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A socio-technical transition perspective on positive tipping points in climate change mitigation: Analysing seven interacting feedback loops in offshore wind and electric vehicles acceleration

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ABSTRACT

This paper engages with climate mitigation debates on positive tipping points, which attract increasing attention but remain divided between technological and social tipping point approaches. Building on recent attempts to overcome this dichotomy, the paper develops a socio-technical transitions perspective which shows how co-evolutionary interactions between techno-economic improvements and actor reorientations can significantly accelerate diffusion. Mobilising insights from political science, discourse theory, business studies, consumption theory, and innovation studies, we elaborate the Multi-Level Perspective to articulate seven feedback loops in tipping point dynamics. We illustrate and test our co-evolutionary perspective with two case studies, UK offshore wind and electric vehicles. These case studies not only demonstrate the importance of interacting feedback loops, but also show a contrasting sequence in tipping point dynamics, with substantial techno-economic deployment *preceding* major actor reorientations in offshore wind, while *following* them in the EV case. The cases also indicate the crucial roles of policymakers in low-carbon tipping point dynamics as well as the importance of policy learning and social, political, and business feedbacks in strengthening and reorienting policy support.

1. Introduction

The concept of tipping point stems from the natural sciences (Lenton et al., 2008; Schellnhuber, 2009; Scheffer et al., 2012), where it commonly refers to a critical threshold at which a small perturbation can push a system over the threshold, leading to relatively rapid qualitative alteration of its state of development because of self-reinforcing feedback loops. An often-mentioned example is lake systems that can tip from clear to turbid water when eutrophication pushes nutrient levels past a particular concentration level, which then changes feedbacks between fish, algae, sunlight, and oxygen (see Lenton, 2020 for more examples). These (often negative) tipping points are frequently portrayed with 'ball-in-basin' representations from socio-ecological systems theory (Gunderson, 2000), in which gradually increasing pressures push a system (the ball) towards the edge of a basin of attraction, where a small additional push can tip it over the threshold towards another basin of attraction (Lenton et al., 2022).

Concerns about climate change and desires to accelerate low-carbon transitions have in recent years increased scholarly interest in *positive* tipping points, which could rapidly shift high-carbon systems to low-carbon states (Lenton, 2020; Otto et al., 2020; Stadelmann-Steffen et al., 2021). The notion that a small, cleverly-focused action or intervention can trigger large-scale system change has appealed to both academics (Farmer et al., 2019; Leventon et al., 2021) and activists, NGOs, and think tanks (e.g. RMI, 2022; social tipping coalition[1]).

We distinguish two main strands in the literature on positive tipping points for low-carbon transitions, which differ in their focus and empirical validation. The first strand focuses on low-carbon technologies and sees the inflection point in S-shaped diffusion curves as the tipping point, where new technologies shift from being expensive, unappealing, and confined to small niches to becoming more affordable, attractive, and entering mass markets (Strauch, 2020; Sharpe and Lenton, 2021; Mercure et al., 2021; Lam and Mercure, 2022; RMI, 2022). This literature strand tends to focus on techno-economic feedbacks between cost reductions and adoption (through learning-by-doing, scale economies, and experience curves), sometimes complemented with actions from benevolent policymakers who initially support new technologies with R&D or adoption subsidies.

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[1] https://socialtippingpointcoalitie.nl/social-tipping-point-coalition/.

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This literature strand has empirical support because the diffusion of technologies like solar-PV, wind, and electric vehicles has accelerated in the past decade, partly driven by impressive cost reductions and experience curves (Way et al., 2022). This strand pays less attention, however, to agency and the various actors and interactions that shape early developments of new technologies and the shift in their orientations and strategies that drive increasing investment, deployment, and support.

The second literature strand focuses on social tipping points and shifts in society-wide norms and behaviours. There is limited empirical evidence for such tipping points in low-carbon transitions, so much of this literature is theoretical and/or speculative. *Theoretical* studies (e.g., Centola et al., 2018; Andreoni et al., 2021) use simple abstract theories like contagion or critical mass to suggest that minority groups can drive wider behaviour and norm change once they reach a critical mass and others start to imitate and follow them. One criticism is that contagion theories are more suited for analysing the spread of information than changes in norms or behaviours (Rogers, 1996; Smith et al., 2020). Another criticism is that these studies use laboratory experiments and self-selected volunteers rather than real-world evidence.

Speculative studies explore the *potential* of social tipping for climate change mitigation (Nyborg et al., 2016; Tàbara et al., 2018; Otto et al., 2020), often extrapolating from historical examples of norm and behaviour change (like smoking bans, slavery abolition, seat belt use) to what could or should happen to address climate change. Although some studies (e.g., Otto et al., 2020) mostly mobilise contagion models for understanding social tipping dynamics, which have been criticised as over-simplistic (Smith et al., 2020), others discuss a wider set of actions and interactions such as social learning, information provision, framing, role models, changing expectations (Nyborg et al., 2016; Winkelmann et al., 2022) as well as feedbacks between shifts in visions, perceptions and motivations, capacity building, and the reconfiguration of social networks and institutional arrangements (Tàbara et al., 2018).

While this literature thus has more to say about actors and agency than the first literature strand, it pays relatively limited attention to technology in relation to behaviour (Latour, 1992). The types of systems where tipping is supposed to occur are also much broader and more diffuse, including socio-cultural systems, governance systems, and the economy (Tàbara et al., 2018) or value systems, education systems, financial markets, and human settlements (Otto et al., 2020), which makes it difficult to make situated and accurate empirical analyses of tipping dynamics. A further criticism is that the dearth of empirical evidence of low-carbon social tipping makes the second literature strand rather speculative, with overtones of wishful thinking. In a critical review, Milkoreit (2023) therefore expresses concerns about the effects of normative motivations (e.g., scholars' desires to offer hope about potential climate mitigation solutions) on the rigor and quality of scholarship on social tipping.

This paper aims to overcome this dichotomy by combining elements from both strands. It will focus on situated technologies and systems (like electricity, mobility, agri-food), because this enables concrete empirical analyses and conceptualisation. Drawing on socio-technical transitions theory (Köhler et al., 2019; Geels and Turnheim, 2022), it understands technologies as socially embedded and shaped by institutions and actors, who act and interact with each other over time. Behaviours, norms, perceptions, motivations, expectations, capacities, and learning are thus not analysed *in abstracto* or with regard to society-as-a-whole, but in relation to specific technologies and socio-technical systems.

Some tipping point scholars point in similar socio-technical directions but remain constrained in some respects. Farmer et al. (2019), for instance, discuss the roles of finance, technology, socio-political mobilisation, and institutions, but address these at an economy-wide level and remain wedded to ball-in-basin representations. Lenton et al. (2022) discuss a wide range of social science theories for both technologies and behaviour change but their selection is limited due to their desire for alignment with modelling and mathematical representations, which leads them to focus on relatively deterministic and un-reflexive *self-reinforcing* feedback mechanisms (such as contagion, increasing returns, information cascades, and percolation models). They thus neglect theories about *reactive* sequences and feedbacks (Mahoney, 2000) in which strategic actors (in business, politics, or civil society) deliberatively respond to each other's moves and countermoves and can *qualitatively* change their orientations, strategies, and actions. Our paper will elaborate these other potential feedback loops for tipping points and associated co-evolutionary theories.

More promisingly, Milkoreit et al. (2018) and Stadelmann-Steffen et al. (2021) suggest that socio-technical tipping points involve multiple actors with different interests and beliefs, and that the change process is better conceptualised as tipping *dynamics* (Stadelmann-Steffen et al., 2021) than as tipping *points* with singular thresholds or control parameters. The reason is that strategic moves and countermoves, interactions learning, reflexivity, and cognitive changes take time to play out and interact. But although both authors usefully advance a broader understanding of agency *in general terms*, they limitedly draw on social science theories to conceptualise change dynamics and co-evolutionary feedbacks.

Building on Milkoreit et al. (2018) and Stadelmann-Steffen et al. (2021), we aim to make the following contributions. First, we will mobilise insights from multiple social science theories to develop a conceptual socio-technical perspective on positive tipping points that articulates seven interacting feedback loops between techno-economic developments and core actor groups such as firms, consumers, policymakers, and civil society actors. Second, we will use this perspective to empirically investigate tipping points in offshore wind and electric vehicles, offering a more comprehensive analysis than the techno-economic tipping point studies of these low-carbon technologies. Third, we will further analyse the temporality of positive tipping point dynamics and show that changing actor commitments sometimes *precede* and sometimes *follow* substantial techno-economic improvements.

The paper proceeds as follows. Section 2 articulates our conceptual perspective, which elaborates socio-technical transitions theory by more precisely specifying seven co-evolutionary feedback loops between relevant dimensions. Section 3 discusses our comparative research design focused on two case studies. Section 4 analyses offshore wind in the UK, while Section 5 investigates electric vehicles in the UK and globally (especially China and Europe). Section 6 analyses the cases. Section 7 concludes.

