge flows between upstream actors (universities, firms, agencies)	Responding to system failures, e.g. improving linkages between actors, addressing institutional problems (in laws, property rights, regulations)	Promoting science hubs and science-industry collaboration; education and training; cluster policies
Transformative change to address grand challenges (since 2010s)	Nurture radical innovation and new pathways; shape directionality of innovation	Promote system transformation, which incumbent actors are slow or reluctant to do	Missions and goals (SDGs, climate targets), assisting new entrants, creating transformative coalitions, learning, experimentation

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Source: Author's elaboration based on Schot and Steinmueller, 2018
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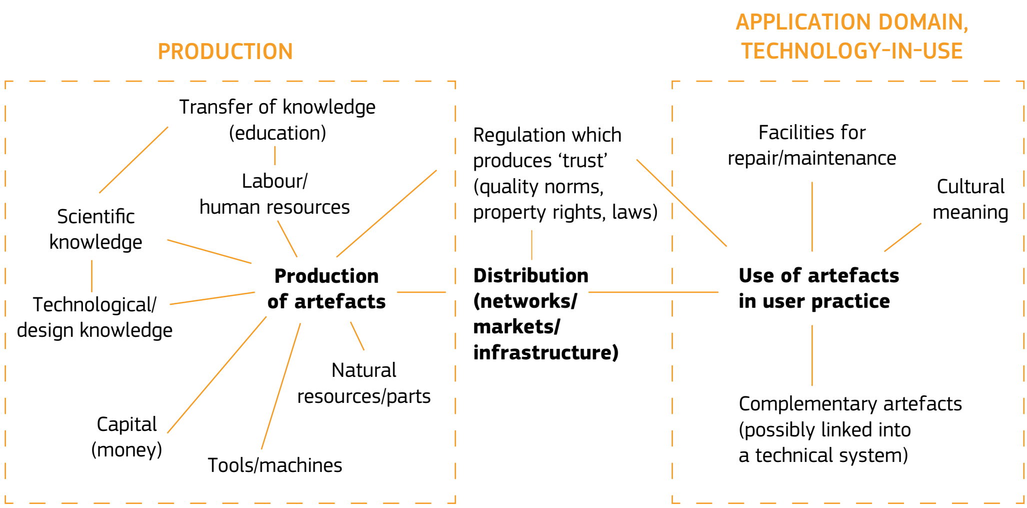
Whilst the first two frames remain relevant, transformative innovation and systemic transitions involve several new policy challenges.

Horizontal policy coordination

Systemic transitions go beyond products and technologies to involve changes in broader socio-technical systems, which refer to all the elements that make energy, mobility and agro-food systems work (Geels, 2004), as schematically represented in Figure 9-2. While innovation policy remains essential, horizontal coordination with other policy domains (e.g. labour markets, competition policy, finance, industry policy, transport/energy/agricultural policy, environmental policy) is crucial to transform entire systems.

Figure 9-2 Schematic representation of socio-technical system elements



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Source: Geels, 2004: 900

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Social, business model and infrastructural innovation

While innovation policy traditionally tends to focus on science and technology, transforming entire socio-technical systems involves not just radically new technologies, but also social, business model and infrastructural innovation (Bulkeley et al., 2013; Bolton and Foxon, 2015; Bolton and Hannon, 2016; Hoppe and de Vries, 2019; Van Waes et al., 2018). Focusing on environmental sustainability, Figure 9-3 provides some examples of innovations that may create the seeds for low-carbon and sustainability transitions.

Figure 9-3 Examples of radical innovations in mobility, agro-food and the energy domain

	Mobility	Agro-food	Energy (electricity, heat)
Radical technical innovation	Battery-electric vehicles, (plug-in) hybrid electric vehicles, biofuel cars, self-driving vehicles	Permaculture, agro-ecology, artificial meat, plant-based milk, manure digestion	Renewable electricity (wind, solar, biomass, hydro), heat pumps, passive house , biomass stoves, smart meters
Grass-roots and social innovation	Car sharing, bike clubs, modal shift to bicycles and buses, tele-working, tele-conferencing	Alternative food networks, organic food, 'less meat' initiatives, urban farming	Decentralised energy production ('prosumers'), community energy, energy cafés
Business model innovation	Mobility services, car sharing, bike sharing	Alternative food networks, organic food	Energy service companies, back-up capacity for electricity provision, vehicle-to-grid electricity provision
Infra-structural innovation	Intermodal transport systems, compact cities, revamped urban transport systems (tram, light-rail, metro)	Efficient irrigation system, agro-forestry, rewilding, multi-functional land use	District heating systems, smart grids, bio-methane in reconfigured gas grid

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Source: Author's elaboration based on Bulkeley et al., 2013; Bolton and Foxon, 2015; Bolton and Hannon, 2016; Hoppe and de Vries, 2019; Van Waes et al., 2018

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Wider set of actors and coalitions

While innovation policy traditionally has an 'upstream' focus (on knowledge flows between universities, firms, policymakers), the implication of the previous two points is that transformative innovation and transition processes require the involvement of a wider set of actors. The inclusion of new entrants, like start-up companies, cities, communities, citizens and NGOs, may help to create transformative coalitions that think out of the box and drive transitions (Diercks et al., 2019; Marletto et al., 2016; Söderholm et al., 2019; Steward, 2012).

EU policy discussions already recognise this idea, which underpins the notion of 'open innovation'. For example, the European Commission's RISE group (research, innovation and science experts) notes that: 'Traditionally, addressing societal challenges has been primarily a 'supply-pushed' concern with the research community playing a central role. (...) Implementation in terms of innovation has, however, often been disappointing. Typically, users and more broadly the demand side, has been insufficiently involved in the design and development of innovative ways to address those societal, global challenges' (EC, 2017a: 160).

The RISE group therefore recommends that: 'It will be crucial to break open the current supply-side research dominance in addressing societal challenges, which has sometimes cornered the discussion and debates to technical debates about measurement, evidence and methodologies' (EC, 2017a: 160).

The Commission's Lamy report similarly calls for wider stakeholder engagement: 'As part of a coherent innovation policy, EU policymakers should be required to regularly identify, in dialogue with stakeholders and citizens, how and what innovation can help them more easily achieve their objectives' (EC, 2017b: 12). 'Fully mobilising and involving stakeholders, end-users and citizens in the post-2020 EU R&I programme, for instance in defining its missions, will not only increase the degree of co-creation, it will also maximise its impact and stimulate a stronger demand for innovative products and services as well as a better grasp of social changes. This will bring open science and open innovation to the next level and turn Europe into a continental living innovation lab' (EC, 2017b: 19).

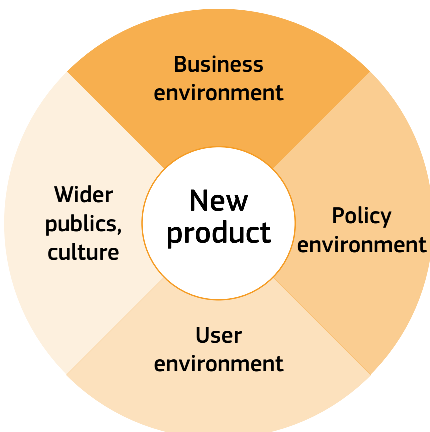
Visions and missions to create drive and directionality

While innovation policy traditionally focuses on rates of innovation, transformative innovation is also about directionality since sustainability transitions aim to solve particular problems and reach particular goals (e.g. 80-90% reduction of greenhouse gas emissions by 2050). Recent debates about mission-oriented innovation policy emphasise the importance of inspiring visions which provide long-term directionality and challenging, yet doable missions that formulate more specific targets (which enable accountability) and are accompanied by financial instruments (that enable concrete action) (Mazzucato, 2018).

Diffusion

While innovation policy tends to focus on the emergence of new ideas and innovations (R&D), transformation and system transitions only happen when radical innovations actually diffuse into markets and society, which includes embedding in business, user, civil society and policy environments (Deuten et al., 1997; Kanger et al., 2019; Mylan et al., 2019), as schematically represented in Figure 9-4.

Figure 9-4 Relevant environments for new products and practices



Source: Adapted from Deuten et al., 1997: 134

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These five challenges suggest that policies for transformative innovation and grand challenges could benefit from a broader conceptual model that goes beyond the linear model and innovation system approaches (Figure 9-1). Section 2 describes such a conceptual model, which provides a big-picture understanding of core processes and mechanisms in systemic transitions. The so-called multi-level perspective provides a general framework, which has been tested and refined with dozens of historical case studies, including shifts from cesspools to sewer systems, from horse-drawn transport to automobiles, from sailing ships to steamships, from traditional factories to mass production (Geels and Schot, 2007). It has also been widely applied to low-carbon transitions (Geels et al., 2016, 2017; Moradi and Vagoni, 2018; Berkeley et al., 2018) and has become a core framework in studies of sustainability transitions (Smith et al., 2010; Köhler et al., 2019). Section 3 empirically illustrates this model with three case studies of sustainability transitions: the German electricity transition, Austrian biomass district heating, and French tram systems. Section 4 discusses the five policy challenges in the three cases and ends with policy messages.

2. Multi-level perspective on socio-technical transitions

2.1 Basic concepts

Drawing on evolutionary economics, the sociology of innovation, and institutional theory, the multi-level perspective (Geels, 2002; 2004; Smith et al., 2010) suggests that transitions come about through the interplay between processes at niche, regime and landscape levels.

Radical innovations tend to emerge in small niches at the periphery of existing systems, through the pioneering activities of entrepreneurs, startups, activists or other relative outsiders (Van de Poel, 2000; Schot and Geels, 2008). Niche innovations like those in Figure 9-3 are 'radical' because they deviate from existing systems on technical, social, business model or infrastructural dimensions, which also implies they often cannot survive mainstream selection pressures. Niches therefore act as 'protected spaces' that shelter radical innovations in early phases and nurture learning and development processes (Smith and Raven, 2012).

Since radical innovations are often enacted by new entrants, they may entail organisational innovation and new business models (Bolton and Hannon, 2016; Van Waes et al., 2018), implying changes in the ways that firms appropriate value from their activities. Business model innovation may be risky and challenging, as the ongoing struggles of Tesla and Uber to become profitable suggest. Niches may also nurture social innovations and grass-roots innovations, although actors, motivations, and forms of protection may be different than those for market-based innovation (Figure 9-5). Grass-roots innovations include changes in social practices and lifestyle and using technologies (see Figure 9-3 for examples), which are typically enacted by volunteers and activists (Seyfang and Smith, 2007; Hargreaves et al., 2013), foreground moral values and collective aspirations, and are highly contextual, often developed in response to local problems (Hossain, 2018). Figure 9-5 summarises some of the differences

Figure 9-5 Comparing the characteristics of market-based and grass-roots innovations

	Market-based innovations	Grass-roots innovations
Context	Market economy	Social economy
Driving force	Profit: Schumpeterian rent	Social need; ideological
Niche protection	Market rules are different: tax and subsidies temporarily shelter novelty from full market forces	Values are different: alternative social and cultural expressions enabled within the niche
Organisational form	Firms	Voluntary associations, co-ops, informal community groups
Resource base	Income from commercial activity	Grant funding, voluntary input, mutual exchanges, limited commercial activity

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Source: Seyfang and Smith, 2007: 92
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between grass-roots innovations and market-based innovations. Despite these differences, temporal developments of both types of innovation can be analysed with strategic niche management categories (learning, network building, visioning), although specific mechanisms vary (as discussed in section 2.2).

