What happens after positive tipping points? A socio-technical analysis of acceleration and deceleration in solar-PV diffusion in Germany and the UK

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A B S T R A C T

This paper contributes to debates on positive tipping points in climate mitigation, which are relevant for accelerating low-carbon transitions. The first contribution is to draw attention to dynamics after the tipping point and criticise the determinism of existing approaches, which excessively focus on irreversible self-reinforcing processes. We conceptually extend Geels and Ayoub’s socio-technical perspective on tipping points by adding potential negative feedback processes on political and socio-cultural dimensions that can decelerate further diffusion after the tipping point. The second contribution is to replicate Geels and Ayoub’s framework with two new case studies and thus enhance its empirical validity. The case studies are solar-PV diffusion in Germany and the UK, which both first accelerated because of positive feedbacks and then slowed down because of negative feedbacks. We explain why solar-PV diffusion almost entirely halted in the UK but regained momentum in Germany after 2016. Our findings demonstrate the importance of analysing both positive and negative feedbacks in low-carbon transitions. Our findings also show that the strength of various feedback processes is shaped by broader economic and political contexts.

1. Introduction

Limiting global warming to well below 2 °C will require rapid low-carbon transitions in core systems such as energy (IPCC, 2022). The emissions gap between current trajectories and future targets (UNEP, 2022) means that acceleration is increasingly important, which is why positive tipping points for low-carbon transition have received more attention in recent years (Otto et al., 2020; Lenton et al., 2022; Stadelmann-Steffen et al., 2021; Tabara et al., 2022).

Tipping points have been defined as “the point or threshold at which small quantitative changes in the system trigger a non-linear change process that is driven by system-internal feedback mechanisms and inevitably leads to a qualitatively different state of the system, which is often irreversible” (Milkcereit et al., 2018: 9). An example from the natural sciences, which is the origin of the tipping point concept, is that a small amount of additional nutrients can push concentration levels past a threshold, where self-reinforcing feedbacks between fish, algae, sunlight, and oxygen lead to eutrophication of lake systems and rapid shifts from clear to turbid water (Lenton, 2020).

The positive tipping point literature has applied similar ideas to human societies and economies, focusing on self-reinforcing positive feedback mechanisms that can accelerate the diffusion of low-carbon (technical, social, business model) innovations and lead to wider system transitions. Some scholars (Strauch, 2020; Sharpe and Lenton, 2021; Mercure et al., 2021; Way et al., 2022) have highlighted the role of increasing-returns-to-adoption mechanisms (such as learning-by-doing, scale economies, complementary innovations, experience curves) that reduce costs and improve the performance of low-carbon technologies, which, in turn, can drive rapid adoption and diffusion. Other scholars (Nyborg et al., 2016; Tabara et al., 2018; Otto et al., 2020; Ginkel et al., 2020; Winkelmann et al., 2022) have highlighted the role of contagion effects, information cascades, or critical mass dynamics in accelerating changes in norms and behaviours. Yet other scholars (Milkcereit et al., 2018; Stadelmann-Steffen et al., 2021; Lenton et al., 2022; Lenton et al., 2023) have developed socio-technical understandings of tipping points that accommodate both techno-economic and agentic drivers, with Geels and Ayoub (2023) advancing a novel socio-technical framework with seven interacting feedback loops between actors and technologies.

Much of the positive tipping point literature focuses on the (actual or desired) acceleration of emerging low-carbon innovations (such as

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electric vehicles, solar-PV, wind energy, plant-based diets), seeing the inflection point in S-shaped diffusion curves as tipping point (Phillips, 2007; Farmer et al., 2019; Strauch, 2020; Aschemann-Witzel and Schulze, 2023; Meldrum et al., 2023). We note that this focus deviates from the natural science literature, where tipping points typically refer to the collapse of existing systems and a shift to a different system state (as in the lake example above). Although some scholars (Allen and Malekpour, 2023; Lenton et al., 2023) rightly suggest that comprehensive analyses of positive tipping points should address both the inflection point of emerging innovations (after which self-reinforcing feedbacks accelerate diffusion) and the destabilisation of existing socio-technical systems, this paper follows much of the existing literature in adopting a narrower focus on the trajectory of emerging innovations.

Another characteristic of much of the positive tipping point literature is that it pays relatively limited attention to what happens after a tipping point has been crossed. This stems from the assumption that self-reinforcing positive feedbacks will continue to drive developments forward, leading to irreversible trajectories (Sharpe and Lenton, 2021; Milkoreit et al., 2018; Lenton et al. 2022). Combined with the promise that small nudges or targeted interventions may be sufficient to cross tipping points, this idea of irreversible self-amplifying feedbacks is part of the appeal of the positive tipping point concept.

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1. **Users and technology:** Increasing user adoption reduces technology costs through increasing returns to adoption mechanisms (such as learning-by-doing, learning-by-using, network externalities, complementary innovations, scale economies, and informational increasing returns), while decreasing costs stimulate further adoption.

2. **Firms, technology, users:** Increasing user adoption improves firm sales and revenues, which lead firms to learn and develop more positive strategic views of new technologies, which makes them more likely to enhance investments in R&D and production assets, which, in turn, improve technical performance and lower costs, which drive further adoption.