2. Conceptual framework

To develop our conceptual perspective on positive tipping points, we build on the Multi-Level Perspective (Geels, 2019; Geels and Turnheim, 2022), which understands socio-technical transitions as resulting from multi-dimensional interactions between radical niche-innovations and existing path-dependent systems, which are stabilised by multiple lock-in mechanisms (Klitkou et al., 2015; Seto et al., 2016). These interactions are shaped by exogenous landscape developments (e.g., macro-economic, geo-political, and ideological trends, wars, and shocks). The MLP suggests that transitions unfold through four phases (Fig. 1): 1) experimentation, when radical innovations emerge in peripheral niches and develop through learning-by-doing in small projects (R&D, pilots, demonstration) (Schot and Geels, 2008), 2) stabilisation, when the innovation finds a foothold in small market niches and technical design rules begin to stabilise, 3) diffusion and disruption, when the innovation enters mass markets and begins to compete head-on with the existing system, which often causes turbulence and conflict on economic, business, and political dimensions, 4) institutionalisation, when a new system becomes anchored in regulatory programmes, user habits, views of normality, and professional standards.

In this perspective, we conceptualise positive tipping points as occurring between phase 2 and phase 3 (schematically represented with an ellipse in Fig. 1), where innovation dynamics shift from a *fragile* state,

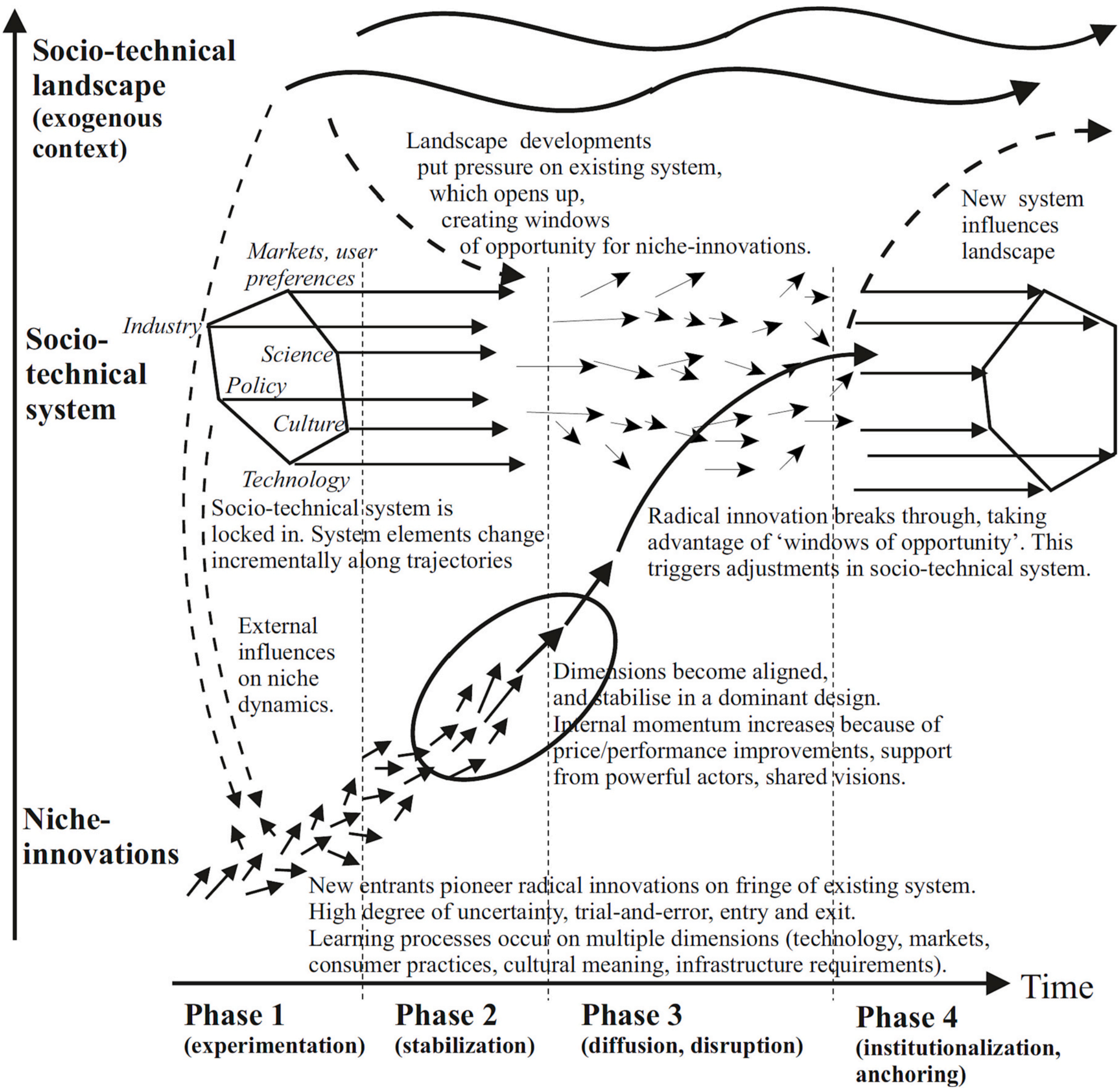

Fig. 1. Multi-Level Perspective on socio-technical transitions with the ellipse highlighting a tipping point.
(Adapted from Geels, 2019: 191).

when the emerging innovation is not yet robust and competitive and thus requires substantial protective and developmental 'work' to be upheld, to a *self-sustaining* state, when the innovation acquires momentum through positive feedbacks and the alignment of multiple socio-technical elements accelerates diffusion into mainstream markets (Hughes, 1994).[2] The ellipse in Fig. 1 also indicates that we prefer to speak of tipping *dynamics* (Stadelmann-Steffen et al., 2021) rather than singular tipping *points* and that we understand them as involving co-evolutionary processes.

Although some MLP-related studies have identified accelerating feedbacks between increasing cumulative deployment, declining costs, growing advocacy coalitions, strengthening policies, and supportive visions (Roberts et al., 2018; Edmondson et al., 2019; Strauch, 2020; Lindberg and Kammermann, 2021), more work is needed to unpack the bold ellipse in Fig. 1 and further elaborate the socio-technical feedback mechanisms in positive tipping dynamics.

As a first step in that direction, we will focus on co-evolutionary feedback loops between four main actor groups in socio-technical systems (firms, consumers, policymakers, wider publics) and technology (Geels and Turnheim, 2022), as schematically represented in Fig. 2. We thus abstract from the reality that each sphere consists of multiple actors. The political domain, for instance, includes not just policymakers, but also political parties, Parliament, courts, and lobby groups (Eder and Stadelmann-Steffen, 2023). The top half of Fig. 2 accommodates economically-oriented feedbacks, where we analytically separate bilateral firm interactions with users through the production and sale of products into a triangle of (bold) arrows to better indicate relevant feedbacks. The bottom half accommodates socio-political processes. Policymakers have diverse responsibilities and can influence firms, users, and technology through various instruments, which is why 'stronger policies' in Fig. 2 go in different directions. Policy evaluations and adjustments in feedback loop 4 can thus affect multiple policy instruments.

Socio-political processes are arguably especially important in early

[2] Because of the focus on innovation, this conceptualization of tipping points is thus somewhat different from the natural science view on the collapse of systems when cumulative stresses push systems across thresholds. The MLP would position such system collapse somewhat later in phase 3, when the combined effect of niche-innovations and landscape pressures can destabilise existing systems (Turnheim and Geels, 2012).

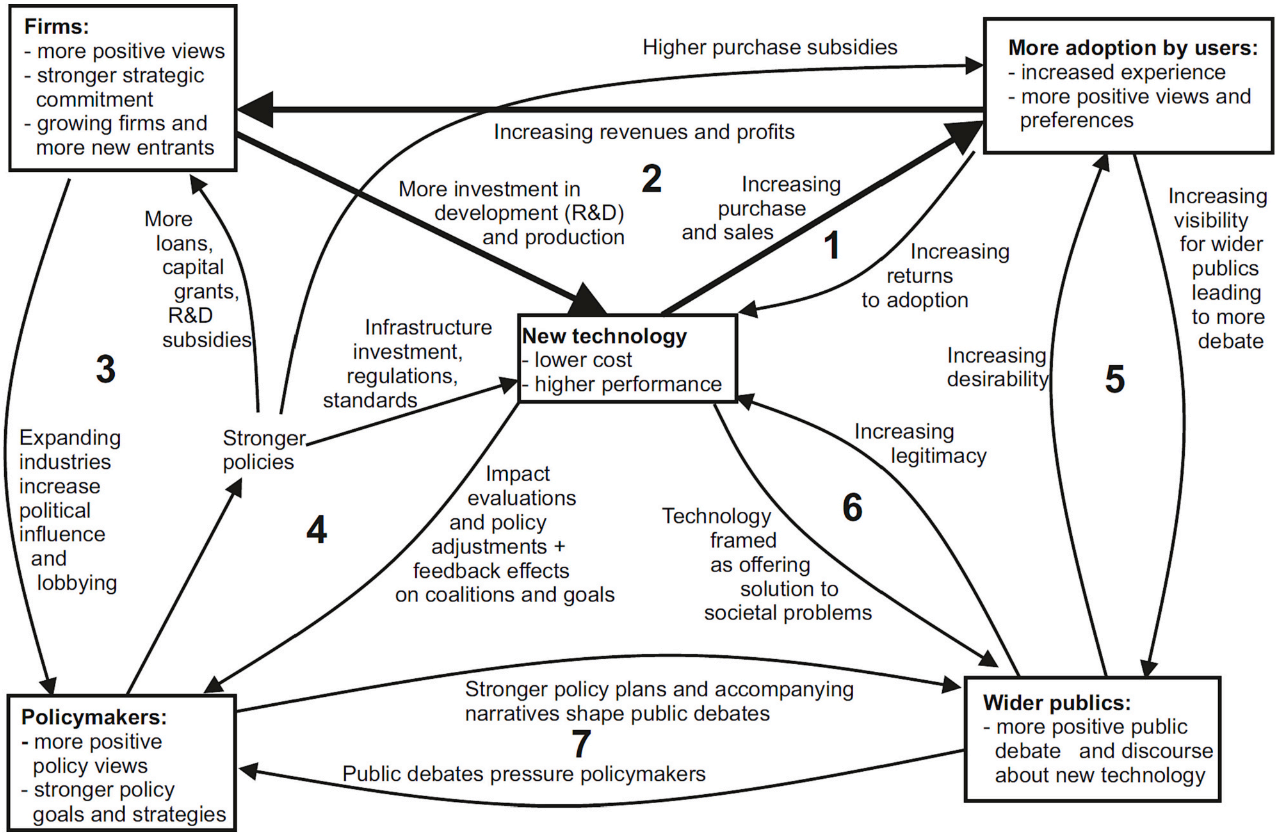

Fig. 2. Schematic representation of seven feedback loops between technology and actors.