Radical niche innovations face uphill struggles against existing energy, agro-food and mobility *systems*, which are stabilised by the alignments between technologies, policies, user patterns, infrastructures and cultural discourses (Figure 9-2), that were created in previous decades. Elements of existing systems are reproduced, maintained and incrementally improved by incumbent actors, such as firms, engineers, users, policymakers and special-interest groups. The perceptions and actions of these social groups are shaped by entrenched shared rules and institutions, called *socio-technical regimes* (Geels, 2004; Fuenfschilling and Truffer, 2014). Innovation in existing systems and regimes is mostly incremental and path-dependent because of various lock-in mechanisms (Klitkou et al., 2015):

- Techno-economic lock-in mechanisms: a) sunk investments (in competencies, factories, infrastructures) that create vested interests against transitional change; b) low-cost and high-performance characteristics of existing technologies due to economies of scale and decades of learning-by-doing improvements.

- Social and cognitive lock-in mechanisms: a) routines, shared mindsets and core capabilities that 'blind' firms and other actors to developments outside their focus (Leonard-Barton, 1992; Nelson, 2008); b) 'social capital' resulting from alignments between social groups; organisations develop 'webs of interdependent relationships with buyers, suppliers, and financial backers' (Tushman and Romanelli, 1985: 177), which may be difficult to change; c) user practices and lifestyles which have been organised around particular technologies (Shove, 2003).

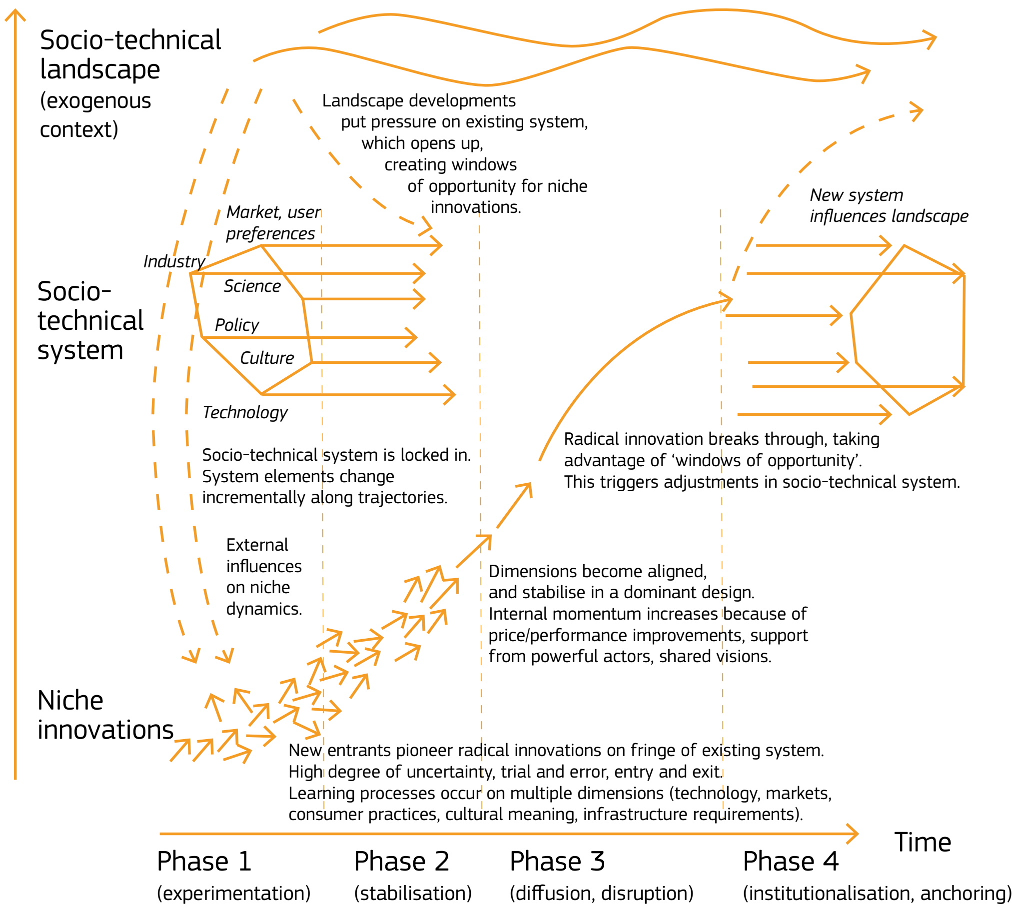
- Institutional and political lock-in mechanisms: a) existing regulations and policy networks favour incumbents and create an uneven playing field (Walker, 2000); b) vested interests use their access to policy networks to water down regulatory change and hinder radical innovation (Hess, 2016).

Because of their commitments to existing socio-technical systems and regimes, incumbent organisations (like coal, oil, and agro-food companies) tend to oppose sustainability transitions (Geels, 2014) or prefer incremental, efficiency-oriented changes (e.g. direct fuel injection in car engines or 'clean coal' power plants). Nevertheless, incumbent firms can (often gradually) reorient to address social or environmental problems (Penna and Geels, 2015) if they are stimulated by attractive financial incentives, forced by legislation or pushed by public opinion, especially when scandals (like 'Dieselgate') erode their social legitimacy.

Niche and regime actors operate in wider secular contexts (called 'socio-technical landscapes'), which accommodate both gradual changes (e.g. demographics, political ideologies, macro-economic trends) and shocks (e.g. accidents, oil crises, wars, recessions) (Van Driel and Schot, 2005).

Although transition specifics vary between domains and countries, the general dynamic is that: a) niche innovations gradually build up internal momentum; b) changes at the landscape level create pressure on the system and regime; and c) destabilisation of the regime creates windows of opportunity for niche innovations, which then diffuse and disrupt (parts of) the existing system (Figure 9-6).

Figure 9-6 Multi-level perspective on socio-technical transitions



Source: Substantially adapted from Geels, 2002: 1 263
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2.2 Core processes in different phases of socio-technical transitions

Socio-technical transitions take several decades and can be divided into four phases with different challenges and core activities. For the first phase, the niche development literature distinguishes three core processes (Kemp et al., 1998; Schot and Geels, 2008): a) experimentation and trial-and-error learning about the techno-economic performance, socio-cultural acceptance and political feasibility of radical innovations; b) building of social networks and transformative coalitions of actors who are willing to develop, nurture and protect the innovation; and c) the articulation of positive visions that provide direction for innovation processes and attract wider attention.

While there are presently many sustainability experiments (Sengers et al., 2019), urban projects (Bulkeley et al., 2016), and local grass-roots initiative projects (Pesch et al., 2019), which act as concrete carriers of niche innovations, an important challenge is to 'overcome the current fragmentation of initiatives, and their tendency to remain isolated or short-lived, which ultimately reduces their potential for lasting and wide-ranging change' (Turnheim et al., 2018: 237). In addition, niche innovations initially face other challenges such as being more expensive than existing technologies, the absence of 'ready-made' markets, and social acceptance problems due to unfamiliarity ('liability of newness').

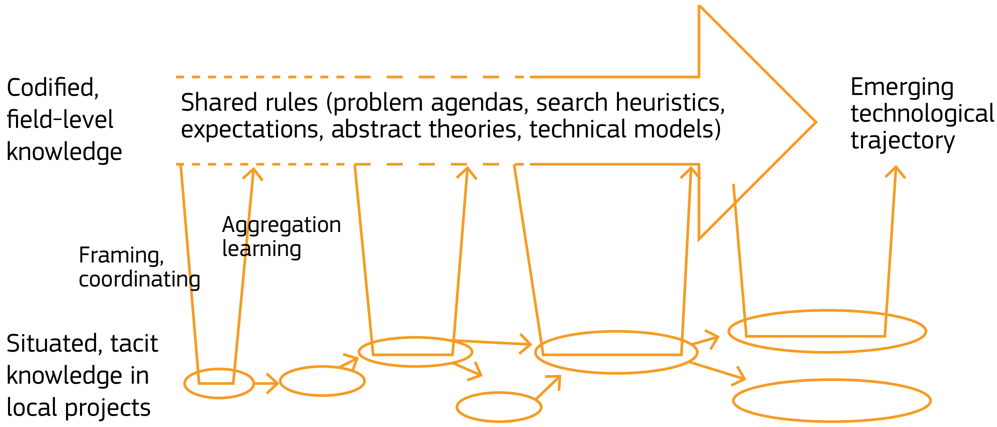
Because grass-roots innovations rely on voluntary commitments, they are also vulnerable to the departure of key champions and a high turnover of volunteers (Hargreaves et al., 2013). Grass-roots innovations may also experience difficulties in securing funding because activists may lack either the professional skills to apply for such funding (e.g. proposal writing, reporting, financial accountability) or the desire to deal with bureaucratic procedures (Hossain, 2018).

In the second phase, niche innovations begin to stabilise because: a) they establish a foothold in small market niches which creates a flow of resources for ongoing innovation activities; b) the articulation of codified design rules, technical models, standards, consumer preferences, and policies, which reduce uncertainties (Geels and Raven, 2006); and c) the creation of communities that share experiences and support dedicated aggregation activities by intermediary actors such as industry associations, engineering communities or innovation agencies (Hargreaves et al., 2013; Kivimaa et al., 2019). These socio-cognitive activities help to gradually stabilise innovation trajectories (Figure 9-7).

Aggregation and cumulative learning among projects may be more difficult for grass-roots movements (GMs) which tend to 'engage in informal learning, mainly due to a lack of intermediary actors. Most GMs do not document their tacit knowledge, such as the institutional learning, skills, and training that their members possess' (Hossain, 2018: 67). The variability and context-specificity of local projects may also complicate the articulation of 'best practice' lessons. And grass-roots activists may resist codification and mainstreaming if this involves the loss of particular values that inspired initial initiatives (Smith, 2012).

In the third phase, the radical innovation diffuses more widely, which includes embedding in various environments (Figure 9-4). *Internal* drivers of diffusion are: a) price/performance improvements, due to learning-by-doing, scale economies, and complementary innovations (Arthur, 1994); b) consumer interest and adoption; c) business investments in production facilities, supply chains, infrastructure; d) policies and institutional change which may shape markets, consumer adoption and business confidence (King and Pearce, 2010); and e) positive cultural discourses which may shape consumer preferences and political support

Figure 9-7 **Innovation trajectory emerging from sequences of local projects**



Source: Adapted from Geels and Raven, 2006: 379
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(Lounsbury and Glynn, 2001). But diffusion can also be facilitated by *external* landscape developments that destabilise the existing regime (Turnheim and Geels, 2012) and thus create 'windows of opportunity' for diffusing innovations (represented by diverging arrows in Figure 9-6).

The third phase is often full of struggles such as: economic competition between new and existing technologies; business struggles between new entrants and incumbents, which may lead to the downfall or reorientation of existing firms (Christensen, 1997); political conflicts and power struggles over adjustments in subsidies, taxes and regulations (Meadowcroft, 2009); and discursive struggles about problem framing and (dis)advantages of particular innovations and transition pathways (Rosenbloom et al., 2016). There is no guarantee that niche innovations inevitably win these struggles. Radical innovations may fail to build up sufficient endogenous momentum or suffer setbacks. Tensions in existing regimes may be contained, such that windows of opportunity for niche innovations do not (sufficiently) materialise. Or incumbent actors may successfully counter-mobilise and thwart niche innovations (Geels, 2014).