3. **Firms and policymakers:** Growing firms (due to increasing sales and revenues) increase their political power and influence, which enables them to shape public policies. Enhanced policy support (e.g., loans, grants, subsidies), in turn, improves the economic performance of firms and their deployment of new technologies.

4. **Policymakers, users, and technology:** Policymakers shape the development and deployment of technologies through infrastructure investments, technology standards, and regulations. Policy effect evaluations may, in turn, lead to adjustments in the settings of policy instruments, in the types of policy instruments, or in policy goals and orientations.

5. **Users and wider publics:** Increasing adoption expands the visibility of new technologies, which may lead to more positive public debates if consumer experiences are positive. Positive public debates, in turn, can improve the legitimacy and desirability of new technologies, driving further adoption.

6. **Wider publics and technology:** Cost reductions, technological improvements, and increased adoption lead to more positive public debates and cultural discourses. Positive public debates and discourses, in turn, enhance the legitimacy and desirability of new technologies.

7. **Wider publics and policymakers:** Increasing public attention and positive discourses about new technologies stimulate policymakers to introduce or strengthen policies. Stronger policies and the accompanying policy discourses can positively shape public debates.

While Geels and Ayoub (2023), and much of the positive tipping point literature, mostly focus on positive self-reinforcing feedback loops that accelerate the diffusion of low-carbon innovations, we draw attention to the possibility of negative feedback loops, especially socio-political ones, which may decelerate diffusion. To substantiate this point and extend Geels and Ayoub’s socio-technical framework, we mobilise insights from political science and discourse theory and import these into research on positive climate mitigation tipping points, which leads to a more nuanced and less deterministic understanding of what happens after tipping points have been crossed.

While policy studies scholars (e.g., Pierson, 1993; Jordan and Matt, 2014; Rosenbloom, 2017) initially analysed positive feedback effects that help stabilise and strengthen new policies (e.g., by creating new interest groups that act to support them (Breetz et al., 2018)), they have, over the past decade, also started to analyse potential negative feedbacks that can lead to the unravelling of policies after they have been introduced (e.g., Weaver, 2015; Patashnik and Zelizer, 2013; Oberlander and Weaver, 2015; Jacobs and Weaver, 2015; Edmondson et al., 2019; Lockwood, 2022). They suggested that implementation of a policy may be followed by bounded political concerns over: (a) increasing costs associated with the policy, (b) unfair distributional consequences of the policy (e.g., some groups benefitting more than others), or (c) unintended negative consequences of a policy (in which some groups experience adverse effects), which through impact evaluations and socio-political debates may lead to political downscaling or removal efforts (negative feedback 4, 7).

Discourse analyses (e.g., Geels and Verhees, 2011; Roberts, 2017; Rosenbloom, 2018; Roberts and Geels, 2018) have similarly found that negative consumer experiences or unintended negative consequences of new technologies on some groups as well as unfair distributional consequences of a technology support policy or increasing costs (for policymakers and taxpayers) may lead to negative public debates, which in turn, can erode the cultural meanings and legitimacy of a new technology [negative feedback 6], diminish consumer interest [negative feedback 5], or exert pressure on policymakers to downscale policy support [negative feedback 7].

The implication of these conceptual extensions is that political and socio-cultural feedbacks may shift from positive to negative after low-carbon technologies have crossed a tipping point (i.e., inflection point in the diffusion curve). Whether or not such negative socio-political feedbacks decelerate further technological diffusion depends on the balance between positive and negative feedbacks. It is possible that continuing positive feedbacks from techno-economic developments (such as learning-by-doing, scale economies, cost decreases), company investments, and corporate lobbying outweigh negative socio-political feedbacks, leading to continued diffusion. The reverse is also possible, leading to decelerated diffusion. The enactment of feedbacks and the result of their interactions is ultimately an empirical question that can only be answered with situated multi-dimensional analyses that investigate actors and social interactions as well as structural contexts (economic, political, cultural) that may vary between countries, leading to different outcomes.

3. **Research design**

We use a comparative case study design to investigate the acceleration and deceleration of solar-PV in Germany and the UK. This research design is suitable for analysing how differences and similarities between the two cases relate to the enactment and unfolding of positive and negative feedback loops by different social groups acting in structural contexts. Case studies are especially suited for analysing qualitative dimensions such as actions and interactions between social groups, and changes in the perspectives and strategies of actors.

We selected solar-PV because this technology plays an important role in low-carbon transition scenarios (IPCC, 2022) and is often seen as globally having crossed a positive tipping point leading to positive reinforcements such as cost reductions that inevitably accelerate further diffusion (Strauch, 2020; Way et al., 2022). Our two country case studies question the implicit determinism of that view, showing that negative feedbacks after the tipping point can decelerate diffusion. Solar-PV thus is a suitable technology to analyse more deeply the multiple feedbacks that led to the tipping point as well as what happened afterwards. Another reason for selecting Germany and the UK is that both countries show interesting similarities (in policy support schemes, and aggregate developments) and differences (in diffusion rates of different solar-PV segments, structural contexts, and the relative influence of particular social groups). A third selection reason is that some dimensions of both cases are relatively well-studied, especially for the early periods, which means we can use some existing empirical material to develop integrative theory-oriented accounts.