transition phases when the economic feedbacks are often negative. The problem in these early phases is that economic actors (firms, users) are often reluctant to invest, develop, and buy new technologies because of high technology costs, high switching costs, small market demand, lock-in effects, and inertia (Klitkou et al., 2015). But because they do not invest or buy, new technologies remain high in costs and low in performance, which hinders the transition. That is why radical innovations first emerge in small, peripheral niches, where users have particular needs or preferences, or policymakers offer protective policy support (Smith and Raven, 2012). Radical innovations can remain stuck in small niches for prolonged periods, even decades, seemingly reinforcing the view that the innovations will never be cost effective.[3]

The core issue for tipping points in socio-technical transitions is therefore how negative feedbacks in the early phases can shift towards positive feedbacks, which enables innovations to move from small niches towards wider deployment and diffusion. To better understand this issue, we mobilise theoretical insights from several literatures that are ontologically compatible with the MLP's foundational theories (evolutionary economics, innovation studies, and institutional theory) (Geels, 2010, 2020) because they see actors as structured and socially embedded. We thus aim to make an initial inventory of a wider set of co-evolutionary feedback loops that drive changes in the orientation and commitment of the focal actors. The discussion of each feedback loop (represented with numbers in Fig. 2) is relatively brief for space reasons and in that sense more indicative than exhaustive.

1. *Users and technology*: The economics of innovation literature (David, 1985; Arthur, 1989) highlights increasing returns to adoption (IRA), which imply that increasing user adoption reduces technology costs (often represented with learning curves or experience curves) and improves performance, which in turn stimulate further adoption. Arthur (1989) identified several specific sources of IRA: learning by doing and using, network externalities, complementary innovation, scale economies in production, and informational increasing returns.[4]
2. *Firms, technology, users*: The behavioural theory of the firm (Greve, 2003) suggests that firms will invest more in the development and production of new technologies if increasing demand and sales provide positive performance feedback such as growing revenues and profits. These investments (in R&D and production assets) will, in turn, improve technical performance and lower costs through scale economies.

   Interpretive and learning theories of the firm (Argyris, 1976; Kolb, 1984; Barr et al., 1992; Thomas et al., 1993), which emphasize the role of beliefs, interpretations and expectations in strategic decision-making, additionally identify first-order learning loops (where actions generate experiences, data and information that improve decision-making) and second-order learning loops (where reflections on experiences and performance feedback can lead to more positive interpretations of new technologies), which can strengthen strategic commitments to new technologies.
3. *Firms and policymakers*: The corporate political activity (Pinkse and Groot, 2015) and policy feedback literatures (Meckling, 2019; Edmondson et al., 2019) suggest that growing new technology firms (with increasing size, number, jobs, and tax contributions) have greater political access and lobbying power, which enables them to shape public policies. Stronger policy support, in turn, can improve the market power of companies and their development or

[3] Solar-PV, wind turbines and electric vehicles, for example, trace their origins to the 1970s and were for decades seen as uncompetitive.

[4] The last two sources refer to firms and wider publics, and thus perhaps fit better in feedback loop 2 and 5.

deployment of new technologies (through favourable loans, capital grants, or R&D subsidies).

4. *Policymakers, technology and users*: Innovation and energy policy literatures (Brand et al., 2013; Kern et al., 2019) have shown that policymakers directly or indirectly (through firms or consumers) shape the development and deployment of technologies through a raft of instruments (e.g., direct infrastructure investments, technology or performance standards, regulations, adoption subsidies, purchase subsidies, capital grants).

   Policy cycle and policy learning theories (Howlett et al., 2009) further suggest that policymakers monitor and evaluate the effects of policies on technology deployment or cost reduction, which may lead to adjustments and stronger (or weaker) policies. First-order policy learning processes can lead to adjustments in the *settings* of policy instruments, while second-order learning processes can lead to changes in the *types* of policy instruments and policy *goals and orientations* (Hall, 1993). The latter types of adjustment often involve political struggles and are shaped by public debates and (corporate) advocacy coalitions (Howlett et al., 2017). Technological change can also have deeper *political* feedbacks, when increasing technological deployment or cost reductions strengthen the influence of new technology coalitions or change political goals and alliances (Schmidt and Sewerin, 2017; Roberts and Geels, 2019), e.g., when low-carbon technology support becomes part of industrial policy as well as climate policy (Meckling et al., 2015).
5. *Users and wider publics*: Diffusion and consumption theories (Arthur, 1989; Rogers, 1996; Lie and Sørensen, 1996) suggest that increasing adoption enhances learning-by-using processes, which can improve familiarity and perceptions of new technologies, and expands their visibility, which may lead to more positive public debates. Discourse theories further suggest that more positive public debates, in turn, can improve the legitimacy and desirability of new technologies, which can drive further adoption and shape consumer preferences (Geels and Verhees, 2011).
6. *Wider publics and technology*: Discourse theories suggest that cost reductions, technological improvements, and increased adoption make it easier for proponents to frame new technologies as solutions to societal problems or as the start of a new era, which positively shapes public debates (Roberts and Geels, 2018). Positive public debates, in turn, can enhance the cultural meanings and societal legitimacy of new technologies, which can then become framed as worthy of more support from policymakers or investors (Lounsbury and Glynn, 2001).
7. *Wider publics and policymakers*: Public attention theories in political science (Burnstein, 2003; Newig, 2004) indicate that increasing public attention to particular problems or technologies, combined with discourses about urgent or desirable action, create pressures on policymakers to take political action and introduce or strengthen policies. Discursive institutionalism (Schmidt, 2008) further suggests that stronger policies, in turn, shape public debates because policymakers aim to explain and legitimate the policies with accompanying communicative discourses (conveyed through policy documents, narratives, and media performances).

This brief inventory and attempted integration of feedback loops from the wider social sciences extends the tipping point literature in two ways. First, it is more agentic than the contagion, imitation, and critical mass models that dominate the tipping point literature (e.g., Otto et al., 2020; Lenton et al., 2022). While the actors in these models are relatively un-reflexive automatons, the actors in the theories we discussed above have routines, capabilities, beliefs, and interests that change through sense-making, learning and strategic processes. Second, while contagion, imitation, and critical mass models focus on mechanisms *within* a particular group (e.g., consumers), our theories focus on reactive feedback loops *across* techno-economic, business, user, policy, and cultural dimensions in which actors strategically respond to each other.

We thus propose that: 1) socio-technical tipping points are processes rather than singular points (Stadelmann-Steffen et al., 2021), which often play out over several years, 2) tipping point dynamics are co-evolutionary, involving both techno-economic developments (such as cost decreases, performance improvements, market adoption) and significant changes in actor orientations and strategies (which 'tip' from negative to positive), 3) these co-evolutionary processes causally interact so that significant reorientations or 'tipping' in one actor group (e.g. policymakers) can shape reorientations in another group (e.g., users and/or firms), which then shape techno-economic developments, which then shape further significant actor reorientations. We suggest that these causal co-evolutionary interactions are essential to accelerate diffusion and drive technologies across tipping points, where negative feedbacks, which initially confine radical innovations to small niches, become more positive.

We further propose that the sequence and activation of feedback loops in tipping point dynamics may vary for different technologies and countries, depending on industrial and institutional contexts (Lockwood, 2022). This means that there may be cases where significant actor orientations *precede* major cost reductions and technology deployment, while there may also be cases showing the opposite. We will empirically investigate this proposition, and the issues of temporality and sequence more generally, with two case studies of positive tipping points.

3. Research design

To explore the conceptual framework and specific propositions, we use a comparative research design, investigating two cases where tipping points have occurred. We use case studies because these are well-suited for investigating qualitative dimensions (such as changing perceptions and strategies), complex interactions, and process tracing (Geels, 2022). We chose a comparative design, because this is useful to show that different interactions between the same causal mechanisms can generate and explain different patterns and outcomes.

We selected offshore wind and electric vehicles (EVs) as our two case studies, because the diffusion of both technologies is accelerating globally (IEA, 2022). We opted for country-case studies because public debates, policies, and user adoption have strong national dimensions. We selected the UK as our focal country because it is a world leader in offshore wind deployment and because its EV diffusion markedly accelerated after 2019. We do, however, note that automakers operate on a global scale and that EV diffusion is a global phenomenon, which is why our EV case study also takes global developments into account (especially for China and Europe). Although car manufacturers operate globally, the UK still has a sizeable car industry, with six companies (Nissan, Toyota, Honda, Mini, Jaguar Land Rover, Vauxhall/Stellantis) producing 1.3 million cars in 2019 (SMMT, 2022). The cases also differ technologically, in the sense that EVs are technological products sold directly to consumers, while wind turbines are capital goods that are used to produce electricity, which is then sold to utilities or consumers. The operationalisation of users and firms thus differs somewhat between the cases.