In the fourth phase, the new socio-technical system replaces the old one and becomes institutionalised in regulatory programmes, industry structures, habits of use, views of normality, professional standards, and training programmes. 'Whole system' transitions are not about single technologies (e.g. renewable energy) – they also involve complementary innovations (e.g. smart meters, energy storage), infrastructure adjustment (e.g. smart grids, bidirectional flows), new business models (e.g. capacity markets), and user practices (e.g. demand response, self-generation) (McMeekin et al., 2019).

3. Empirical examples

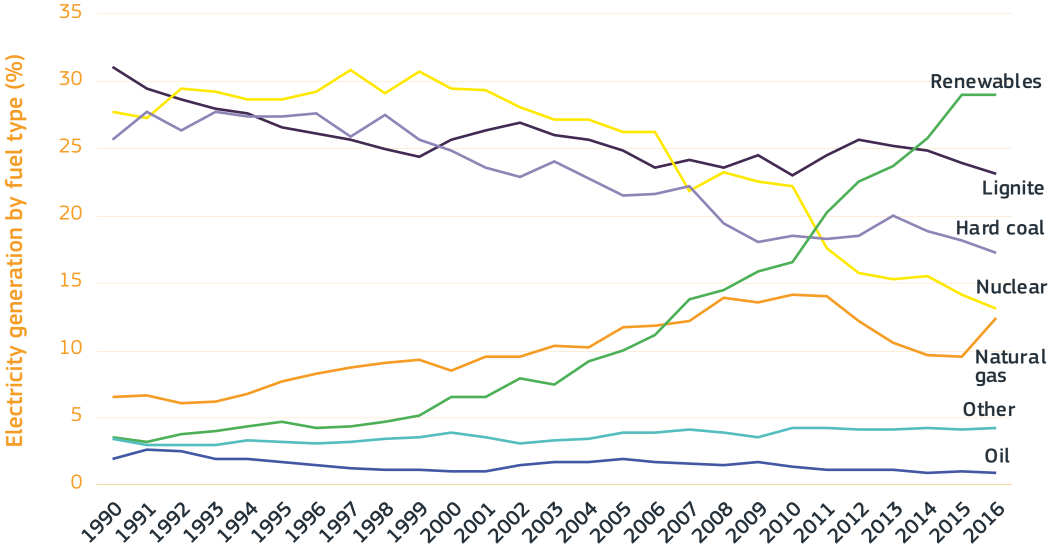
Three brief case studies aim to illustrate the socio-technical transition perspective: the German electricity transition (1986-2016), Austrian biomass district heating systems (1970-2013), and French urban tram systems (1971-2016). The three cases were chosen because they all became linked to grand challenges (e.g. climate change, urban quality of life), had economic growth and export implications, transformed entire systems, involved multiple actors, activities and dimensions (techno-economic, social, political, cultural), and are longitudinal processes that progressed through several phases. Because of their complexity, the case studies are not comprehensive but selectively emphasise parts of the theoretical perspective. The German electricity transition emphasises multi-level interactions, showcasing how niche innovations can disrupt the existing regime in the context of landscape developments and shocks. The Austrian and French cases focus more on the emergence and diffusion of niche innovations, showcasing two different kinds of niche-regime interactions. Although Austrian biomass district heating systems were initially pioneered by new entrants, incumbent regime actors reoriented in later phases and their involvement further accelerated diffusion. French tram systems, in contrast, were developed by incumbent regime actors (transport ministry and railway industry) from the start, and subsequently involved new entrants (particularly cities and entrepreneurial mayors) in local deployment. Both cases emphasise learning processes, knowledge stabilisation, changing visions and social networks.

3.1 German electricity transition (1986-2016)

Electricity from renewable energy technologies (RETs) in Germany increased from 3.6% in 1990 to 29.0% in 2016, while nuclear energy and hard coal declined substantially (Figure 9-8). Natural gas increased until 2010, then declined, before bouncing back in 2016, while brown coal declined between 1990-2000 and then fluctuated. This unfolding supply-side energy transition provides a good illustration of the multi-level perspective.

In the first period (1986-1998), niche innovations were nurtured in the context of a stable regime. Wind turbines and solar PV were supported by R&D programmes introduced after the 1970s' oil crises, but deployment remained limited in the 1980s because of poor performance and high costs (Jacobsson and Lauber, 2006). The 1986 Chernobyl accident was a landscape shock that stimulated some deployment of wind turbines by new entrants such as environmentally motivated citizens, farmers, and anti-nuclear activists who wanted to demonstrate the feasibility of alternatives. The accident also created negative public attitudes towards nuclear power, which was supported, however, by successive Conservative-Liberal governments.

Figure 9-8 German electricity generation by source, 1990-2016



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Source: AG Energiebilanzen
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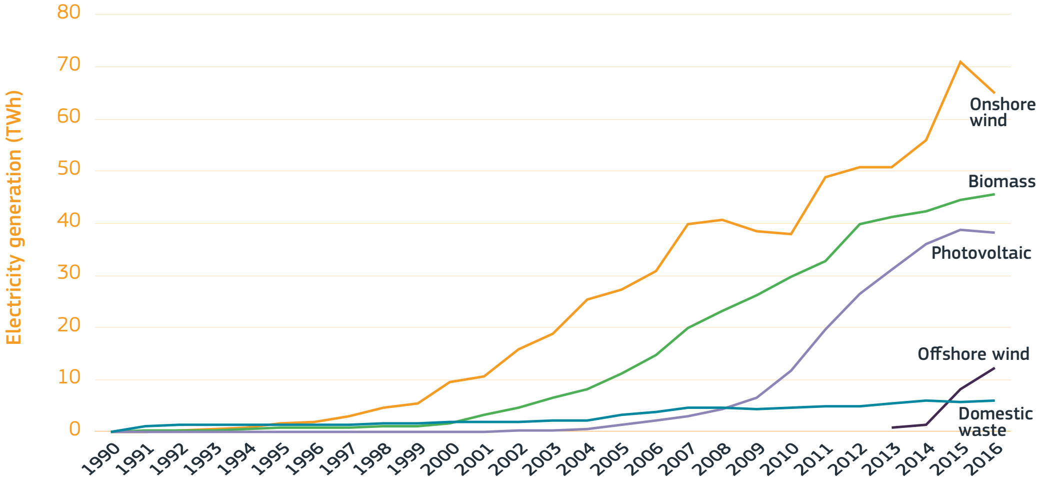
Proposals for RET market support were defeated in parliament, although the 1991 proposal succeed 'by accident' as the government was preoccupied with German reunification (Jacobsson and Lauber, 2006). It was not expected that the resulting Feed-in Law would have major effects and, in 1994, the Environment Minister Angela Merkel thought it unlikely that Germany would ever generate more than 4 % renewable electricity (Lauber and Jacobsson, 2016). However, the Feed-in Law, which obliged utilities to purchase renewable electricity at 90 % of the retail price, made onshore wind deployment economically feasible and stimulated significant deployment in the 1990s (Figure 9-9). The success of German turbine manufacturers (Enercon, Husumer Schiffswerft, Tacke) also attracted industrial policy support in the peripheral regions of Northern Germany, which expanded the RET advocacy coalition (Geels et al., 2016).

To hinder RETs, incumbent utilities lobbied the government which, in 1997, proposed to reduce feed-in tariffs. But public protests by the RET advocacy coalition (including environmental groups, solar and wind associations, metal- and machine workers, farmer groups and church groups) led to the rejection of the proposal by the German parliament and the continued protection of RETs (Jacobsson and Lauber, 2006).

Figure 9-9 Electricity generation from German renewable energy technologies, excluding hydro, 1990-2016



Source: AG Energiebilanzen
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In the second period (1998-2009), the election of a 'Red-Green' coalition government between the Social Democratic Party and the Green Party (1998-2005) was another landscape shock, which disrupted the cosy regime-level relations between utilities and policymakers (Geels et al., 2016). The new government decided to phase out nuclear energy and support RETs with the Renewable Energy Act (EEG, 2000), which guaranteed fixed, premium payments for renewable electricity over a 20-year period, with tariffs varying with the maturity of the technology.

Renewable electricity subsequently diffused rapidly from 6.6% in 2000 to 15.9% in 2009 (Figure 9-8) because of reinforcing developments in multiple environments:

- In the policy environment, generous and stable feed-in tariffs created attractive market opportunities.
- In the business environment, new entrants (like households, farmers, municipal utilities, project developers and other industries) dominated RET deployment, while the incumbent utilities produced only 6.5% of renewable electricity in 2010 (Figure 9-10). The very rapid diffusion of solar PV after 2006 (Figure 9-9) was unforeseen and driven by feed-in tariffs that far exceeded generation cost as the price of solar PV panels fell rapidly. 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 (Dewald and Truffer, 2011). Solar PV became an industrial success story as total sales for the German PV industry grew from EUR 201 million in 2000 to EUR 7 billion in 2008. Export sales grew from EUR 273 million in 2004 to approximately EUR 5 billion in 2010 (BSW-Solar, 2010).
- In the public domain, broad advocacy coalitions and positive discourses about renewable energy, ecological modernisation and green growth supported and legitimated RET diffusion and policy support (Geels et al., 2016).

Figure 9-10 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

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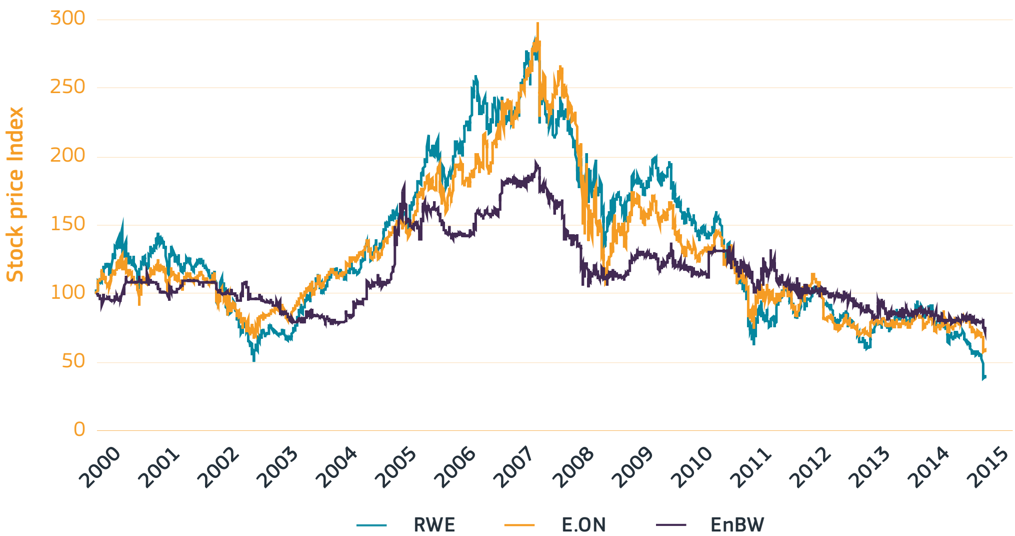
Source: Klaus Novy Institut, 2011
Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/partii/chapter9/figure_9-10.xlsx

Instead of addressing renewable energy, incumbent regime actors focused on other issues. In 1998, the liberalisation of the electricity sector triggered a wave of mergers and acquisitions which resulted in the big-four utilities (RWE, E.ON, Vattenfall, EnBW) capturing 90% of the wholesale market by 2004. By the mid-2000s, the big-4 were investing in new coal- and gas-fired power plants to meet expected growth in demand (Kungl and Geels, 2018). They also focused on European and global expansions, which boosted growth and stock prices (Figure 9-11). 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.