The analysis of the two case studies focuses on the actions and perceptions of the main social groups (firms, users, policymakers, wider publics) with regard to the technology, and the enactment of the seven feedbacks in Fig. 1. For the user category, we analyse different kinds of users (e.g., households, public buildings, farmers, large landowners, energy communities, and project developers) and for the firm category, we analyse different types of firms (e.g., installation, manufacturing, and financial firms).

For techno-economic developments and public attention, our analysis uses quantitative data extracted from newspapers and publicly available statistical databases. We use data from the Fraunhofer ISE database to construct the deployment curve for solar-PV in Germany. To construct a UK diffusion curve, we accessed solar-PV deployment data from the UK office for National Statistics. From the International
Renewable Energy Agency, we collected data on renewable electricity cost to investigate the cost trend. One complication for techno-economic developments is that the UK and German government databases use slightly different solar-PV size categories. Both countries qualify small scale solar-PV as between 0 and 10 kW. German databases qualify mid-scale installations as between 10 kW and 100 kW, while UK databases use a 10-50 kW range. Large-scale includes installations from 100 kW in Germany and larger than 50 kW in the UK.

For public attention, we accessed electronic databases of *The Times* and *The Independent* for the UK and *Die Zeit* and the *Süddeutsche Zeitung* for Germany, which cover a range of political perspective, and used newspaper counts of ‘solar-PV’ as a proxy for public attention. We collected all the articles and plotted the normalised average per year to trace media coverage of solar-PV, which we use as a proxy for public attention. Because this indicator does not indicate how issues are discussed, we also used secondary sources to analyse changing contents of public discourses about solar-PV over time.

Additionally, our case studies use information from secondary sources such as academic publications and reports to investigate actions and changes in actor perspectives and strategies. In this regard, our paper does not aim to collect original data, but to combine existing information in multi-dimensional narratives and interpret the enactment of different feedback mechanisms. By explicitly indicating the feedback mechanism in the text [in italics between square brackets], we present the brief case studies as analytical theory-oriented narratives rather than detailed chronological accounts (George and Bennett, 2004). We have divided each narrative into two periods, with the first period analysing the processes and positive feedbacks leading up to the tipping point, and the second period analysing continuing positive feedbacks and emerging negative feedbacks after the tipping point. The case studies use both quantitative and qualitative information to analyse unfolding processes over time.

Using quantitative information, we follow much of the existing literature and identify technology deployment tipping points
conventionally as the inflection point in diffusion curves where user deployment markedly accelerates. Tipping points in actors’ perceptions are identified by following actors’ strategies over multiple years to detect changes. For instance, the tipping point for policymakers is assessed from changes in policy goals and instruments; for firms, it is inferred from changes in perceptions and investment decisions. We infer tipping point in public debates from a rise in public attention and changing content of public discourses, while rapid adoption indicates tipping points in user perceptions and behaviours.

4. Germany solar-PV

Solar-PV has expanded substantially in the past two decades, producing 9.9% of German electricity in 2021 (Fraunhofer ISE, 2021). German solar-PV emerged slowly and crossed a positive tipping point in deployment around 2008/9, leading to accelerated change (Fig. 2). By 2013/14, however, diffusion decelerated due to negative feedbacks counteracting positive feedbacks. Although change accelerated again after 2016, our analysis focuses primarily on processes leading to the positive tipping point and the subsequent deceleration.

4.1. Positive feedbacks leading up to 2008/9 tipping point in solar-PV deployment

Policy measures such as R&D subsidies, the 1990 Feed-In Law, and the 1000 roof project created a small market niche for solar-PV in the 1990s, which stimulated the emergence of solar-PV manufacturers [feedback 2] that lobbied for more support [feedback 3] (Hoppmann et al., 2014; Geels et al., 2016). Manufacturing firms (in solar-PV, metal, and machine-building), green NGOs (Greenpeace, Eurosolar), and workers’ associations also built a PV-coalition that lobbied directly and through the media for a policy strategy to make Germany a first mover in solar-PV [feedback 3, 7] (Jacobsson and Lauber, 2006; Meckling, 2019). The formation of a Red-Green government (1998–2005) increased the political receptiveness for this lobby, which, combined with positive evaluations of the Feed-In Law in stimulating the industry and creating jobs [feedback 4], led policymakers to introduce the Renewable Energy Sources Act (EEG) in 2000(Oschmann, 2016), leading to a policy tipping point.

The EEG policy, which offered long-term payment for renewable electricity generation, and the 100,000-roof program, introduced in 1999, increased the solar-PV market and company investments [feedback 2]. The Green Party’s success in the 2002 election was followed by the EEG-2004 amendment, which increased feed-in rates for rooftop PV and removed the 100kWp cap for large-scale systems in fields [feedback 4, 7]. This policy amendment kick-started accelerated adoption and firm investment [feedback 2] in all segments (Fig. 3), which led to the 2008/9 deployment tipping point.