The two case studies, which are relatively short because of space constraints, focus on techno-economic developments and the four main actor groups: firms, users, policymakers, and wider publics (represented as public attention and discourse). For both case studies, we also addressed supply chains and jobs in the later phases, because these became important issues for policymakers and industry. For the same reason, we also address financial firms in the later phase of the offshore wind case. The empirical cases thus point to limitations in our conceptual framework with regard to the 'firm' category, which insufficiently captures relevant empirical complexities. We will revisit this limitation in the conclusions.

The case studies use quantitative information from statistical databases to trace techno-economic developments such as performance improvements, cost developments, jobs, and deployment. The case studies also use quantitative information from newspaper databases to trace public attention, using newspaper counts for 'offshore wind' and 'electric vehicles' as a proxy. While this indicator says little about *how* issues are discussed, it is useful because mass media coverage "constitutes by far the most important vehicle for shared attention and political communication" (Newig, 2004: 159). Specifically, we searched the electronic databases of *The Times*, *The Independent* and the *Financial Times*, which we selected to span a spectrum of political views, for the chosen keywords. We collected all the articles and plotted the normalised average per year. The case studies also use qualitative information to address changes in perceptions, strategies, and goals. For users, policymakers, and public discourses, we used information from academic publications. For firms, we additionally collected information from annual reports, which we report in the form of quotes that show changes in beliefs and strategies.

Using quantitative information, we identify technology deployment tipping points conventionally as the inflection point in diffusion curves (generated electricity for offshore wind and vehicle stock for EVs), where user deployment markedly accelerates. Tipping points in actor orientations are more qualitative and challenging to identify because they are not singular points but change processes that unfold in the space of a few years. For companies, we identify tipping points as significant changes in views and (investment) strategies. For policymakers, we identify tipping points as significant changes in policy goals and instruments. For public debates, we identify tipping points as significant increases in the amount of public attention or changes in discursive content. For users, tipping points reveal themselves through rapidly increasing adoption.

Because of our interest in temporal flow, sequences, and interacting feedback loops, the case studies use a process tracing methodology, which is presented as "more appropriate than other methods in the study of phenomena characterized by complex causality or multiple causal pathways" (Falleti, 2016: 456). Process tracing investigations are concerned with explanations "that indicate how the process unfolds over time" (Poole et al., 2000: 12) by tracing how conjunctions and steps in a developmental sequence generate particular outcomes or patterns (Bennett and Checkel, 2015). George and Bennett (2004) distinguish different kinds of process tracing such as detailed narrative, use of hypotheses, analytic explanation, and more general explanation. Our investigation aims for analytic explanation which "converts a historical narrative into an *analytical* causal explanation couched in explicitly theoretical forms" (p. 211).

We do this by organising our case studies along the analytical categories in the five boxes in Fig. 2 (technology, firms, users, policymakers, publics) and by explicitly indicating the feedback mechanism in the text [*in italics between square brackets*] when they occur. Because the case studies trace developmental sequences over time, actor groups can appear multiple times if they are analytically relevant. Combining quantitative and qualitative information, the case studies thus investigate how agency, techno-economic developments and interacting feedback loops generate both technological deployment tipping points and tipping points in actor orientations.

4. Offshore wind in the UK

The UK has become a world leader in offshore wind deployment, accounting for 28.9 % of global cumulative installed capacity by 2020 (GWEC, 2021). UK offshore wind electricity generation increased from 0.4 % of power production in 2009 to 11.0 % in 2021. In the early 2000s, policymakers provided capital grants for relatively small demonstration projects, which enabled firms to learn about applying (onshore) wind technologies in new (offshore) environments (Kern et al., 2014). Cumulative installation and electricity production with offshore wind turbines then accelerated after 2009 (Fig. 3), which in deployment terms can thus be seen as the tipping point. However, our temporal actor analysis will show that significant 'tipping' and reorientations in their perceptions and strategies occurred several years later, between 2015 and 2017.

Policymakers (2002–2009): The post-2009 deployment acceleration was substantially driven by a policy change in the Renewables Obligation (RO). The RO was introduced in 2002 as a technology-neutral instrument to increase the deployment of renewable electricity technologies (RETs) by utilities by requiring them to meet particular targets. The RO policy provided the same number of Renewable Obligation Certificates (ROCs) for all RETs, which utilities could trade with each other to reach their required number. Evaluations showed that the RO policy was insufficiently effective [*feedback 4*], which through policy learning led to the realisation that technology-differentiated instruments were needed that provided more support for less developed and more expensive RETs (Geels et al., 2016). Combined with increasing public concerns about climate change [*feedback 7*] and the introduction of the 2008 Climate Change Act, which increased the UK's GHG reduction target to 80 % by 2050, this realisation led to the 2009 RO, which represented a significant policy change because it abandoned the technology-neutral approach and doubled the support for offshore wind by allocating two ROCs per MWh [*feedback 4*], creating an attractive support premium estimated at £100/MWh on top of the retail price (Heptonstall et al., 2012). This relatively generous and long-term (20 years) support helped to create a subsidised market for offshore wind and boosted investor confidence.

Public attention and support (2009/10): Public attention for offshore wind substantially increased in 2009/10 (Fig. 4), because of positive public and political debates about the revised RO policy, which legitimated the policy [*feedback* 7]. Although offshore wind was one of the most expensive RETs at the time, positive public debates legitimated the technology [*feedback 6*], with discourses focusing on themes like decarbonisation, energy security, the UK's excellent offshore wind conditions, future jobs and industry growth, and higher social acceptance than onshore wind (Kern et al., 2014).

Firms (early 2010s): The 2009 policy change and positive discourses substantially increased the interest of both UK-based and international energy companies in UK offshore wind [*feedback 3*], leading to enhanced deployment in subsequent years. Because of the policy change, companies came to see UK offshore wind deployment as commercially attractive, as quotes from their annual reports indicate (Table 1). But companies also had hesitations because the new market depended strongly on government subsidies, which implied uncertainties about possible policy reversals and doubts about long-term economic viability (Table 1). To lobby for favourable policy changes [*feedback 3*], firms also participated in the newly created Offshore Wind Developers Forum and the Offshore Wind Cost Reduction Taskforce, which enabled them to interact with policymakers (Kern et al., 2014).

The subsidised deployment of ever-larger wind turbines in the early 2010s enabled learning-by-doing processes [*feedback 2*], which allowed firms to deepen their technical capabilities, broaden real-world data-gathering, and gradually increase their confidence in the technical and economic potential of offshore wind (Carbon Trust, 2020).

Users (early 2010s): In the early years, energy companies were both developers and users of wind farms, which produced electricity that they sold to UK utilities or to consumers. This became more differentiated in the mid-2010s, linked to the shift from balance sheet finance to project finance, when complex alliances of project developers and investors developed offshore wind assets, which they then sold to operators to generate and sell electricity.

Policymakers (early 2010s): Policymakers were encouraged by the effects of the RO policy on firm strategies and offshore wind deployment, but diagnosed that costs had to decrease to drive further diffusion and that private investors should be mobilised to provide the large amounts of finance (in the order of £billions) for offshore wind farms (Hall et al., 2017). In 2013, policymakers therefore introduced a new financing instrument, Contracts for Difference (CfD), for which potential low-carbon electricity suppliers could compete in bi-annual auctions.

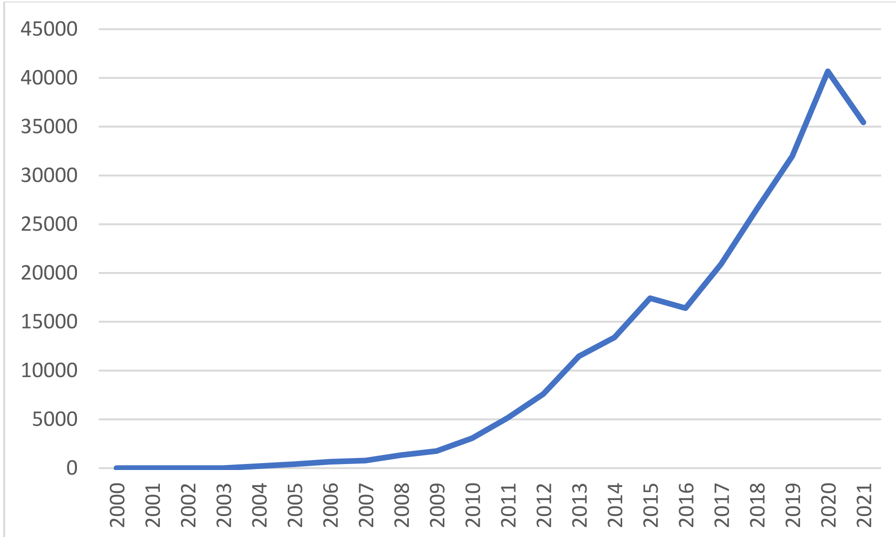

Fig. 3. Electricity generated by offshore wind turbines in GWh, 1990–2021.[a]
[a]Declining electricity generation in 2016 and 2021 were due to less than average wind conditions in the North Sea (BEIS, 2022).
(Constructed using data from the Digest of UK Energy Statistics; Electricity Statistics; Renewable sources; Table 6.6.1).