Figure 9-11 Normalised stock price performance of three German utilities



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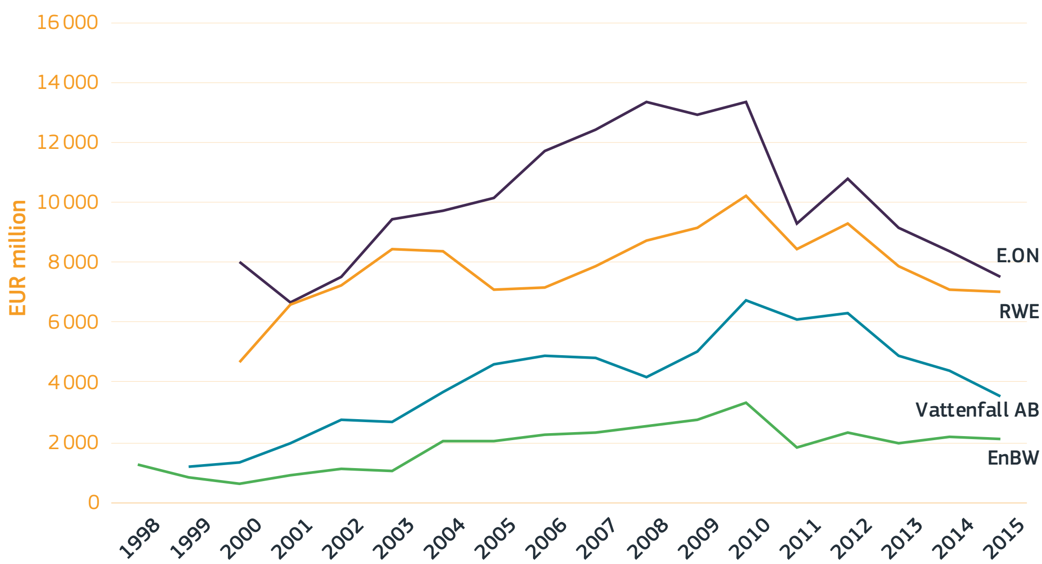
Source: Frankfurt stock exchange www.finanzen.net
Note: Vattenfall is not included in the figure because it is a Swedish state-owned company.
Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/partii/chapter9/figure_9-11.xlsx

In the third period (2009-2016), RETs further diffused thanks to feed-in-tariffs, positive discourses and declining RET prices. The price of PV modules, for instance, decreased by more than 65 % between 2007 and 2011 as a result of scale economies in Chinese production, oversupply, and price dumping (Goodrich et al., 2013). RET diffusion was also facilitated by another landscape shock (the 2011 Fukushima accident) which destabilised the regime as the government performed a U-turn and reintroduced the nuclear phase-out, with a target date of 2022. The government also adopted an official energy transition policy (Energiewende) that included ambitious future targets for renewable electricity (35 % by 2020, 40-45 % by 2025, 55-60 % by 2035 and 80 % by 2050).

The existing regime destabilised and experienced various problems during this period (Geels et al., 2016): a) the expansion of renewables reduced the market share of existing fossil plants and decreased wholesale electricity prices because of the 'merit order effect' (solar PV and wind, with low marginal costs, were dispatched first in power generation); b) the aftermath of the financial crisis (another landscape shock) depressed economic activity and reduced electricity demand, which eroded the economic viability of newly built fossil plants; and c) the nuclear phase-out decision implied write-off costs. These developments reduced net incomes of the big-4 utilities after 2011 (Figure 9-12) and created doubts about the viability of traditional business models. Consequently, incumbent utilities began strategic reorientation activities (Kung and Geels, 2018). In 2014, E.ON split into two companies: one focused on renewables, distribution grids and service activities, the other holding conventional assets in large-scale electricity production and trading activities. In 2015, Vattenfall put up its German lignite activities for sale. And in 2015, RWE announced plans to separate its renewables, grid and retail business into a new sub-company.

Figure 9-12 Net profits of the big-4 utilities in Germany, 1998-2015



Source: Kungl and Geels, 2018: 79

Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/partii/chapter9/figure_9-12.xlsx

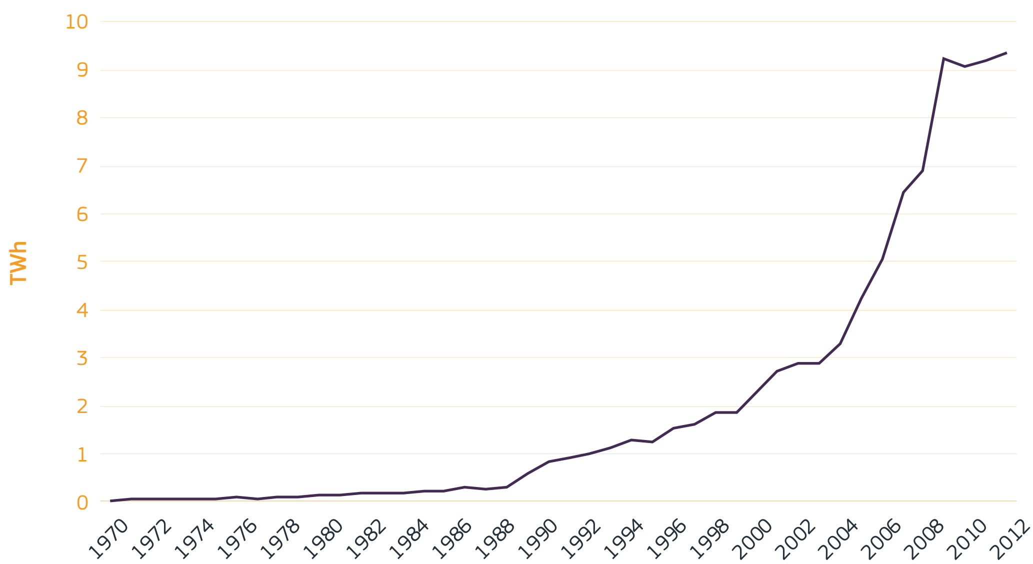
The diffusion of RETs also experienced several unforeseen problems (Geels et al., 2016): a) many German PV manufacturers went bankrupt because of Chinese competition, which eroded the salience of the green growth discourse; b) the deployment of renewables (especially solar PV) increased EEG (Renewable Energy Act) surcharges from 1.3 eurocents/kWh in 2009 to 6.24 eurocents/kWh in 2014, making German retail electricity prices the highest in Europe; c) these increasing surcharges provided ammunition for political opposition from utilities and the Economics Ministry; and d) intermittent renewables threatened grid stability and increased price volatility, leading to negative prices on sunny, windy days when supply exceeded demand.

These RET-related problems and the economic problems of utilities (which were seen as 'too big to fail') led to government efforts to slow RET expansion and increase support for the utilities: a) feed-in tariffs were reduced in several rounds (Hoppmann et al., 2014); b) from 2017 onwards, feed-in tariffs were replaced by a bidding system for target capacity (which required capabilities and resources that suited big players); and c) offshore wind deployment was stimulated, which provided attractive diversification opportunities for incumbents because of size and cost structures.

3.2 Biomass district heating systems in Austria (1970-2013)

Biomass district heating (BMDH) is a complex socio-technical system that uses pellets and waste wood from Austria's abundant forests as input for generating heat in boilers which is then disseminated through piped infrastructures and extracted by heat exchangers in target buildings (houses, schools, hospitals). Austrian BMDH systems emerged in the early 1970s, stabilised and slowly diffused between 1986-2002, and rapidly expanded after 2002 (Figure 9-13).

Figure 9-13 Annual heat production from Austrian BMDH, 1970-2013



Source: Statistik Austria, 2015
Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/partii/chapter9/figure_9-13.xlsx

The first period (1970-1986) was characterised by local tinkering with BMDH systems by new entrants such as sawmill owners, carpenters, monasteries and agricultural cooperatives which utilised wood residues and imported boilers (from Sweden) to provide heat services to nearby buildings. Farmers, who often own forests in Austria, teamed up in cooperatives to address high investment costs and to pool resources such as time, skills and fuel (Seiwald, 2014). Installers, operators and local plumbers lacked engineering skills and experience, leading to design mistakes and over-dimensioning in early BMDH systems (Madlener, 2007). In this early niche development phase, plant operators shared little information and were secretive about operational problems. There was limited feedback to technology suppliers and no institutionalised learning or performance evaluation.

The second period (1986-2002) saw slow but steady growth of these small- to medium-scale, village, heat-only system (400 kWth to 1 MWth), enhanced interactions and informal knowledge exchange among BMDH innovators, and increasing interest and support from agricultural policymakers who saw BMDH as a means for regional revitalisation, providing opportunities for alternative incomes in agro-forestry. Provincial energy agencies and the newly created Austrian Biomass Association acted as intermediary organisations which collected and compared local operating experiences, formulated generic lessons and insights and organised workshops to facilitate network building and disseminate more codified knowledge (Geels and Johnson, 2018). Energy agencies in pioneering provinces (Lower Austria, Styria) also provided training and financial support for BMDH developers, assisted by heat-mapping exercises, and advised in BMDH construction via 'technology introduction managers' (Rakos, 1995). BMDH also benefitted from regional innovation policies that supported research and product development in the fields of energy efficiency and renewable energy sources. 'Research and development in energy technology has a long and strong tradition in Austria and has been successful in creating world-class industries, e.g. for small-scale biomass boilers' (IEA, 2014).

Early diffusion in this second period was driven by developments in multiple environments:

- In the business environment, learning-by-doing and dedicated aggregation activities gradually reduced operational problems and improved techno-economic performance. Dedicated supply chains for biomass, pellet boilers and prefabricated heat pipes emerged in the 1990s (Kalt and Kranzl, 2009) which, in turn, stimulated specialisation and innovation.

- In the user environment, local residents began to switch to BMDH, which was slightly more expensive than traditional stoves (that burned biomass, coal or oil) but offered greater comfort and convenience, e.g. continuous heat without smoke emissions and no need for storage space and manual handling of fuel (Seiwald, 2014). The switch to BMDH required few adjustments in user skills and routines, although consumers did experience some difficulties in understanding the bills for heat services, particularly the addition of service charges (for recovery of fixed costs, maintenance and metering) besides consumption-based charges (Metschina, 2014). To stimulate use among local farmers, municipalities also began to adopt BMDH to heat public buildings, such as schools, town halls, hospitals and swimming pools.

- In the policy environment, in the early 1990s, the federal Ministry of Agriculture started to complement provincial BMDH support which led to subsidies and capital grants that could amount to 60% of investment costs (Geels and Johnson, 2018). This reduced the commercial risks for BMDH system builders and operators. From the mid-1990s, the Environmental Promotion Fund also provided support for BMDH.

- While narratives in the public sphere initially framed BMDH as a potential response to rural problems (e.g. unemployment, declining industrial base and depopulation), these were complemented in the mid-1990s by discourses that were portrayed as a response to climate change.

In the third period (2002-2013), diffusion accelerated as two other technical configurations also gained momentum (Seiwald, 2014): a) large-scale BMDH-CHP plants (between 10-65 MWth), which produced both heat and power and were operated by incumbent organisations like energy utilities; and b) small-scale micro-grids (between 100-400 kWth), which provided heat for a limited number of closely situated buildings and were often operated by energy service companies (ESCos) that pioneered new business models like energy service contracting[1]. The following developments assisted rapid diffusion:

- In the user environment, housing associations, hotels and public-building operators became interested in micro-grids because of their operational ease and cost-effectiveness, while large-scale BMDH-CHP plants mainly focused on electricity production to the grid.