For the small-scale household segment, the amended EEG policy made rooftop solar-PV an attractive opportunity for investment and consumption. Households financed adoption from savings or loans from local banks, leading to a four-fold installation increase between 2004 and 2008. The mid-scale category, which deployed solar-PV on farm buildings and public buildings (e.g., schools, town halls, municipalities), grew rapidly because of EEG support and civil society energy activism, particularly from the anti-nuclear movement and energy communities (Beveridge and Kern, 2013; Punt et al., 2022; Wierling et al., 2018), and a willingness to lend by cooperative banks and lending cooperatives (Punt et al., 2022). Deployment of large-scale field-based solar-PV systems by project developers, farmers, energy firms, and PV module producers grew slowly after the EEG-2004 amendment and more rapidly after 2009 when increased deployment in the other segments boosted the confidence of project developers and investors (like banks, asset management firms, investment funds) [feedback 2], which increased the availability of funding.

Growing deployment increased strategic commitments and investments by solar-PV manufacturers and the installation sector (Hoppmann et al., 2013), which enhanced learning-by-doing and scale economies [feedback 2] (Nemet, 2019). Solar-PV developed into an industrial success story, as total sales of the German PV industry grew from 201 million euros in 2000 to 7 billion euros in 2008. Export sales grew from 273 million euros in 2004 to 5 billion euros in 2010 (BSW-Solar, 2010), leading to a tipping point in company strategies in the second half of the 2000s. This expansion increased the industry’s political strength [feedback 3] and provided economic arguments for continued solar-PV support (Lauber and Jacobsson, 2016).

Increased deployment and industrial success in the late 2000s also stimulated public attention to solar-PV, leading to tipping in public debates (Fig. 4) and the articulation of positive public discourses about green growth (Hoppmann et al., 2014), which improved the desirability and legitimacy of solar-PV technology and policy support [feedback 5, 6, 7].

Increasing deployment and manufacturing also enabled learning processes, scale economies, and increasing returns to adoption, improving technology performance and reducing solar-PV costs [feedback 1, 2]. Module prices decreased from 3200 EUR/kWp in 2008 to 470...
EUR/kWp by 2019 (Fig. 5) (Hoppmann et al., 2014) as production shifted to cheaper Chinese firms. Still, the balance of system costs, which include converters, decreased less and therefore constituted an increasing part of total costs (Fig. 5). Decreasing prices stimulated further deployment in all segments, culminating in the 2008/9 tipping point.

4.2. Negative feedbacks and deceleration after the solar-PV deployment tipping point

Positive techno-economic feedbacks continued after the 2008/9 tipping point, with costs for small-scale and large-scale solar-PV further decreasing (Figs. 5, 6) because of economies of scale, learning processes, R&D, increasing returns to adoption, cheaper financing costs (Kavlak et al., 2018), and module efficiency improvements (IRENA, 2022) [feedback 1, 2].

Although these cost decreases stimulated adoption, negative feedbacks and weakening positive feedbacks led to socio-political changes that decelerated solar-PV deployment after 2013/14. An important negative feedback was that rising solar-PV deployment increased EEG surcharges (Nemet, 2019), which led to policy debates about the high costs of solar-PV support [negative feedback 4]. In 2009, the newly elected centre-right government therefore amended the EEG to limit policy costs, linking the EEG rate to a deployment growth ‘corridor’ (Grau, 2014) and introducing dynamic degression to control the deployment rate [negative feedback 1].

A weakening positive feedback was the declining share of German firms in solar-PV production as cheaper Chinese modules, which benefited from generous Chinese state support for PV manufacturing (Wen et al., 2020), flooded the German market (Hoppmann et al., 2014; Lockwood, 2022). By 2013, this share was <5% (Wen et al., 2020) due to bankruptcies across the German solar-PV manufacturing sector. Combined with a slowdown in the installation sector (because of decreasing annual deployment (Figs. 2, 3)), gross employment in solar-PV decreased to 2007 levels by 2014–2015 (Fig. 7). Shrinking jobs and German PV-manufacturing eroded the industry’s political power and weakened the economic arguments for continued policy support [weakening feedback 3].

Public attention to solar-PV also decreased after 2009/10 (Fig. 4), as the 2007/8 financial crisis and subsequent recession changed public debates, while public discourses about high policy costs and declining German manufacturing eroded the salience of the green growth rationale [negative feedback 7]. The narrative of not wanting to subsidise Chinese PV-manufacturing legitimated further downward EEG-amendments (Nemet, 2019) such as an 11–16% FIT-cut and dynamic degression for 2010–2011 varying with system size [negative feedback 4, 7] (Hoppmann et al., 2014). Decreasing solar costs legitimated further downward policy adjustments [negative feedback 4] through the EEG-2012 and EEG-2014 amendments, which both decreased feed-in-tariffs, downscaled the growth corridor, and started a policy shift from FITs towards auction instruments (Hoppmann et al., 2014; Leiren and Reimer, 2018).