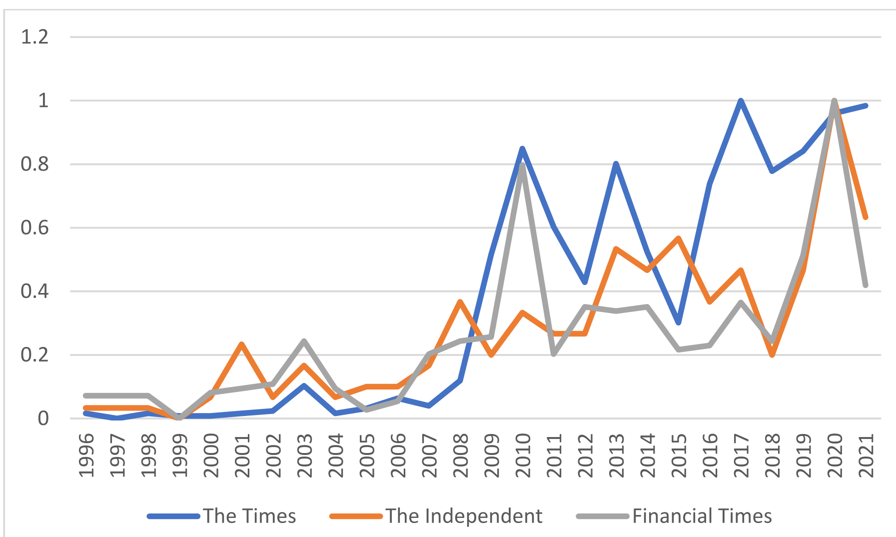

Fig. 4. Public attention for offshore wind represented using the yearly number of articles in selected UK national newspapers as proxy.

The winner would receive a CfD with a guaranteed fixed 'strike price' for 15 years.[5] The auction design aimed to reduce costs because developers would compete on price, while the strike price was designed to attract private investors by providing long-term certainty and offering protection against wholesale price volatility.

Technological and cost improvements (mid-2010s): Learning processes and policy support enabled the deployment of ever-larger offshore wind turbines [*feedback 2, 3*], which after the mid-2010s significantly increased in height and capacity (Fig. 5), operating at higher efficiencies and lower cost. Wind farms were also built further offshore in deeper waters with stronger winds, which increased the load factor. These developments were enabled and supported by many complementary technical innovations in materials, electronics, gearing mechanisms, seabed foundations, turbine blades, installation ships and vessels (with specialised cranes and drilling tools), operations and maintenance software and access systems, site surveying and investigation technologies, meteorological and wind forecasting techniques, and the construction of a subsea electricity grid infrastructure to connects the turbines to offshore substations (Sovacool et al., 2017; Carbon Trust, 2020).

The global offshore wind electricity price fluctuated in the early 2010s but then decreased by 49 % between 2014 and 2020 (Fig. 6) because of scale economies, learning-by-doing and learning-by-using [*feedback 1, 2*], making it increasingly competitive with coal- and gas-generated electricity. The strike price for UK offshore wind in four successive auction rounds (for capacity coming online 4–5 years later) decreased by 68 % between 2015 and 2022 (Fig. 7), making it increasingly attractive for UK utilities.

Specific drivers of the price decreases were the following (Carbon Trust, 2020) [*feedback 1, 2*]: 1) cost reductions (per MW) in wind

[5] If the wholesale electricity price was lower than the agreed 'strike price', the generator would receive a top-up payment to make up for the difference. If the wholesale price was above the strike price, the generator pays back the surplus.

Table 1
Quotes from selected annual reports and company statements, indicating both interest and some hesitation about UK offshore wind in the late 2000s and early 2010s.

Dong Energy (2009: 1)[a]	"The move is a result of the British government's increase in funding towards sustainable energy (…) It's encouraging that the investment regime has now been created to allow us to implement our strategy of considerably expanding DONG Energy's position within sustainable energy. With the 2 ROCs, we can now begin the construction of Walney I and II".
Vattenfall (2009: 10)[b]	"This is due in part to a strategic re-prioritisation from land-based wind power to more profitable offshore projects in the UK, among other places"
Equinor (2009: 26)[c]	"The main focus areas are offshore wind and carbon management. However, with the new energy industry still in an early phase of development, it is too early to 'pick all the winners' of the future".
Dong Energy (2013: 15)[d]	"The fact that offshore wind energy is still more costly than energy based on conventional technologies is a pressing challenge. To make wind energy competitive in the longer term, it is crucial that the cost is brought down."
Centrica (2013: 15)[e]	"Whilst the outlook for the UK business has been impacted by short-term political uncertainty, we are taking positive action across the Group to position the business for the long term, for the benefit of both customers and shareholders"

[a] https://www.globenewswire.com/fr/news-release/2009/04/22/5778/0/en/DONG-Energy-to-build-further-offshore-wind-farms-in-the-UK.html.
[b] https://group.vattenfall.com/siteassets/corporate/investors/annual-reports/2009/annual_report_2009.pdf.
[c] https://cdn.sanity.io/files/h61q9gi9/global/8c1f03d90cce94f66bb6bb006954e945f564880f.pdf?statoil-annual-report-20f-2009.pdf.
[d] https://orstedcdn.azureedge.net/-/media/www/docs/corp/com/investor/financial-reporting/annualreports/dong_energy_annual_report_management_2013_review_en.ashx?la=en&hash=7617E76F8A109977844D88B2B9FEFDAFB1F930E1&hash=7617E76F8A109977844D88B2B9FEFDAFB1F930E1&rev=4d20334ef74c4884a95559a6f67b6b50.
[e] https://www.centrica.com/media/1139/centrica_annual_report_2013.pdf.

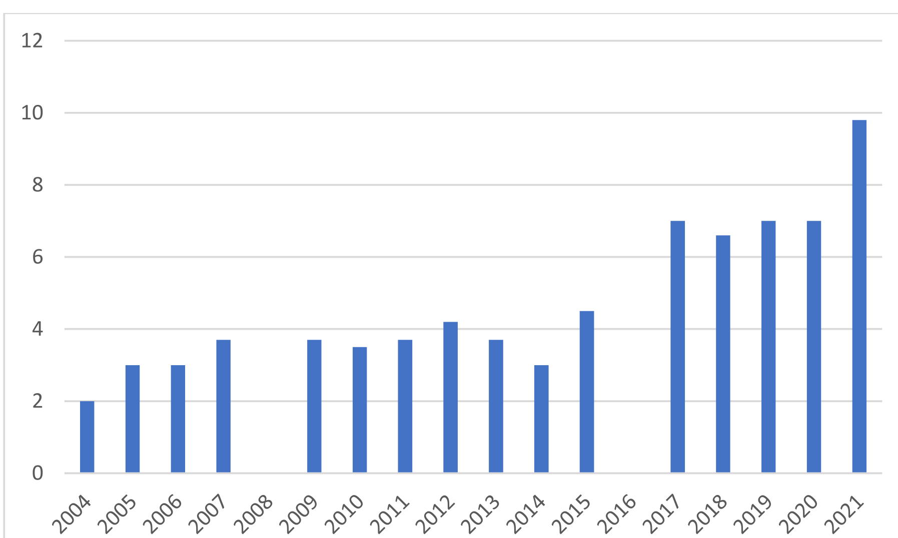

Fig. 5. Increasing average size of offshore wind turbines (in MW) (Carbon Trust, 2020: 31).

turbines due to scale economies, learning-by-doing, and component improvements (Sovacool et al., 2017), 2) cost reductions in seabed foundations and undersea cables, due to scale economies, technical improvements, and reduced material costs, 3) lower installation and commissioning costs, as specialised vessels and increased experience reduced installation times and improved labour productivity, 4) lower operation and maintenance costs, due to improvements in controls, data analytics and technical designs (which also increased durability and reduced maintenance needs), 5) reduced cost of capital, due to increased access to equity and debt financing (further discussed below) and lower risk profiles, as increased experience enhanced the confidence of lenders in offshore wind, lowering interest rates from 3 % over the LIBOR[6] rate in 2012 to 1.5 % in 2019 (Fig. 8).

Firms (2015–2017): The policy change from RO to CfD created some uncertainties for developers about the state of the UK market, especially around the first auction round in 2014/15. But the learning processes, technical improvements, and cost reductions increased the confidence of companies in offshore wind [*feedback 2*], who in the 2015–17 period came to see offshore wind as moving towards a mass market that would be increasingly self-sustaining with less and less need for subsidies. This tipping point led firms to reorient their strategies towards expansion, market leadership, and further cost reductions, which would enable them to compete in future CfD auction rounds (Table 2).

Financial firms (mid-2010s): Since offshore wind farms are expensive to build (but relatively cheap to operate), financing is an important issue for developers. In the early years, developers mostly used balance sheet finance where the project's assets appear in the company's accounts and project money comes from bonds (debt), loans, new share issuing, or earnings from other operations (BEIS, 2019a). Over time, however, developers increasingly used project finance (Fig. 9), which treats the wind farm as a separate legal entity (a special purpose vehicle) and enabled private investors (like pension funds, insurance funds, sovereign wealth funds) to take on higher percentages of the cost of investment through equity (shares in the project) or debts (loans on a non-recourse basis) (BEIS, 2019a).