- In the business environment, incumbent actors from the electricity regime reoriented to BMDH-CHP because the Green Electricity Act (2002) established an attractive feed-in tariff for electricity generated from biomass CHP. The involvement of incumbent organisations advanced BMDH diffusion by making available greater financial resources and more profound technical and operational capabilities. BMDH diffusion stimulated complementary innovations in biomass collection and processing, prefabricated heat pipes (which reduced infrastructure installation costs and increased system efficiencies) and pellet boilers (which became easier to handle and more fuel-efficient). The creation of specialised clusters and supply chains made Austrian manufacturers world-leading exporters of pellet boilers (Geels and Johnson, 2018). Business opposition came from chimney cleaners and coal dealers whose jobs were threatened, and from natural gas suppliers who also wanted to expand into rural areas, giving rise to 'significant conflicts between agricultural lobbies and the gas industry' (Rakos, 1995: 879).

- In the policy environment, BMDH continued to benefit from support policies, such as the Green Electricity Act (2002), the CHP Law (2009), and the Law for the Expansion of District Heating and Cooling Networks (2009). From the mid-2000s, BMDH also became part of wider biomass strategies (such as the 2006 Biomass Action Plan and the 2010 Austrian Energy Strategy 2020), which emphasised energy self-sufficiency, sustainability, green growth, and export opportunities for Austria's world-leading biomass energy systems (Geels and Johnson, 2018).

- Ongoing policy support in this period was legitimated by public discourses that combined environmental benefits and economic goals through notions such as self-sufficient 'energy regions' and the inclusion of BMDH in national biomass strategies which emphasised energy autarky, green growth and exports. The Federal Minister

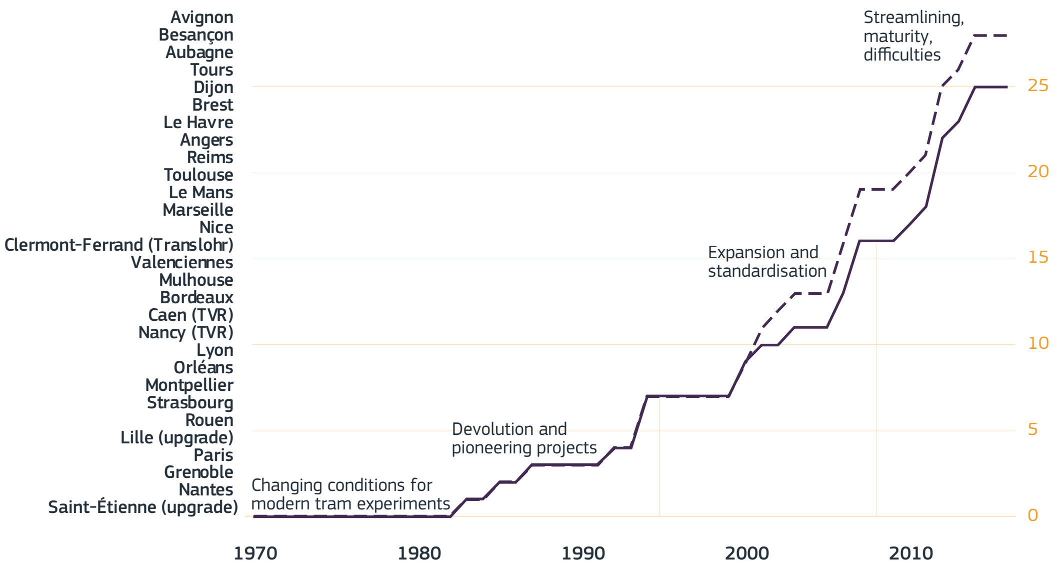
1 In energy service contracts, customers pay a monthly rate for the provision of heat (and electricity), leaving the construction and operation of biomass plants, located on the client's premises, to ESCos.

for Agriculture, Forestry, Environment and Water Management supported this vision in the preface to a Bio-Energy Report: 'We can produce in Austria, on balance, as much energy from domestic, renewable sources as we consume by ourselves. This makes us independent from expensive, fossil energy imports such as oil and gas and brings about a boom in the economy as well as positive employment effects with new green jobs' (Austrian Energy Agency, 2012, p. 2).

3.3 Urban tram systems in France (1971-2016)

Trams were widely used in the first half of the 20th century but disappeared from many European cities in the 1950s and 1960s to make way for motorised transport. From the 1970s onwards, however, they made a comeback which was particularly strong in France where tram systems spread to 15 out of 19 cities of more than 300 000 inhabitants and, in some instances, to cities with fewer than 200 000 inhabitants (Figure 9-14). For larger cities (over 400 000 inhabitants) penetration reached 27 %, 53 % and 80 % by 1994, 2001 and 2010, respectively.

Figure 9-14 Modern tramway diffusion in French cities (solid line: tramways; dotted line: tramways and rubber-tyred tramways)



Source: CERTU, 2013

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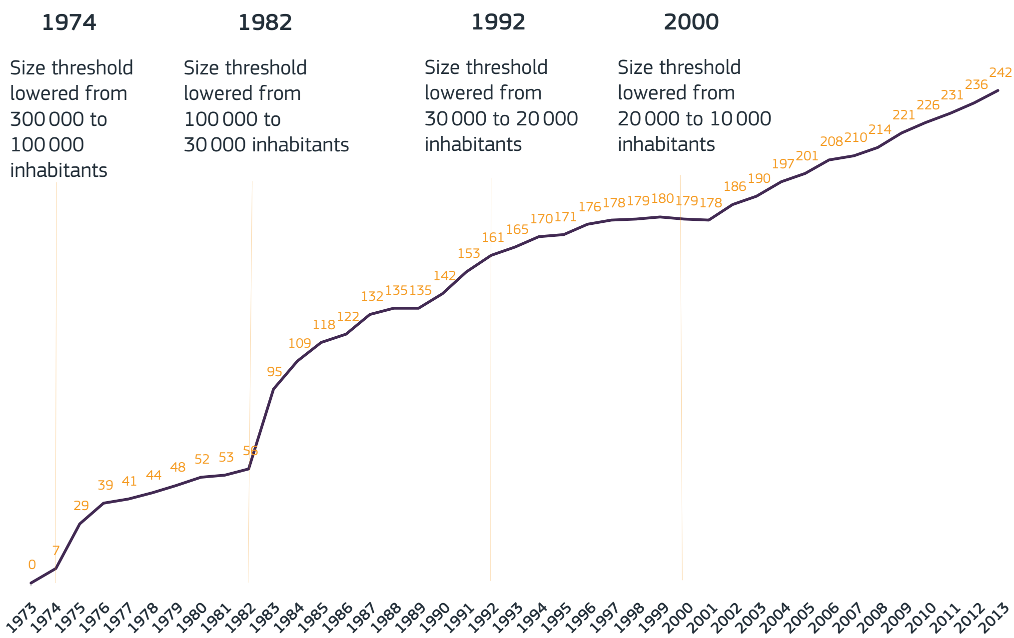
Because urban tram systems are expensive infrastructure projects, they often involve lengthy planning and design periods before actual construction. In the first period (1971-1983), the success of high-speed railways (TGV) and concerns about urban congestion and car accidents led policymakers to prepare the ground for tram systems. In 1971, they introduced the 'versement transport' financing instrument which raised employment tax locally to pay for large public transport schemes. First introduced in Paris as support for metro-like schemes, it was gradually extended to smaller cities (Figure 9-15) and used to support tram systems.

Figure 9-15 Evolution of French municipalities collecting local transport tax, 1973-2013



Source: GART, 2015

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The early support coalition for trams comprised incumbent actors with congruent motivations and skills (Turnheim and Geels, 2019): a) the Transport Ministry saw trams as a means of addressing local transport problems and industrial exports; b) the railway industry (GEC Alsthom) saw trams as a diversification opportunity, using its technological skills to enter new markets; and c) the national rail operator (SNCF) wanted to use its network management skills to enter the urban public transport market. In 1974, Transport Minister Marcel Cavaillé set up a working group with members of this coalition which coordinated R&D programmes and developed a top-down vision of rail-based, public transport as a radical solution to transform urban transport systems. The 1975 Cavaillé Circulaire called on eight cities to explore this vision and test new tram technologies with on-the-ground projects, funded through versement transport. This created space for the newly elected Socialist mayors (in Nantes, Strasbourg and Grenoble) to advance radical new transport ideas for their cities which, in the late 1970s, led to more detailed design and planning studies.

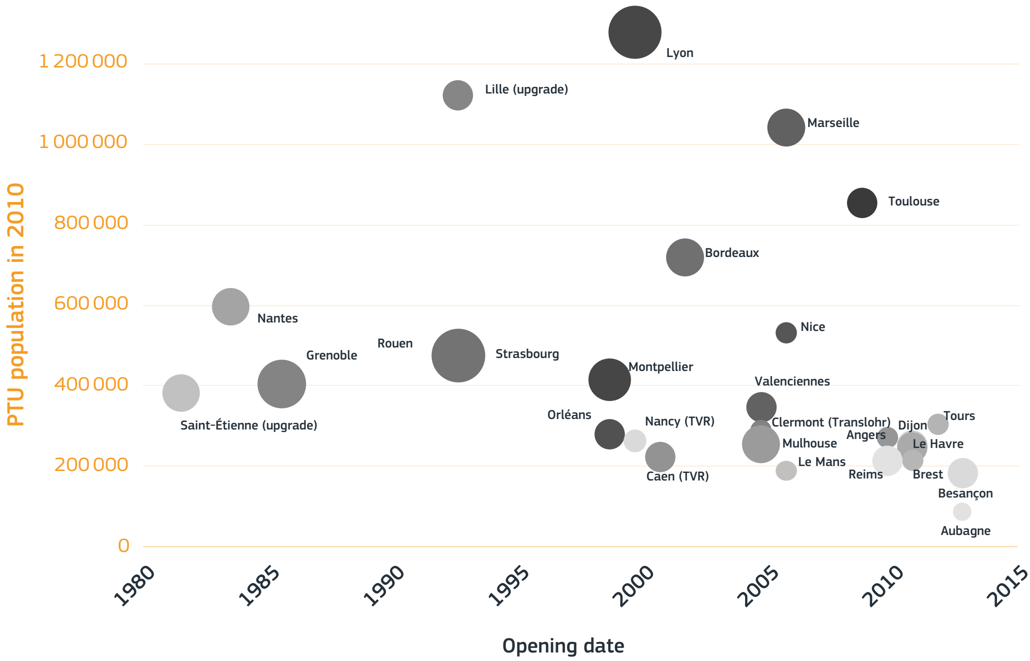
In the second period (1985-1995), pioneering tram projects were stimulated by 'landscape' developments such as Mitterrand's 1981 election, which led to stronger strategic state intervention and the devolution of planning powers to cities (through the 1982 Gaston Defferre laws), including public transport responsibilities and resources (through the 1982 domestic transport guidance law, LOTI). Local tram projects promoted by city mayors were also enabled by planning and design support from technical bureaucracies and generous public funding, ranging from between 15 % and 40 % of capital costs in this period (ACUF, 2007), which was legitimated by high-level visions and a modernist and patriotic discourse about high-tech industrial achievement (Turnheim and Geels, 2019).