These successive policy adjustments began to lower deployment rates by 2013/14 in all three market segments (Figs. 2, 3). Decreasing deployment rates and shrinking domestic manufacturing weakened the solar-PV coalitions’ political power [negative feedback 3], but this did not lead to complete policy scrapping, partly because of the institutional strength of manufacturing in Germany and partly because German firms did secure a strong position in the construction of machine-tools for PV-module manufacturing, which was small but profitable (Lockwood, 2022).

After several years of deceleration, solar-PV deployment started to accelerate again after 2016/17, especially in the large-scale segment (Fig. 3). This related to a shift to mixed policy instruments for different segments with the aim of improving market integration and eliminating excess incentives (Leiren and Reimer, 2018): installations up to 100 kW were supported with feed-in-tariffs; installations between 100 and 750 kW were marketed directly, with premiums paid to the electricity consumers.

Fig. 5. Average end customer net system price for installed rooftop systems with rated nominal power from 10 to 100kWp (Fraunhofer ISE, 2023: 46).

Fig. 6. Utility-scale solar-PV total installed cost trends in Germany and UK, 2010–2021 (constructed using data from IRENA, 2022).
producers; and utility-scale installations ≥ 750 kW participated in auctions where producers could bid for generating certain amounts of renewable electricity (IEA, 2017). Continued cost decreases in electricity from utility-scale solar-PV installations (Fig. 6) enabled large-scale producers in particular to offer increasingly competitive bids [feedback 2] (Leiren and Reimer, 2018). Bidding prices decreased between 2015 and 2022, with the lowest price recorded at 43 €/MWh in 2018 (Fig. 8). These competitive bids enabled large-scale solar-PV to win many renewable electricity auctions, leading to renewed acceleration after 2016/17.

5. UK solar-PV

Solar-PV expanded rapidly in the early 2010s, but stagnated since then (Fig. 9), generating 3.9 % of UK electricity in 2021 (BEIS, 2021). Our analysis focuses on the processes leading to the positive tipping point in 2013 and the deceleration after 2015.

5.1. Positive feedbacks leading up to the 2013 solar-PV deployment tipping point

Various energy policy initiatives between 2000 and 2006 (Major Photovoltaics Demonstration Programme, Clear Skies programme, and Low Carbon Buildings Programme) created real-world solar-PV
demonstration projects that stimulated learning processes in company alliances, which gradually increased confidence [feedback 2] (Smith et al., 2014). Commercial adoption remained limited, however, because solar-PV was still expensive [negative feedback 1], and policymakers were unwilling to introduce market creation policies like Feed-in-Tariffs (FiTs) (Smith et al., 2014). NGOs (e.g., Friends of the Earth, Greenpeace), firms (construction companies, roofing contractors), and several Labour backbenchers therefore organized a campaign to raise the visibility of solar-PV and lobby for feed-in-tariffs [feedback 3, 6, 7] (Inderberg et al., 2018; Geels and Turnheim, 2022).

This campaign coincided with the 2008 Energy Bill, which favoured nuclear energy besides carbon-capture-and-storage and offshore wind. This created a bargaining opportunity for Labour backbenchers, who made their support for nuclear power conditional on inclusion of FiTs for small-scale renewables in the legislation (Smith et al., 2014). This bargaining strategy worked and the Labour government, somewhat reluctantly, introduced a Feed-in-Tariff in April 2010, without this being embedded in a wider solar-PV strategy. The 2010 Fit policy was thus not supported by wider policy tipping. The newly elected (May 2010) coalition government maintained the Fit and also pledged to become “the greenest government ever”. The Fit kickstarted subsequent solar-PV deployment (Fig. 9), which was not expected by policymakers (Smith et al., 2014) or bodies like the Committee on Climate Change, which in 2010 still assumed that “the contribution of solar-PV to sector decarbonisation in the 2020s is likely to be limited” (CCC, 2010: 254).

Households perceived Fit-supported solar-PV as a lucrative opportunity which resulted in rapidly increasing deployment of small-scale solar installations between 2010 and 2014 (Fig. 9). Early adopters were pro-environmental, middle-class households with the financial means to install solar panels on their rooftops (Collier et al., 2023).

Fig. 9. Cumulative UK installed capacity of solar-PV (in MW) by capacity size (constructed using data from the UK Office for National Statistics; Solar photovoltaics deployment).

Fig. 10. Public attention for solar PV, represented using the yearly number of articles in selected UK national newspapers (The Independent and The Times) as proxy.
Entrepreneurial investors also saw opportunities, launching schemes such as “Rent a roof” or “Free solar” in which they cheaply installed solar panels on people’s roofs and received FiT-payments for multiple years (Inderberg et al., 2018; Iskandarova et al., 2021). Small-scale adopters were unorganised and did not develop into a bottom-up movement or socio-political force, which differed from the German case (Lockwood, 2022).

The mid-size solar-PV segment also increased between 2010 and 2014 but remained much smaller than in Germany, where expansion was driven by a civic movement. Mid-size deployment was mostly done by energy communities and cooperatives (Curtin et al., 2018), which remained relatively small in the UK, partly because of a lack of financing due to the banks’ reluctance to lend (Curtin et al., 2018; Lockwood, 2022).