The shift in financing also changed actor coalitions. Our analysis of the 56 wind farm projects between 2005 and 2021 shows increasing differentiation in the development and ownership alliances, with a marked increase in the participation of institutional investors after 2015, which is indicative of a tipping point. Wind farm development thus increasingly involved complex coalitions of project developers, utility firms, institutional investors, banks, and corporations (Wind Europe, 2020). Due to their unfamiliarity with offshore wind and the complexity of the RO policy, financial investors initially charged relatively high interests rates. As they gained more experience [*feedback* 2] and as policymakers introduced Contracts-for-Difference (which

[6] LIBOR is the London Inter-Bank Offered Rate, which is an interest-rate average calculated from estimates submitted by the leading banks in London.

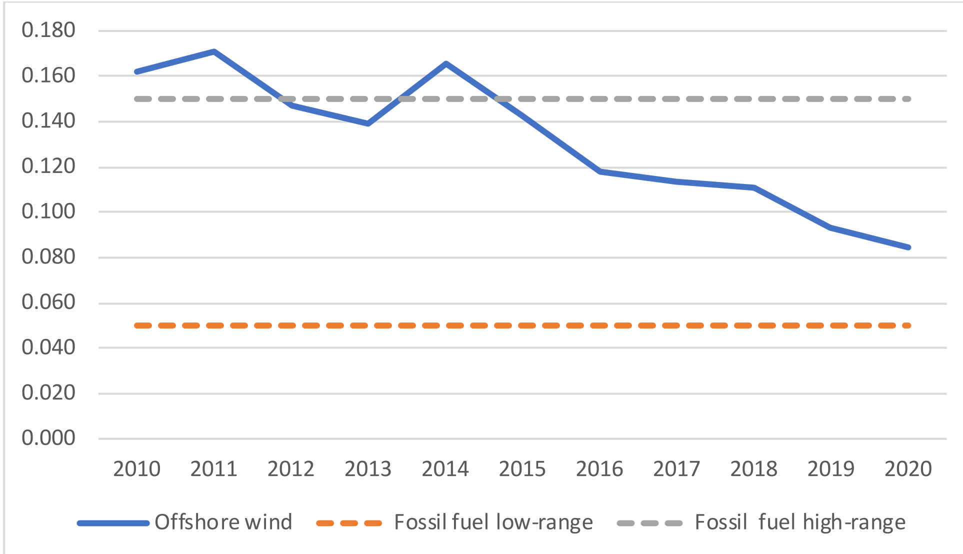

Fig. 6. Global average levelised costs of electricity from offshore wind, 2010–2020 (in constant 2020 US dollars per kWh), compared to high and low fossil fuel range.
(Constructed using data from IRENA, 2021).

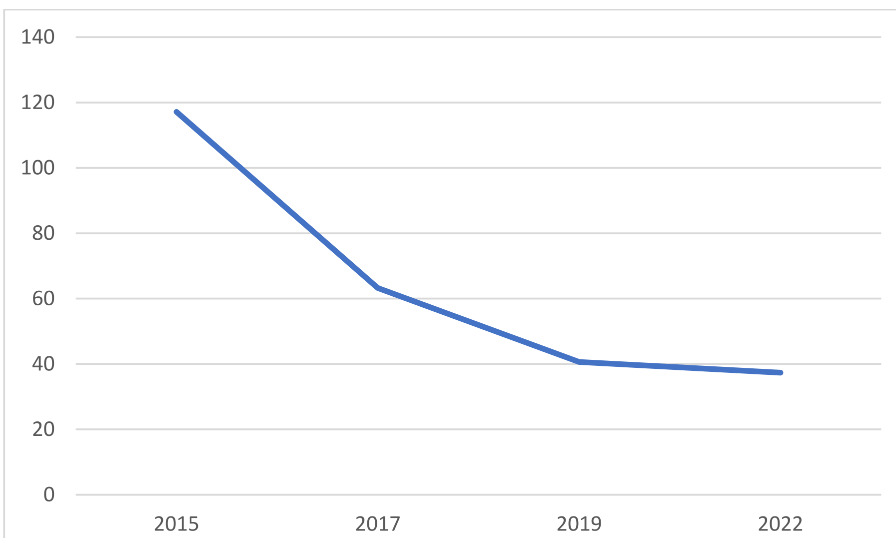

Fig. 7. Strike price results (in £/MWh) for offshore wind electricity in four successive auction rounds (for capacity coming online 4–5 years later).

provided long-term certainty), investors came to see offshore wind as less risky and consequently lowered interest rates (Hall et al., 2017). The de-risking of the offshore wind as an investment opportunity lowered the cost of capital from 10 % in 2010 to below 7 % in 2020 (Carbon Trust, 2020).

Supply chain firms and jobs (mid-2010s): Most technical components were initially imported, e.g., turbine blades from globally leading firms Siemens and Vestas. Over time, however, a domestic supply chain emerged as international suppliers aimed to reduce shipping costs (for instance of ever-larger turbine blades) and UK firms began to specialise and move into the emerging market [*feedback 2*]. This development was accelerated by the shift to Contracts-for-Difference, which required large projects to submit a supply chain plan that would promote domestic innovation and skills [*feedback 3*]. International wind turbine manufacturers, for instance, set up production facilities in the UK: Vestas in 2011, Siemens in 2014, and GE Renewable Energy in 2021 (Noonan and Smart, 2017; Nehls, 2021). The UK firm JDR Cables and UK-based BiFab became world leaders in subsea cable technology and turbine foundations respectively (BEIS, 2019b).

By 2016, the domestic content of UK offshore wind projects had increased to about 32 % (Noonan and Smart, 2017). The 2019 *Offshore Wind Sector Deal* set targets to further expand the UK content to 60 % by 2030. The number of jobs associated with offshore wind increased substantially since 2015, which is also indicative of a tipping point as firms committed more resources to hiring people (Fig. 10). Growth especially came from manufacturing, construction, electricity production, and professional, scientific, and technical activities (e.g., design, planning, R&D).

Public attention and support (post-2015): Public attention for offshore wind further increased after 2015 (Fig. 4), with discourses emphasising issues like cost reduction, economic competitiveness, jobs and growth (Aldersey-Williams et al., 2020). Public support and positive discourses helped to further legitimate the technology and policy support [*feedback 6,* 7] (MacKinnon et al., 2022).

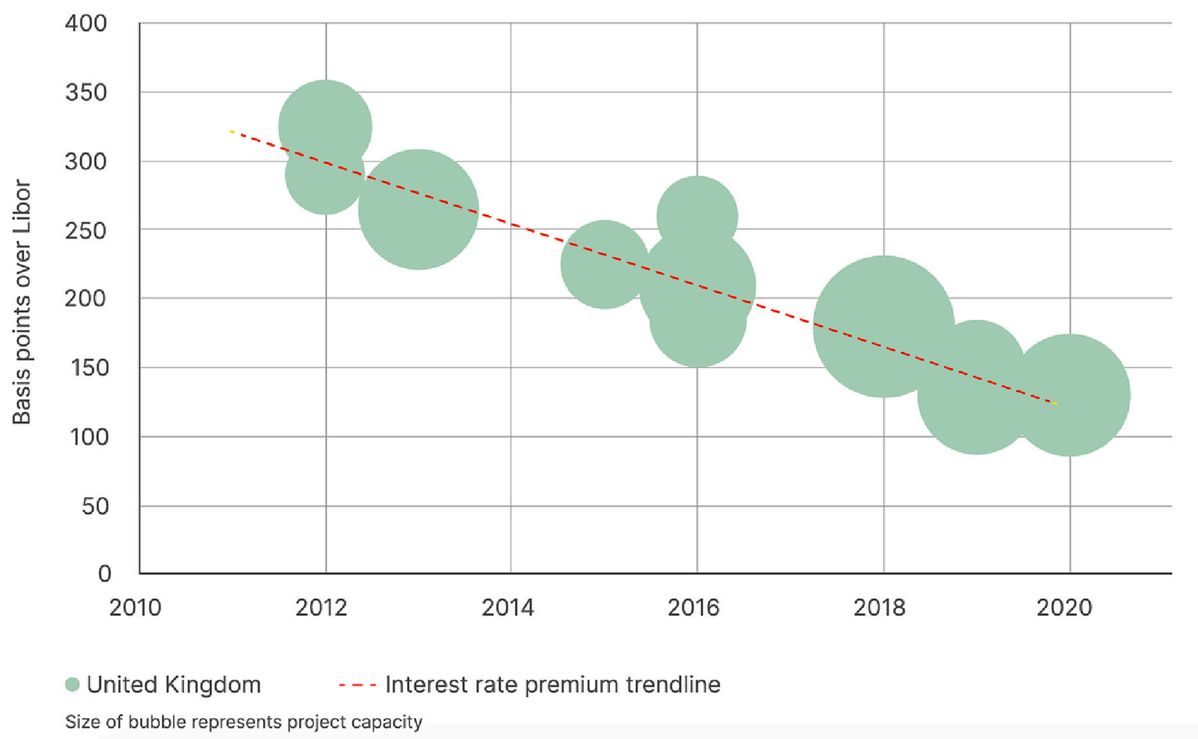

Fig. 8. Interest rates for offshore wind: Basis points above LIBOR per MW financed 2010–2020 (Wind Europe, 2020: 26).

Table 2
Quotes from selected annual reports and company statements, indicating strategic reorientation towards offshore wind in the mid-2010s.