In 1985, Nantes opened the first modern tramway system which established technical and commercial viability of the new designs (based on adaptations of existing rail-industry knowledge). Learning from the Nantes project (which encountered some local opposition during construction), Grenoble's tramway system, opened in 1987, included compensation for local businesses, low-floor carriages for better accessibility for disabled users, and full pedestrianisation of a segment crossing the urban centre (Laisney, 2011). The Strasbourg project was designed in 1985, revoked in 1988, and reintroduced in 1989 by the incoming Socialist mayor who framed it as a civilisation battle to reconquer public space from cars (Laisney, 2011). Opened in 1994, the system had low-floor carriages, bay windows, a hyper-futurist design and was developed to act as a public transport backbone with park-and-ride facilities and buses acting as feeders/extensions.

Lessons from one project fed into the next, and knowledge gradually stabilised as technical bodies, research centres and government-affiliated technical services (including the 'technical committee for the standard French tram', established in 1982) acted as intermediary organisations that aggregated, standardised and codified technical knowledge (Hamman, 2015).

Trams spread rapidly in the third period (1995-2008) as the success of Strasbourg led to a flurry of new tram projects, both in large cities (Lyon, Bordeaux, Marseille) and smaller ones (Figure 9-16). Central government funding became more codified via 1994 and 2001 'guidance circulars' which specified evaluation criteria (including social and security objectives) and institutionalised technical expertise. CERTU (the assessment centre on networks, transport and public works) and governmental technical services delivered technical manuals, evaluation guidelines, technical notes and travel observatories that further stabilised tram design and operational features (Hamman, 2015).

Figure 9-16 Adoption of modern tramways by French cities (excluding Paris) according to urban area population



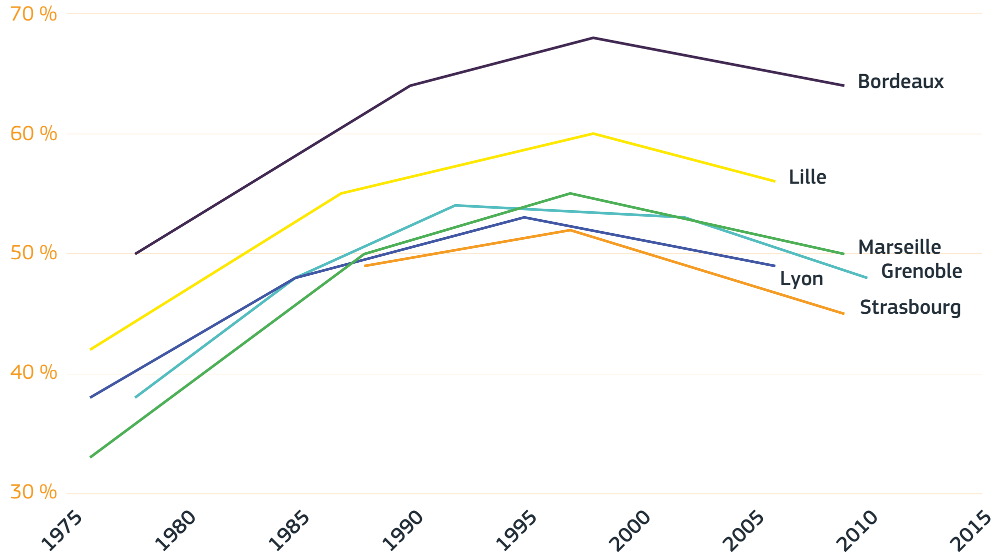
Source: CERTU, 2013
Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/partii/chapter9/figure_9-16.xlsx

In the policy environment, strategic mobility plans (plans de déplacements urbains, PDU) became mandatory (requiring cities to develop alternatives to cars) and increasingly linked to energy and air-pollution measures. Local policymakers increasingly embraced trams as vehicles for urban marketing, promoting 'emerging' urban areas (often for business and tourism attractiveness) and projecting a modern city image (Kaminagai, 2014). In 2003, central government funding for light rail was reduced, which delayed several projects and increased reliance on loans and cross-financing (Turnheim and Geels, 2019).

Lighter top-down government influence (e.g. reduced funding) increased dynamics in the business environment, as Alstom faced competition from consultancy and engineering companies, while SNCF increasingly competed with other local transport service operators (Keolis, Connex/Veolia Transport, RATP).

Users also enthusiastically embraced trams, although lengthy construction projects sometimes encountered local opposition. From the late 1990s, increasing tram use led to declining car use in various French cities (Figure 9-17).

Figure 9-17 Evolution of car use (percentage of journeys) in selected French cities with tramways



Science, research and innovation performance of the EU 2020

Source: CERTU, 2013
Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/partii/chapter9/figure_9-17.xlsx

The public discourse also changed during this period, as tram debates moved beyond transport-specific considerations and became linked to wider issues such as urban transformation, quality of life and environmental problems. Thus, tram visions took on new meanings that aligned with emerging norms and values (e.g. access, sustainability, liveability, urban renewal) which broadened the attractiveness of trams and helped to build a broad discourse coalition, so that trams became 'irresistible' for mayors of medium and large cities (Hamman, 2015).

In the fourth period (2008-2016), trams became further linked to environmental objectives as the 2007 'Grenelle Environment' (a multi-party debate between government, local authorities, trade unions, business and voluntary sectors) committed, amongst others, to building more urban light-rail projects. In 2008, although the government increased central funding again, the money was spread thinly over more projects, new tram designs aimed at streamlining and cost-cutting.

Motivations for tram projects became highly convergent, emphasising 'urban sustainable development and environmental preservation, renewal or requalification of urban space, mature technology, positive effects on job creation' (Pissaloux and Ducol, 2016: 183). French tram manufacturers (e.g. Alstom), operators (e.g. Keolis, Transdev, RATP) and engineering firms (Vinci, Bouygues) increasingly turned to export markets, building on earlier experiences: 'the building consultants, the transport operators and the designers intervene in response to a growing number of cities in the world, on the base of the references created in the French cities' (Kaminagai, 2014: 62).

4. Conclusions and policy recommendations

4.1 Socio-technical transitions

The three examples have demonstrated that socio-technical transitions are longitudinal processes which progress through phases with different activities and causal mechanisms. The radical innovations emerged in sheltered niches, but their transformative effects were not realised until they were diffused more widely, which (inevitably) takes time and involves embedding processes in business, policy, user and cultural environments. The German electricity transition most clearly also involved landscape developments (e.g. 1998 election, Chernobyl and Fukushima accidents, financial-economic crises) and regime disruption, which was only briefly addressed in the other two cases (e.g. disruption of Austrian chimney cleaners and coal dealers, and a decline in car use in French cities).

All three cases also involved multiple actors and dimensions, which demonstrates that socio-technical transitions are not just about universities, firms and markets (as in innovation system approaches), but are also about households, cities, communities, NGOs and the wider public. In all three cases, radical innovations became linked to grand challenges (particularly climate change and quality of life), although this alignment was often strengthened in later phases as visions became broader and combined multiple issues (a pattern called 'issue linkage'). Furthermore, the cases illustrate socio-technical transitions are non-linear processes, characterised by surprises, unintended consequences, setbacks and twists and turns, which means that transformative effects are difficult to predict correctly. All three cases also showed that environmentally oriented socio-technical transitions can have positive economic and export effects, which substantiates the suggestion from the Commission's expert group on green growth and jobs, cited in the introduction. The German case, however, shows that positive green growth effects may be eroded when competitors, such as Chinese manufacturers, successfully enter the new economic domain.

4.2 Five policy challenges in the case studies

The five policy challenges mentioned in the introduction also played out in all three cases, although in different ways.

Horizontal policy coordination. Although innovation policy (particularly R&D support, demonstration projects and knowledge aggregation) was important in all three cases, sector-specific policies (energy, agricultural, transport, environmental) were also clearly relevant, especially for deployment and diffusion:

- In the German energy transition, R&D support and demonstration projects helped to create technological niches for wind and solar PV in the 1980s and 1990s. But renewable energy policy (particularly feed-in tariffs) was crucial to create market niches and drive subsequent diffusion. Responsibility for renewable energy policy changed from the Ministry of Economic Affairs to the Ministry for Environmental Affairs in 2002 and back again in 2014, which suggests that horizontal coordination may involve turf battles between ministries.

- In the Austrian BMDH transition, innovation policy helped to generate knowledge and improve techno-economic performance in the 1980s and 1990s. But other policy domains were also important: agricultural policy provided financial support to BMDH operators, which reduced investment risks and facilitated learning-by-doing (especially in the early phases); environmental and climate policy subsidised green innovations (like BMDH); regional energy policy (especially provincial energy agencies) helped with knowledge aggregation, codification and dissemination (in the early phases), while federal energy policy stimulated the reorientation of energy utilities through the CHP feed-in tariff (in the later phases); and economic and industrial policy stimulated energy clusters, green growth and exports (in the later phases).

- Innovation policy was crucial for the development of French tram designs, by stimulating R&D, technical learning, and codification. However, transport policy, environmental policy and industrial policy also supported the development and deployment of tram systems.

Social, business model and infrastructural innovation. While technological innovation was crucial in all three cases, other forms of innovation were also important:

- Community energy (particularly collectively owned wind turbines) was an important social innovation which made citizens and communities active participants in Germany's energy transition. In the later phases, the diffusion of intermittent renewables (wind, solar PV) also required infrastructural innovations, such as grid extensions, smart grids, back-up capacity and energy storage.

- Infrastructural innovation was central to the Austrian BMDH transition involved, which policymakers stimulated by providing financial support (e.g. capital grants) that reduced investment risks. It also involved business model innovation (e.g. energy service companies) and some social innovation (shift towards heating services), which were mostly left to the market.

- French tram systems involved the building of new infrastructures, but also had wider transformative effects as cities started to close off city centres to cars and to align pedestrianised areas with tram systems. The modal shift from cars to trams (and buses) also constituted important social innovations.

Wider set of actors and coalitions. All three cases involved wider sets of actors than the 'upstream' groups (universities, research centres, firms) that are central to innovation system approaches, although their roles vary:

- The German energy transition was mainly driven by new entrants like households, farmers, municipal utilities and project developers which, together with environmental groups, solar and wind associations, metal- and machine workers, farmer groups and church groups, formed a powerful advocacy coalition lobbying for stronger support policies. In addition, the traditional regime-level coalition between utilities and the government was disrupted by the election of a Red-Green government (1998-2005) which introduced EEG support and nuclear phase-out policies that had an unfavourable effect on the big-4 utilities.

- The Austrian BMDH transition was also pioneered by new entrants (e.g. woodworkers, farmers) without dedicated policy support during the first period. In the second and third periods, these new entrants were supported by various policies that enabled the building of green clusters and energy regions. In the third period, incumbent actors like energy utilities reoriented and also became involved, focusing particularly on large-scale BMDH-CHP systems which were supported by attractive feed-in tariffs. Over time, the actor coalition expanded to include domestic boiler manufacturers, installers, municipalities, farmers, energy service companies and various kinds of users (households, housing associations, hotels and public-building operators).

- In contrast to the other two cases, French tram systems were pioneered by incumbent regime actors (railway companies, national rail operator, the Transport Ministry, and technical services), although new entrants (cities, mayors) were also important for local implementation and on-the-ground learning, which led to cumulative design improvements. Over time, the actor coalition widened to include consultancy and engineering companies, other local transport service operators, citizens, and advocates of various societal issues (environment, climate change, air pollution, congestion and safety).