Deployment in the small-scale and mid-size segments generated learning processes that improved company confidence [feedback 2], which, in turn, stimulated rapid growth in large-scale solar farms after 2013 (Fig. 9). Large-scale solar-PV deployment by large landowners, farmers, and commercial project developers was stimulated by Feed-in-Tariffs for installation smaller than 5 MW (Smith et al., 2014) and by the Renewables Obligation, which in 2011 doubled payments for solar installations larger than 5 MW (Lockwood, 2022).

The unexpectedly rapid diffusion of solar-PV stimulated policy learning processes, which changed the views and strategic orientations of policymakers [feedback 4], who by 2013 finally developed a Solar-PV Strategy which stated that solar-PV “is a reliable source of renewable energy with an important role to play in the UK energy generation mix” (DECC, 2013: 70).

Public campaigns, policy debates, and increased deployment enhanced public attention for solar-PV from the late 2000s (Fig. 10), which, in turn, stimulated visibility, desirability, and user adoption [feedback 5], marking a tipping point in public debates.

Another positive feedback was that increased deployment boosted the interest, strategic commitment, and activities of firms, which learned-by-doing, gained experience (IRENA, 2022), improved technologies, and lowered costs [feedback 2]. Since the UK had limited domestic solar-PV manufacturing capacity, this feedback mostly applied to installation firms, which increased in numbers from 200 in 2009 to 5000 in 2011 (Inderberg et al., 2018). Although some overseas PV-module manufacturers opened offices in the UK (DECC, 2013), most solar panels were produced abroad and imported. In the absence of domestic manufacturing firms, the political influence of UK solar firms was smaller than in Germany [feedback 3] (Lockwood, 2022).

Increased adoption was stimulated by declining costs [feedback 1], which for utility-scale solar-PV installation costs decreased by 65 % between 2010 and 2013 and 90 % between 2010 and 2021 (Fig. 6). This cost decrease was driven by declining prices of imported modules, which was mainly due to international developments such as scale economies in Chinese manufacturing (IRENA, 2022), and by lower installation costs, driven by increased experience and innovations that improved labour productivity [feedback 2] (KPMG, 2015).

Cost decline, increased deployment, and attractive RO subsidies also encouraged the entry of big investors [feedback 2] such as venture capital and infrastructure funds (e.g., Foresight Solar Fund, Bluefield Solar Income Fund) who became prime funders of utility-scale solar farms. Although all three segments expanded after the 2013 tipping point, large-scale solar expanded fastest, becoming by far the largest UK solar-PV segment (Fig. 5).

5.2. Negative feedbacks leading to deceleration

Some positive techno-economic feedbacks continued after the 2013 tipping point such a continued cost decreases (Fig. 6). Although such cost decreases normally stimulate more adoption [feedback 1], several negative socio-political feedbacks gathered strength, leading to significant deceleration in deployment after 2015 (Fig. 9).

A core negative feedback was increasing political concern about rising costs of policy support for solar-PV deployment [negative feedback 4] (Gillard, 2016). These concerns increased over the course of several years. The 2007/8 financial crisis and the subsequent recession and austerity policy introduced by the newly elected (2010) Coalition government decreased policymakers’ willingness to spend money on green measures and led the Treasury in 2011 to establish the Levy Control Framework, which capped green spending through Feed-in-Tariffs and Renewables Obligation (Lockwood, 2013; Gillard et al., 2017). To reduce costs, policymakers in 2011 also announced plans to reduce FiTs for 4-250 kW schemes by 50 %. In response, solar-PV advocates and civil society groups launched the “Cut don’t kill” campaign, which contested the proposed revision and took the government to court, winning its case and delaying the cuts [feedback 7]. Nevertheless, in April 2012 policymakers published their somewhat adjusted decision, which cut tariffs for new schemes by 50 %. In August 2012, they further increased reductions to 70 % (Smith et al., 2014).

Political concerns about people’s energy bills remained, however, leading PM David Cameron to reportedly order aides in 2013 to “get rid of all the green crap” (Geels and Turnheim, 2022). After winning the election, the Conservative government announced in 2015 an ‘energy policy reset’, which further reduced the FiT by 65 %, closed the RO for large-scale solar projects in 2015 and for small-scale solar in 2016 (DECC, 2012). In 2019, policymakers scrapped the FIT for small-scale renewables.

These policy changes slowed deployment in all three PV-segments to a trickle (Fig. 9), which, in turn, led bankruptcies of many installation companies [negative feedback 2], which by 2017 had decreased to 1680 (Inderberg et al., 2018).

PV-firms and civil society actors campaigned against the steep policy support reductions but their campaigns had limited effects [weak positive feedback 7], firstly, because their size and influence were relatively small (especially compared with Germany), and, secondly, because they had limited access to the Westminster political system, which is relatively closed and centralised (Lockwood, 2022). These negative feedbacks overwhelmed the positive feedback from continued cost decreases, almost completely halting PV-diffusion after 2016.