Vattenfall (2015: 16)[a]	"Offshore wind capacity to double if cost reductions continue. Reduced subsidy support for renewables, which increases uncertainty for onshore wind."
Vattenfall (2016: 35–37)[b]	"Vattenfall's ambition is to continue to strive for on and offshore cost-efficiency to remove the need for subsidies altogether (…) We want to be a leader in the development, construction and operation of on- and offshore wind power".
Equinor (2016: 15)[c]	"For renewables, technological improvements to reduce cost in the areas of construction and maintenance for both fixed and floating offshore wind applications is a priority".
SSE (2016: 13)[d]	"SSE engaged constructively with the UK Government during the closure of the RO and sees continued opportunities for renewables, chiefly though potential expansion in its portfolio of offshore wind assets."
RWE (2017: 38)[e]	"This is an area in which our subsidiary wants to continue growing, in particular in investing in wind farm projects".

[a] https://group.vattenfall.com/siteassets/corporate/investors/annual-reports/2015/vattenfall_annual_and_sustainability_report_2015_eng.pdf.
[b] https://group.vattenfall.com/siteassets/corporate/investors/annual-reports/2016/vattenfall_annual_and_sustainability_report_2016_eng.pdf.
[c] https://cdn.sanity.io/files/h61q9gi9/global/0e20f74dbf8e00cd8837e8eb2526c212c069860c.pdf?statoil-2016-annualreport-20-F.pdf.pdf.
[d] https://www.annualreports.com/HostedData/AnnualReportArchive/s/LSE_SSE_2016.pdf.
[e] https://www.rwe.com/-/media/RWE/documents/Shortcuts/rwe-annual-report-2017pdf/RWE-annual-report-2017.pdf.

Policymakers (late 2010s): Building on deployment successes in previous years and supported by firms and public opinion, policymakers further escalated their commitment to offshore wind [*feedback 3, 4, 7*], deepening the technology's lock-in as one of the country's main decarbonisation trajectories. The 2019 *Offshore Wind Sector Deal* set a target of 30 GW capacity by 2030, while committing £557 million funding for bi-annual CfD auctions for the next ten years. The 2020 *Energy White Paper* further increased the target to 40GW, while the 2022 *Energy Security Strategy* raised it to 50GW.

5. Electric vehicles in the UK and globally

The diffusion of electric vehicles, commonly defined as including both Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs), rapidly accelerated in recent years, with the global stock reaching 16.3 million in 2021 (Fig. 11) and 750,000 in the UK (Fig. 12). EVs accounted for 9 % of the global car sales in 2021, 19 % in the UK, 16 % in China, 17 % in Europe, and 4.5 % in the USA (IEA, 2022). Based on EV stock data, which represent cumulative deployment, the worldwide tipping point is around 2020 and the UK tipping point around 2019. Our actor analysis will show, however, that perceptions and strategies tipped earlier, which thus forms an interesting contrast with the offshore wind case.

Firms (late 2000s, early 2010s): Most automakers initially had negative views of the technical and economic potential of EVs (Table 3). To keep up with new entrants like Tesla (which introduced the high-end Tesla Roadster in 2006) and with first-mover incumbents like Toyota (which had successfully introduced the Toyota Prius HEV), Mitsubishi and Nissan, they defensively engaged in R&D [*feedback 2*] (Penna and Geels, 2015). In response to increasing climate-related policy pressures and public debates, automakers gradually increased their EV engagements after 2009, but they continued to have doubts about whether EVs were developed for sustainability or commercial reasons (Bohnsack et al., 2020).

Policymakers (2009–2015): Increasing public concerns about climate change and the 2008 Climate Change Act pressured UK policymakers to develop climate-relevant transport policies [*feedback 7*], which in the 2009–2015 period mostly focused on stimulating coordination and innovation for electric vehicles [*feedback 3*]. Policymakers created the Office for Low Emission Vehicles (OLEV) in 2009 (to coordinate interactions between automakers, policymakers, and research organisations) and the Advanced Propulsion Centre in 2013 (to drive and coordinate R&D in low-emission powertrains). Policymakers and UK automakers also agreed to both invest £500 million, totalling £1

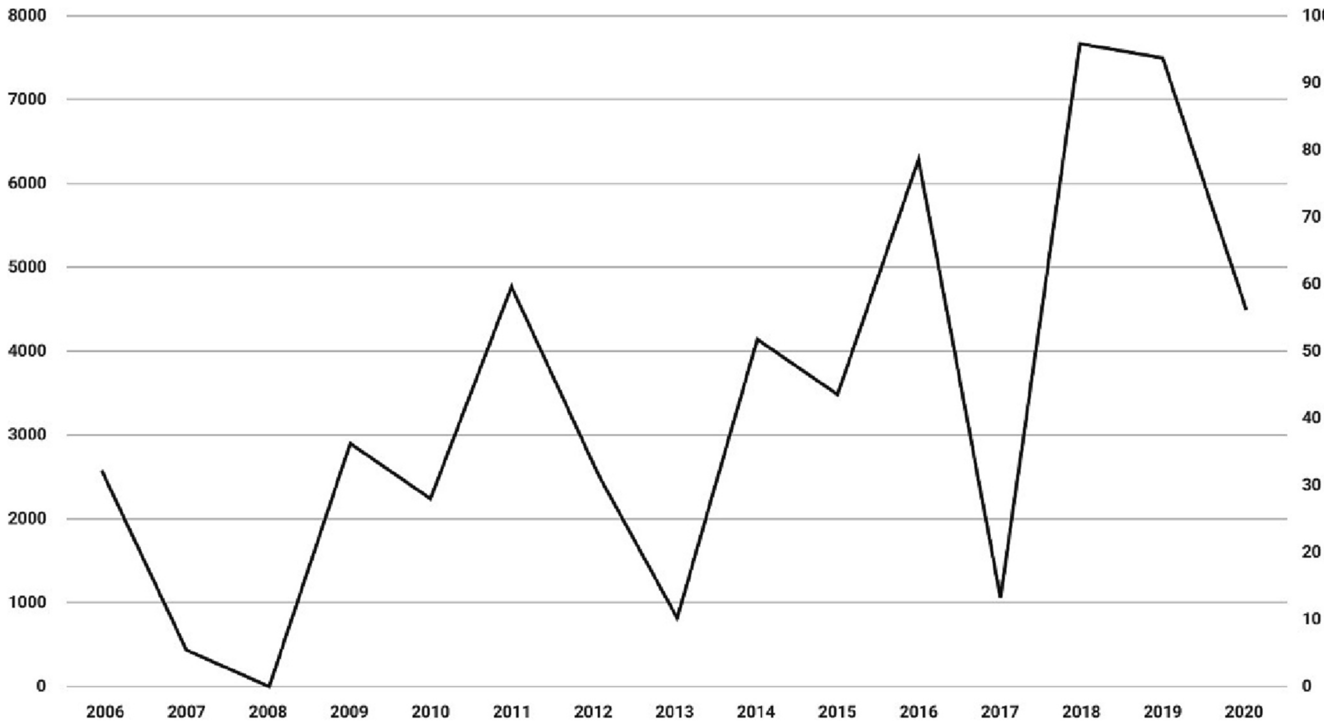

Fig. 9. Annual new offshore wind construction[a] (MW, left-hand side) and their share of using project finance (%, right-hand side) (PFI, 2022: 38).
[a]Construction is low in some years because offshore wind farms are large, lumpy projects.

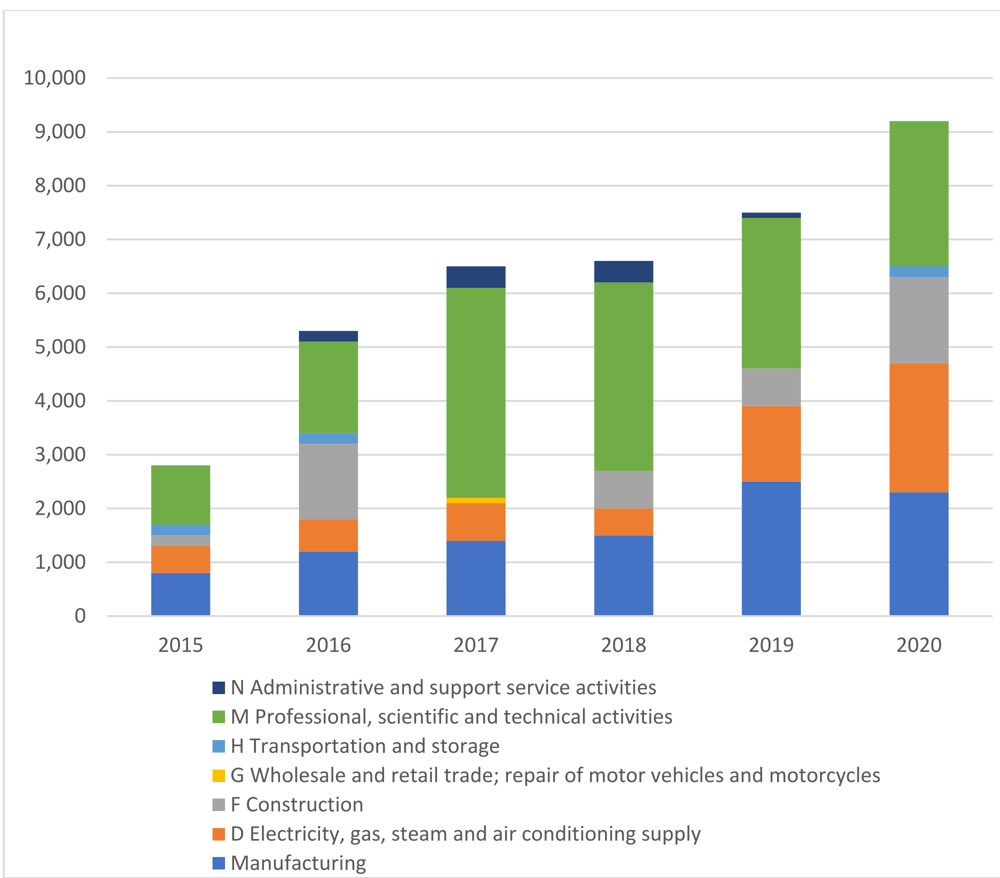

Fig. 10. Breakdown of jobs in offshore wind by sector measured in FTE, 2015–2020.
(Constructed using data from the Office of National Statistics; Low Carbon and Renewable Energy Economy survey estimates).