Visions and missions to create drive and directionality. Future visions were important in all three cases, but they evolved during the transitions as actors learned more about technical performance and functionalities and as more actors (with different concerns) joined the advocacy coalitions. The alignment with grand challenges often became more pertinent in the later phases of transition, rather than driving them from the start, although the cases do vary.

- In the German energy transition, visions in the 1980s and 1990s were inspired by anti-nuclear and pro-renewable sentiments, but federal policy support occurred mainly 'by accident'. The Red-Green government coalition (1998-2005) did develop a long-term vision which anticipated that wind and solar PV innovations could become economically viable in the 2020s (through scale economies and learning-by-doing processes) if sufficiently nurtured, which led to the 2000 EEG support policy. The energy transition mission (with ambitious targets and explicitly linked to climate change) did not emerge until 2011, in the context of a landscape shock (Fukushima), the nuclear phase-out decision, strong RET-growth and a broad-based advocacy coalition.

- Visions of Austrian BMDH also evolved as the transition unfolded. In the mid-1980s, BMDH was seen as a means for local economic development and the revitalisation of rural areas. By the mid-1990s, environmental and climate change benefits were also being emphasised. And by the mid-2000s, BMDH became part of wider plans and strategies through its inclusion in the 2006 Biomass Action Plan and 2010 Austrian Energy Strategy 2020. This linking of BMDH to multiple policy goals (agricultural, environmental, economic) helped to create legitimacy and wider advocacy coalitions that underpinned continued policy support.

- French tram development was driven from the start by a dedicated, top-down vision, formulated by the Transport Ministry and railway industry, and motivated by specific concerns about local transport problems (noise, air pollution, parking, accidents) and export potential. The vision broadened over time and became linked to quality-of-life issues, climate change, and deeper urban reconfiguration (closing off city centres to cars, pedestrianisation, etc.).

Diffusion. In all three cases, the dissemination of radical innovations beyond initial niches required not only innovation policy (which remained important for performance improvement, cost reduction, knowledge development and stabilisation), but also sectoral policies (e.g. energy, agriculture, transport), as described above under horizontal policy coordination. Therefore, the cases support the suggestion in the Commission's recent BOHEMIA report: 'Conditions for uptake of new solutions (...) are often defined by sectoral policies (e.g. regulation, standards, procurement), and it is through alignment between sectoral and R&I policies that change can be accelerated' (EC, 2018c: 30). All three cases also demonstrate that diffusion involves processes in business, policy, cultural and user environments. The latter, however, was not discussed in depth, which may be due to the characteristics of the cases, two of which were about infrastructure systems and one concerned supply-side electricity generation. Diffusion in all three cases was stimulated by: a) dedicated financial instruments that reduced business investment risks; b) positive discourses and visions (discussed above) that legitimised policy support; and c) cross-ministerial alliances and high-level political support (often from ministers).

- RET-diffusion in Germany's energy transition was stimulated by: a) stable and attractive feed-in tariffs because guaranteed minimum payments for 20 years reduced investment risks for new entrants; b) positive green growth discourses; c) broad-based advocacy coalitions; and d) top-level political support (from Chancellor Merkel after 2011) which has weakened, however, in recent years because of concerns over rising costs and the disruption of incumbent utilities.

- The diffusion of Austrian BMDH was stimulated by: a) knowledge aggregation, codification and dissemination activities that stabilised the innovation and reduced uncertainties; b) capital grants that reduced investment risks, which are often substantial for infrastructure systems like BMDH; c) financial incentives (e.g. feed-in tariffs) that created attractive market conditions for company involvement; and d) broadening visions and support coalitions.

- French tram diffusion was driven by: a) new financing instruments (like versement transport) which reduced investment risks; b) planning and design support from technical bureaucracies; c) political support from local mayors (as trams demonstrated their capacity to support electoral wins) and the Transport Minister Cavaillé; d) positive visions and discourses; and e) a broad-based support coalition with growing export success.

4.3 Messages for transformative innovation policy

Instruments from all three innovation policy frames (Figure 9-1) are important for transformative innovation and socio-technical transitions and should be strengthened to address grand challenges. In addition to the well-known instruments from the first two policy frames, the following policy messages summarise important avenues for transformative innovation policy which include, and go beyond, the five policy challenges discussed above.

Emergence of radical innovations

- Support a wide range of sustainability innovations, not just technological but also social, infrastructural and business model innovations (Figure 9-3).

- Support more real-world experiments, pilots, demonstration projects and living labs, which move innovations beyond the R&D phase and enable open-ended learning with multiple stakeholders about technical performance, market uptake, social acceptance and environmental impacts.

- Build transformative innovation coalitions which not only include 'traditional' actors (universities, research centres, firms), but also new entrants (NGOs, cities, startups, pioneers) that are willing to challenge conventional wisdom and to think 'out of the box'.

- Nurture new market creation (e.g. through subsidies, public procurement, feed-in tariffs) and new business models so that radical innovations can become economically viable.

Diffusion

- Insights and findings from local projects and experiments should be shared, compared, aggregated, codified and disseminated, which could be done by intermediary actors such as innovation or implementation agencies.

- Research, development and innovation policy can help improve price/performance characteristics of innovations, which stimulate diffusion.

- Adoption by consumers can be stimulated with targeted financial instruments (purchase subsidies, low-interest loans, tax exemptions), information provision (media campaigns, labels, celebrity endorsements) and adjustments in economic framework conditions.

- Uptake of innovations in businesses can be supported with financial instruments that reduce investment risks (e.g. interest-free loans, capital grants, investment subsidies), regulations (e.g. renewable energy obligations for utilities, electric-vehicle sales targets for automakers, environmental standards for home builders), and public infrastructure investment.

- Policymakers can support the social acceptance of innovations by developing positive visions and debates and by involving societal groups through public participation.

Disruption and system reconfiguration

- Reconfiguring entire systems should go beyond technological 'silver bullets' and promote synergies among multiple innovations.

- Since transitions are full of surprises, non-linearities and unintended consequences, adaptive governance approaches are recommended, based on iterative cycles of policymaking and planning, implementing, evaluating and learning.

- To mitigate potential resistance from incumbent firms, policymakers could assist them in strategic reorientation processes or provide compensation (e.g. sunset clauses).

Cross-cutting policy recommendations

- Horizontal coordination between policy domains (innovation, transport, energy, industry, education, skills) is important, especially in the later phases.

- Meeting the large investment needs for diffusion and infrastructure change will require policies that change market incentives, reduce risks and uncertainties, and incentivise private investment, as well as more fundamental reforms of the financial system.

- Long-term change and directing innovative trajectories towards grand challenges should be promoted through ambitious visions, missions and targets.

5. References

ACUF, (2007), Financement des transports publics urbains. Association des communautés urbaines de France.

Arthur, W.B. (1994), Increasing Returns and Path Dependence in the Economy, Michigan: University of Michigan Press.

Austrian Energy Agency, (2012), Austria 2012. Basic Data Bio-energy. Vienna, Austria.

Berkeley, N., Bailey, D., Jones, A. and Jarvis, D. (2018), Assessing the transition towards battery electric vehicles: a Multi-Level Perspective on drivers of, and barriers to, take up, *Transportation Research Part A: Policy and Practice*, 106, 320-332.

Bolton, R. and Foxon, T.J. (2015), Infrastructure transformation as a socio-technical process – implications for the governance of energy distribution networks in the UK, *Technological Forecasting and Social Change*, 90, Part B, 538-550.

Bolton, R. and Hannon, M. (2016), Governing sustainability transitions through business model innovation: Towards a systems understanding, *Research Policy*, 45(9), 1731-1742.

BSW-Solar, (2010), Statistic data on the German photovoltaic industry: http://en.solarwirtschaft.de/fileadmin/content_files/factsheet_pv_engl.pdf, accessed 31 May 2011.

Bulkeley, H., Broto, V.C., Maassen, A. (2013), Low-carbon transitions and the reconfiguration of urban infrastructure, *Urban Studies*, 51(7) 1471-1486.

Bulkeley, H., Coenen, L., Frantzeskaki, N., Hartmann, C., Kronsell, A., Mai, L., Marvin, S., McCormick, K., van Steenbergen, F. and Voytenko Palgan, Y. (2016), Urban living labs: governing urban sustainability transitions, *Current Opinion in Environmental Sustainability*, 22, 13-17.

CERTU, (2013), Transports Urbains Collectifs, Évolution 2007-2012, Centre d'Etudes sur les Réseaux, les Transports, l'Urbanisme et les constructions publiques.

Christensen, C., (1997), The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail. Harvard Business School Press, Boston, MA.

Deuten, J.J., Rip, A. and Jelsma, J. (1997), Societal embedding and product creation management, *Technology Analysis & Strategic Management*, 9(2), 131-148.

Dewald, U. and Truffer, B. (2011), Market formation in technological innovation systems: Diffusion of photovoltaic applications in Germany, *Industry and Innovation*, 18(3), 285-300.

Diercks, G., Larsen, H., Steward, F. (2019), Transformative innovation policy: Addressing variety in an emerging policy paradigm, *Research Policy*, 48(4), 880-894.

EC, (2017b). LAB-FAB-APP, Investing in the European Future We Want, Report of the independent High-Level Group on maximising the impact of EU Research & Innovation Programmes, European Commission, Directorate-General for Research and Innovation, Brussels.

European Commission, (2016), Changing Gear in R&I: Green Growth for Jobs and Prosperity in the EU, Report of the European Commission expert group 'R&I policy framework for green growth & jobs', European Commission, Directorate-General for Research and Innovation, Brussels.

European Commission, (2017a), Europe's Future: Open Innovation, Open Science, Open to the World, Reflections of the RISE group (Research, Innovation and Science Policy Experts), European Commission, Brussels.

European Commission, (2018a), a Clean Planet For All - a European Strategic Long-term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy, European Commission, Brussels, (COM(2018) 773 final).

European Commission, (2018b), a Renewed European Agenda for Research and Innovation – Europe's Chance to Shape its Future, European Commission, Brussels, (COM(2018) 306 final, 5.5.2018).

European Commission, (2018c), Transitions on the Horizon: Perspectives for the European Union's future research and innovation policies, Final report from project BOHEMIA, 'Beyond the horizon: Foresight in support of the EU's future research and innovation policy', European Commission, Directorate-General for Research and Innovation, Brussels.

European Commission, (2019). Reflection Paper: Towards a Sustainable Europe by 2030, European Commission, Brussels.

Fuenfschilling, L. and Truffer, B. (2014), The structuration of socio-technical regimes – Conceptual foundations from institutional theory, *Research Policy*, 43(4), 772-791.

GART, (2015), L'année 2013 des transports urbains, Groupement des Autorités Responsables de Transport, Paris.

Geels, F.W. (2002), Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case study, *Research Policy*, 31(8-9), 1257-1274.

Geels, F.W. (2004), From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory, *Research Policy*, 33(6-7), 897-920.

Geels, F.W. and Raven, R.P.J.M. (2006), Non-linearity and expectations in niche-development trajectories: Ups and downs in Dutch biogas development (1973-2003), *Technology Analysis & Strategic Management*, 18(3/4), 375-392.

Geels, F.W. and Schot, J.W. (2007), Typology of socio-technical transition pathways, *Research Policy*, 36(3), 399-417.

Geels, F.W. (2014), Regime resistance against low-carbon energy transitions: Introducing politics and power in the multi-level perspective, *Theory, Culture & Society*, 31(5), 21-40.