Recent goal changes such as the 2019 net-zero commitment and the government’s 2021 Net Zero Strategy, which articulates the ambition for a decarbonised electricity system by 2035 (HM Government, 2021), again changed the context as policymakers developed more positive views of solar-PV. Large-scale solar-PV was included in the 2021 Contract-for-Difference auctions, which created a new support mechanism. The 2022 British Energy Security Strategy even envisaged a five-fold increase in installed solar-capacity by 2035, reaching 70 GW. Although solar-PV deployment slightly increased in recent years, the speed is slower than in the early 2010s and it remains to be seen if these new goals will be achieved.

6. Discussion

Aggregate solar-PV developments followed similar trajectories in Germany and the UK, in which slow emergence was followed by acceleration after a tipping point in deployment was crossed (around 2008/9 in Germany and 2013 in the UK), which was then followed by deceleration (around 2013/14 in Germany and 2015 in the UK) because of negative socio-political feedbacks that counteracted some of the continuing positive feedbacks (like cost decreases). This deceleration in both countries negates deterministic views of solar-PV as inevitably continuing its rapid diffusion because it has crossed a global tipping point leading to sustained cost decreases (Strauch, 2020; Way et al., 2022). It also highlights the importance of analysing agency and structural contexts in specific countries and analysing techno-economic as well as social, political and cultural developments.

One important difference between the two cases is that German solar-PV diffusion happened earlier than in the UK. This temporal
difference implies that the two cases are not independent, because the UK could benefit from German developments by adopting the same policy instrument (Feed-in-Tariffs) and by importing solar-panels that were already experiencing scale economies, learning processes, and cost decreases. Another important difference is that solar-PV diffusion in Germany accelerated again after 2016, which did not happen in the UK. We will explain this difference in terms of more and stronger positive feedbacks in Germany, which weakened in some respects in the 2010s, but remained stronger than in the UK.

We will now provide more detailed explanations of these similarities and differences in aggregate developments by further analysing the balance of positive and negative feedbacks in both countries, which relate to actors and structural contexts. We first discuss differences and similarities in feedbacks leading up to the positive tipping point.

- In the emergence and early acceleration period, Germany had a solar-PV manufacturing industry, which grew in size (until shrinking in the early 2010s due to Chinese competition) due to positive feedback 2 and increased its political influence through positive feedback 3. These positive feedbacks were weaker in the UK, which only had an installation sub-sector that mostly installed imported solar panels.

- Germany also had a stronger solar-PV advocacy coalition than the UK, which included green NGOs, workers’ associations, civil society energy activism, and manufacturing firms. This coalition lobbied policymakers earlier and more effectively than in the UK through feedback 7, which led to the introduction of a German Feed-in-Tariff in 2000, compared to 2010 in the UK.

- The German FIT introduction also benefitted from a favourable political context, namely the presence of the Green Party in government (1998–2005), which made policymakers more willing to introduce FiTs as part of a broader green growth strategy, which was effective in driving diffusion through feedback 3 and 4. This deviated from the UK, where FIT's were introduced in 2010 as part of an ad-hoc political deal between backbenchers and the government. This means that policymaking tipping did not occur in the UK, in contrast to Germany.

The German FIT instrument was also more resilient because it benefitted from broader and deeper socio-political support through feedback 3 and 7, which enabled it to survive subsequent changes in government. These feedbacks were weaker in the UK, making the FIT instrument less resilient and more susceptible to changes in government and negative feedbacks in the 2010s.

- Public debates in Germany were more credibly anchored in a green growth discourse and supported by widespread civil society energy activism, which strengthened the desirability and legitimacy of solar-PV through feedback 5 more in Germany than in the UK. This also helps explain why the mid-size solar-PV segment (e.g., community energy, schools, town halls) was much larger in Germany than in the UK.

Although the introduction of Feed-in-Tariffs (and their 2004 amendment in Germany) was the immediate push that helped solar-PV cross the tipping point and accelerate diffusion in both countries, the above analysis shows that the effectiveness and resilience of this policy instrument should be seen as the outcome of preceding techno-economic and socio-political feedbacks, including changes in intentions and strategies of important actor groups. This confirms the validity and usefulness of the socio-technical framework, discussed in section 2, for analysing positive tipping points.

An important inductive finding is that the activation and strength of different feedbacks also depends on structural contexts. The following context differences were particularly important for the two cases. First, unlike the UK, the German economy still has a manufacturing orientation, which provides more favourable conditions for feedback 2 and 3. Second, the German banking and financial system is more decentralised, local, and open for diverse stakeholders than in the UK (Hall et al., 2016), which made it easier for small- and medium-sized projects to secure financing. The more centralised UK financial system only supported large-scale projects, which helps explain why that segment has come to dominate. Third, the UK’s Westminster political system is relatively closed for outsiders and new entrants (Bailey, 2007; Lockwood, 2022), which made it difficult to solar-PV advocates to gain political access. In contrast, Germany’s coordinated market economy (Hall et al., 2016).
and Soskice, 2001) and coalition government tradition created more political access opportunities for stakeholders and solar-PV advocates to shape policymaking (feedback 3, 7). Fourth, Germany has a stronger energy-oriented civil society with active cooperatives, citizen groups, and activists, which made feedback 5 and 7 more salient than in the UK.