Geels, F.W., Kern, F., Fuchs, G., Hinderer, N., Kungl, G., Mylan, J., Neukirch, M. and Wassermann, S. (2016), The enactment of socio-technical transition pathways: a reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990-2014), *Research Policy*, 45(4), 896-913.

Geels, F.W., Sovacool, B.K., Schwanen, T. and Sorrell, S. 2017, Socio-technical transitions for deep decarbonization, *Science*, 357(6357), 1242-1244.

Geels, F.W. and Johnson, V. (2018), Towards a modular and temporal understanding of system diffusion: Adoption models and socio-technical theories applied to Austrian biomass district-heating (1979-2013), Energy Research and Social Science, 38, 138-153.

Goodrich, A.C., Powell, D.M., James, T.L., Woodhouse, M. and Buonassisi, T. (2013), Assessing the rivers of regional trends in solar photovoltaic manufacturing. *Energy & Environmental Science*, 6, 2811-2821.

Hamman, P. (2015). Negotiation and social transactions in urban policies: the case of the tramway projects in France, Urban Research & Practice, 8(2), 196-217.

Hargreaves, T., Hielscher, S., Seyfang, G. and Smith, A. (2013), Grassroots innovations in community energy: The role of intermediaries in niche development, *Global Environmental Change*, 23(5), 868-880.

Hess, D.J. (2016), The politics of niche-regime conflicts: Distributed solar energy in the United States, *Environmental Innovation and Societal Transitions*, 19, 42-50.

Hoppe, T. and De Vries, G., (2019). Social innovation and the energy transition, Sustainability 11:141; doi:10.3390/su11010141.

Hoppmann, J., Huenteler, J. and Girod, B. (2014), Compulsive policy-making: The evolution of the German feed-in tariff system for photovoltaic power, *Research Policy*, 43(8), 1422-1441.

Hossain, M. (2018), Grassroots innovation: The state of the art and future perspectives, *Technology in Society*, 55, 63-69.

IEA, (2014), Energy Policies of IEA Countries: Austria, 2014 Review, International Energy Agency, Paris, France.

Jacobsson, S. and Lauber, V. (2006), The politics and policy of energy system transformation: Explaining the German diffusion of renewable energy technology, *Energy Policy*, 34(3), 256-276.

Kalt, G. and Kranzl, L. (2009), Renewable Energy in the Heating and Cooling Sector in Austria. Energy Economics Group, Intelligent Energy Europe, Brussels, Belgium.

Kaminagai, Y. (2014), Tramway : une école française. IAU ÎdF, Paris.

Kanger, L., Geels, F.W., Sovacool, B.J. and Schot, J.W. (2019), Technological diffusion as a process of societal embedding: Lessons from historical automobile transitions for future electric mobility, *Transportation Research Part D: Transport and Environment*, 71, 47-66.

Kemp, R., Schot, J. and Hoogma, R. (1998), Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management, Technology Analysis and Strategic Management, 10(2), 175-196.

King, B.G. and Pearce, N.A. (2010), The contentiousness of markets: Politics, social movements, and institutional change in markets, Annual Review of Sociology, 36, 249-268.

Kivimaa, P., Boon, W., Hyysalo, S. and Klerkx, L. (2019), Towards a typology of intermediaries in sustainability transitions: a systematic review and a research agenda, *Research Policy*, 48(4), 1062-1075.

Klaus Novy Institut, (2011), Marktakteure. Erneuerbare Energie Anlagen in der Stromerzeugung 2011. Im Rahmen des Forschungsprojektes: Genossenschaftliche Unterstützungsstrukturen für eine sozialräumliche Energiewirtschaft.

Klitkou, A., Bolwig, S., Hansen, T. and Wessberg, N. (2015), The role of lock-in mechanisms in transition processes: The case of energy for road transport, *Environmental Innovation and Societal Transitions*, 16, 22-37.

Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemaade, F., Avelino, F., Bergek, A., Boons, F., Fuenfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M.S., Nykvist, B., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D. and Wells, P. (2019), An agenda for sustainability transitions research: State of the art and future directions, *Environmental Innovation and Societal Transitions*, 31, 1-32.

Kungl, G. and Geels, F.W. (2018), Sequence and alignment of external pressures in industry destabilization: Understanding the downfall of incumbent utilities in the German energy transition (1998-2015), Environmental Innovation and Societal Transition, 26, 78-100.

Laisney, F. (2011), Atlas du tramway dans les villes françaises, Éditions R. ed. Leonard-Barton, D. 1992, Core capabilities and core rigidities: a paradox in managing new product development, *Strategic Management Journal*, 13, special issue, 111-125.

Lounsbury, M. and Glynn, M.A. (2001), Cultural entrepreneurship: Stories, legitimacy, and the acquisition of resources, *Strategic Management Journal*, 22(6-7), 545-564.

Madlener, R. (2007), Innovation diffusion, public policy, and local initiative: The case of wood-fuelled district heating systems in Austria. *Energy Policy* 35, 1992-2008.

Marletto, G., Franceschini, S., Ortolani, C. and Sillig, C. (2016), Mapping Sustainability Transitions: Networks of Innovators, Techno-economic Competences and Political Discourses, Springer.

Mazzucato, M. 2018, Mission-oriented innovation policies: Challenges and opportunities, Industrial and Corporate Change, 27(5), 803-815.

McMeekin, A., Geels, F.W. and Hodson, M. (2019), Mapping the winds of whole system reconfiguration: Analysing low-carbon transformations across production, distribution and consumption in the UK electricity system, *Research Policy*, 48(5), 1216-1231.

Meadowcroft, J. (2009), What about the politics? Sustainable development, transition management, and long term energy transitions, *Policy Sciences*, 42(4), 323-340.

Metschina, (2014), Biomass district heating in Austria, Landwirtschaftskammer Steiermark, Styria, Graz.

Moradi, A. and Vagoni, E. (2018), a multi-level perspective analysis of urban mobility system dynamics: What are the future transition pathways?, *Technological Forecasting and Social Change*, 126, 231-243.

Nelson, R.R. (2008), Bounded rationality, cognitive maps, and trial and error learning, Journal of Economic Behaviour & Organization, 67(1), 78-89.

Mylan, J., Morris, C., Beech, E. and Geels, F.W. (2019), Rage against the regime: Niche-regime interactions in the societal embedding of plant-based milk, *Environmental Innovation and Societal Transitions*, in press; https://doi.org/10.1016/j.eist.2018.11.001

Penna, C.C.R. and Geels, F.W. (2015), Climate change and the slow reorientation of the American car industry (1979-2011): An application and extension of the Dialectic Issue LifeCycle (DILC) model, *Research Policy*, 44(5), 1029-1048.

Pesch, U., Spekkink, W. and Quist, J. (2019), Local sustainability initiatives: Innovation and civic engagement in societal experiments, *European Planning Studies*, 27(2), 300-317.

Pissaloux, J., Ducol, F. (2016), XII. Réflexions sur le retour récent du tramway comme mode de transport urbain et périurbain, in: Droit et Gestion Des Collectivités Territoriales. Vol. 32, 2012.

Rakos, C. (1995), Diffusion of biomass district heating in Austria, in: Chartier, P., Beenackers, A.A.C.-M., Grassi, G. (Eds.), *Biomass for Energy, Environment, Agriculture and Industry*. Elsevier Science Ltd, Oxford, 875-885.

Rosenbloom, D., Berton, H. and Meadowcroft, J. (2016), Framing the sun: a discursive approach to understanding multi-dimensional interactions within socio-technical transitions through the case of solar electricity in Ontario, Canada, *Research Policy*, 45(6), 1275-1290.

Schot, J.W. and Geels, F.W. (2008), Strategic niche management and sustainable innovation journeys: Theory, findings, research agenda and policy, *Technology Analysis & Strategic Management*, 20(5), 537-554.

Schot, J.W. and Steinmueller, E. (2018), Three frames for innovation policy: R&D, systems of innovation and transformative change, *Research Policy*, 47, 1554-1567.

Seiwald, M., (2014), The (up) scaling of renewable energy technologies: Experiences from the Austrian biomass district heating niche, *Moravian Geographical Reports*, 22, 44-54.

Sengers, F., Wieczorek, A.J. and Raven, R. (2019), Experimenting for sustainability transitions: a systematic literature review, *Technological Forecasting and Social Change*, in press.

Seyfang, G. and Smith, A, (2007), Grassroots innovations for sustainable development: towards a new research and policy agenda, *Environmental Politics* 16(4): 583-603.

Shove, E. (2003), Comfort, Cleanliness and Convenience: The Social Organization of Normality, Oxford: Berg.

Smith, A., Jan-Peter Voβ, J.-P. and Grin, J. (2010), Innovation studies and sustainability transitions: the allure of a multi-level perspective and its challenges, *Research Policy*, 39(4), 435-448.

Smith, A. (2012). Civil society in sustainable energy transitions, in: Verbong, G. and Loorbach, D. (eds.), 2012, *Governing the Energy Transition: Reality, Illusion or Necessity?*, Routledge, 180-202.

Smith, A. and Raven, R. (2012), 'What is protective space? Reconsidering niches in transitions to sustainability', *Research Policy*, 41(6), 1025-1036.

Söderholm, P., Hellsmark, H., Frishammar, J., Hansson, J., Mossberg, J. and Sandström, A. (2019), Technological development for sustainability: The role of network management in the innovation policy mix, *Technological Forecasting and Social Change*, in press.

Statistik Austria (2015), Energy Balances, Austria 1970-2013 detailed information, from http://www.statistik.at/web_en/static/energy_balances_austria_1970_to_2013_detailed_information_029791.xlsx (author accessed 14 April 2015).

Steward, F. (2012), Transformative innovation policy to meet the challenge of climate change: sociotechnical networks aligned with consumption and end-use as new transition arenas for a low-carbon society or green economy. *Technology Analysis & Strategic Management*, 24(4), 331-343.

Transports et Politiques Locales de Déplacement, 183-196.

Turnheim, B. and Geels, F.W. (2012), Regime destabilisation as the flipside of energy transitions: lessons from the history of the British coal industry (1913-1997), *Energy Policy*, 50, 35-49.

Turnheim, B., Kivimaa, P. and Berkhout, F. (Eds.), (2018), *Innovating Climate Governance: Moving Beyond Experiments*, Cambridge University Press.

Turnheim, B. and Geels, F.W. (2019), Incumbent actors, guided search paths, and landmark projects in infra-system transitions: Rethinking Strategic Niche Management with a case study of French tramway diffusion (1971-2016), *Research Policy*, 48(6), 1412-1428.

Tushman, M.L and Romanelli, E. (1985), Organizational evolution: a metamorphosis model of convergence and reorientation, in: L.L. Cummings and B.M. Staw (eds.), *Research in Organizational Behavior*, Vol. 7, Greenwich, CT: JAI Press, 171-222.

Van de Poel, I. (2000), On the role of outsiders in technical development, *Technology Analysis & Strategic Management*, 12(3), 383-397.

Van Driel, H. and Schot, J. (2005), Radical innovation as a multi-level process: Introducing floating grain elevators in the port of Rotterdam, *Technology and Culture*, 46(1), 51-76.

Van Waes, A., Farla, J., Frenken, K., De Jong, J.P.J. and Raven, R. (2018), Business model innovation and socio-technical transitions. A new prospective framework with an application to bike sharing, *Journal of Cleaner Production*, 195, 1300-1312.

Walker, W. (2000), Entrapment in large technology systems: Institutional commitments and power relations, *Research Policy*, 29(7-8), 833-846.