After the positive tipping point had been crossed, solar-PV development in both countries experienced two similar kinds of negative feedbacks, which counter-acted the continued positive feedback from cost decreases due to scale economies and learning-by-doing processes in manufacturing (feedback 2).

- In both countries, increasing costs of solar-PV support led to political concerns through negative feedback 4, which in the early 2010s led to successive downward policy adjustments that dampened user adoption and decelerated diffusion. In both countries, this coincided with the election of centre-right governments (CDU/CSU/FDP in Germany in 2009 and Conservative Party and Liberal Democrats in the UK in 2010), which after the 2008 financial crisis and subsequent recession were keen to limit government spending on green issues.

- Both countries also experienced headwinds from critical public discourses through negative feedback 5 and 7, which eroded the legitimacy of policy support. UK negative discourses focused mostly on unfair distributional consequences such as ‘fat cats’ receiving too much financial support for large-scale schemes, while German negative discourses focused on unintended negative consequences such as FITs supporting the deployment of Chinese solar panels, which outcompeted German-made ones.

These empirical results confirm the relevance of the two conceptual extensions of the socio-technical framework in section 2, which suggested that negative socio-political feedbacks after a tipping point can decelerate diffusion. The resulting policy cutbacks in the UK were deeper and more drastic than in Germany, almost entirely halting new solar-PV deployment. This was partly due to weaker positive feedbacks in support of solar-PV and the feed-in-tariff (which was introduced through a political deal rather than in response to broader socio-political pressures) and partly due to UK structural contexts such as stronger austerity politics and long-standing opposition against green policies within the Conservative Party.

Germany also substantially downscaled feed-in-tariffs but maintained some policy support because some positive feedbacks continued, albeit in weaker form. Although the decimation of solar manufacturing firms weakened positive feedback 3, the survival of some machine-tool firms and Germany’s general manufacturing orientation meant that positive feedback 3 still exerted some influence that was able to counteract the negative feedbacks. This allowed solar-PV deployment to continue at a slower rate, until the shift to auction instruments and continued cost decreases enabled renewed acceleration after 2016/17, especially in the large-scale segment.

Table 1 provides a schematic summary of both cases, showing the varying depths of changes in the orientations and strategies of the main four actor groups before and after the tipping point in deployment (i.e., inflection point) (in 2008/9 in Germany and in 2013 in the UK).

Fig. 11 schematically summarises the main developments in both cases in terms of the strength and orientation (positive, negative) of the seven feedback loops, showing that most feedback loops (except for feedback loop 1 and 2) were stronger in Germany than in the UK before the deployment tipping point (with feedback loop 3 mostly absent in the UK because of the small solar manufacturing base). For Germany, it also shows that the strength of feedback loop 3, 4 and 5 weakened after the tipping point but remained positive, whereas feedback loop 6 and 7 tipped towards negative orientations (in political and cultural dimensions). For the UK, the Figure shows that more feedback loops (namely 4, 6 and 7) became negative after the tipping point and that there was no positive business feedback loop to mitigate this.
7. Conclusions

We have made two contributions to the important debate on positive tipping point in climate mitigation. First, we have replicated the socio-technical perspective on tipping points with two new case studies, demonstrating its analytical usefulness and broadening its empirical validity. The cases of solar-PV development in Germany and the UK showed the importance of analysing both techno-economic feedbacks and the processes that shape perceptions, orientations, and strategies of social groups (e.g., firms, users, policymakers, and civil society organisations).

Secondly, we have criticised the deterministic overtones of the focus on self-reinforcing irreversible positive feedbacks in the tipping point literature, which assumes that diffusion will automatically continue after a tipping point in deployment has been crossed. Moving beyond that deterministic approach and drawing on political science and discourse theories, we conceptually elaborated our socio-technical framework to argue that diffusion can decelerate after a tipping point due to the activation of negative socio-political feedbacks. Both cases empirically confirmed these conceptual elaborations, finding that negative socio-political feedbacks halted solar-PV developments in the UK after 2015. In Germany, negative socio-political feedbacks also decelerated diffusion between 2013 and 2016, but the balance of positive and negative feedbacks then allowed renewed acceleration. We thus conclude that negative socio-political feedbacks can slow down diffusion after a tipping point and highlight the importance of analysing the balance of positive and negative feedbacks.

An inductive finding, which warrants further research, is that the broader contexts (economic, political, cultural) in which actors are situated are important for tipping points, because these contexts shape the strength and activation of different feedbacks. Future research could also fruitfully attempt to bring other feedback loops and actors into the socio-technical framework, for instance by further differentiating political actors (e.g., Parliament, Ministries, political parties, think tanks, judiciary) or different kinds of business actors (e.g., financial actors, suppliers, manufacturers, industry associations, consultancies). Post-tipping point processes are also an important topic for future research, because negative socio-cultural and political feedbacks can decelerate developments as both our cases showed. Interactions between positive and negative feedbacks are an especially important and interesting topic in that regard. The patterns and underlying mechanisms of acceleration and deceleration thus promise to be fertile ground for future tipping points research.

References


CRediT authorship contribution statement

Martina Ayoub: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. Frank W. Geels: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

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