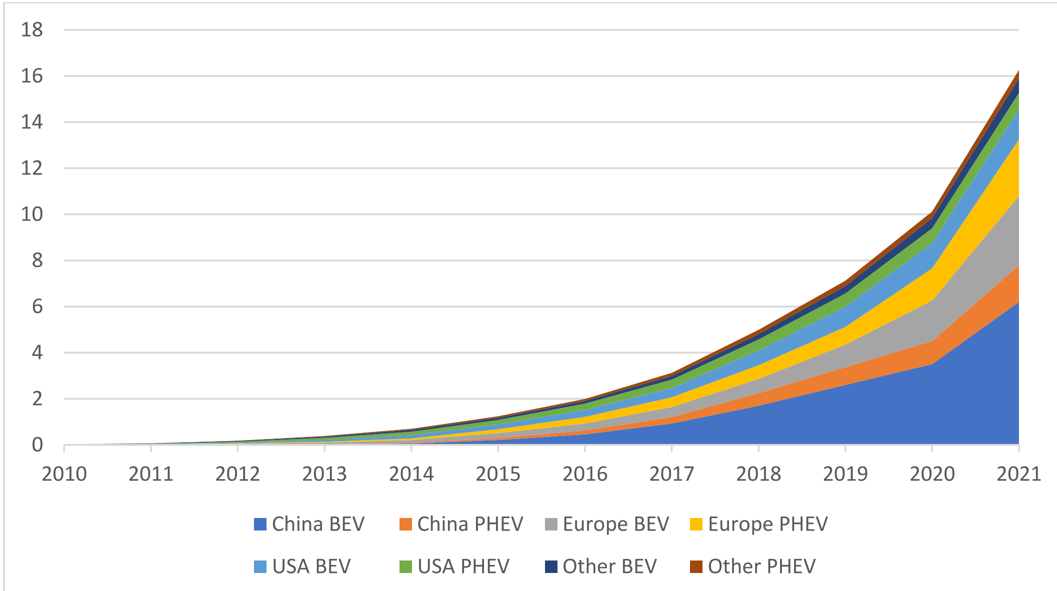

Fig. 11. Global stock of electric vehicles (BEV and PHEV) in millions 2010–2021.
(Constructed using data from IEA, 2022).

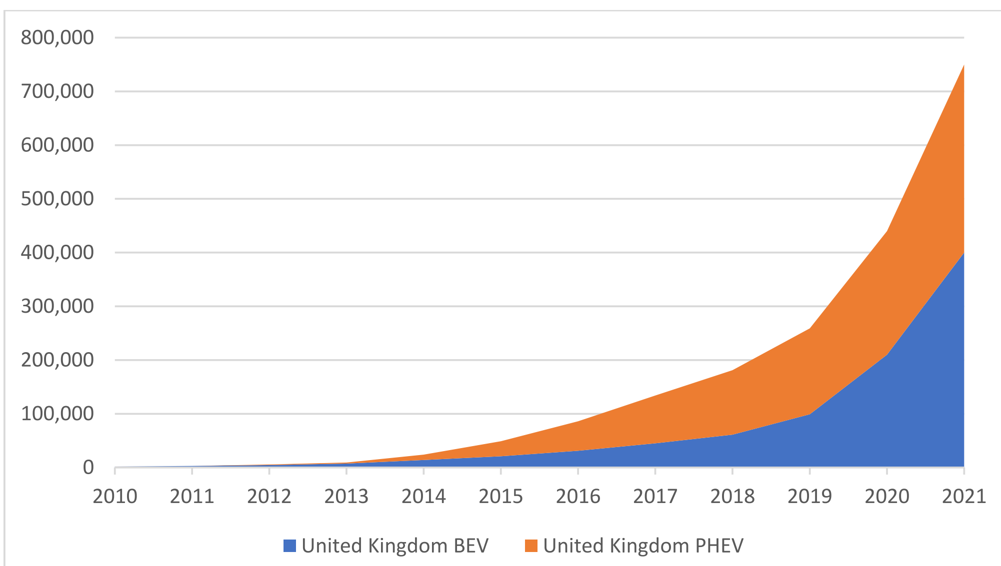

Fig. 12. UK stock of electric vehicles (BEV and PHEV) 2010–2021.
(Constructed using data from IEA, 2022).

billion over ten years (Skeete, 2019). From 2011 to 2015, OLEV disbursed £400 million to support R&D projects, the building of recharging infrastructure (via the Plugged-in Places scheme) and providing consumer adoption incentives. The 2011 Plug-in Car grant stimulated EV adoption by paying consumers 25 % of BEV and PHEV purchase, up to £5000 (Geels and Turnheim, 2022).

International policy pressure also increased. In 2009, the European Commission introduced new car emission regulations for 2015 (130 gCO_2/km). Its 2011 Transport White Paper further stated ambitions of reducing transport GHG emissions by 60 % in 2050 and identified EVs as a core technology. China, which saw EVs as an opportunity to enter automotive manufacturing, stimulated both the production and use of EVs, introducing national purchase subsidies in 2010. Combined with provincial subsidies, Chinese EV adoption incentives reached $18,500 in 2013 (Anadon et al., 2022), but were gradually reduced afterwards as EV costs decreased. Chinese policymakers also supported charging station construction in 2012.

Public attention and support (early 2010s): Public attention for EVs increased somewhat after 2009/10 (Fig. 13), as UK climate change debates came to focus on transport. Early discourses focused on both positive aspects (emission reduction, quietness, smoothness, home-charging) and negative aspects (limited range, battery charging times, cost) (Axsen et al., 2013; Bunce et al., 2014), which legitimated the technology [*feedback 6*] and policy support [*feedback 7*] and indicated directions for future technological improvement.

Users (early 2010s): The positive dimensions of public debates stimulated adoption by early EV users [*feedback 5*], who were mostly middle-aged, male, well-educated, affluent urbanites with pro-environmental attitudes and an active interest in new technology (Morton et al., 2017). These early adopters were willing to pay more for

Table 3
Automaker's perceptions and strategic orientations towards electric vehicles in 2008/9, evidenced by quotes from annual reports and press statements (quotes from Bohnsack et al., 2020, except for Nissan, 2009).

Toyota	"We feel electric cars cannot replace normal vehicles. […] There will be a market for this vehicle, but a limited one."
Daimler	"The chances appear better on the fuel cell than the battery electric side."
Honda	"Battery-based electric vehicles aren't really practical at this point in time" (…) "It's questionable whether consumers will accept the annoyances of limited driving range and having to spend time charging them."
Hyundai	"The usage of that kind of 100 % electric vehicle will be very, very limited."
Ford	"I don't think it'll be a high volume. It'll be tailored for city driving and a limited range."
Nissan (2009:8)	"The environment and global warming are still crucial issues. In this area, Nissan has chosen to concentrate on zero-emission vehicles, and we intend to be the world leader in electric vehicles"
Mitsubishi	"Mitsubishi's vision for addressing environmental issues is 'Leading the EV era, towards a sustainable future.' To realize this vision, we have started mass production of the new-generation electric vehicle iMiev and have begun rollout of the iMiev in Japan, looking to expand rollout globally"

EVs, which even with subsidies were more expensive than normal cars. Their houses often had off-road parking, which facilitated home-charging. Range anxiety was a concern, because early EVs had limited ranges and battery-charging facilities were not widespread along motorways, which hampered longer journeys (Axsen et al., 2013).

Technological and cost developments (2010–2020): User experiences stimulated automakers to focus research and development activities on improvements in battery capacity, size, and efficiency [*feedback 2*], which almost tripled the average BEV driving range between 2010 and 2021 (Fig. 14). To reduce EV charging times, automakers also increased the average charging power from 50 Kw in the early 2010s to 140Kw in 2021 (BNEF, 2021). These developments reduced user concerns and improved the appeal of EVs [*feedback 2*], which prepared the ground for widespread adoption after 2015.

EVs are simpler than internal combustion engine vehicles (ICEV) because they remove the need for components like crank shafts, pistons, and transmission. They are also (still) more expensive than ICEVs because of battery-costs, although power electronics and electric motors also add costs. However, the price of Li-ion battery packs fell by 89 % between 2010 and 2020 (Fig. 15), due to learning-by-doing and scale economies (BNEF, 2021; Geels and Turnheim, 2022) [*feedback 1, 2*], which reduced the purchase price differences between EVs and ICEVs and increased their appeal to wider consumer segments (since EV running costs are substantially lower). EVs are expected to reach price parity with ICEVs by 2024/25 if cost reductions along the learning curve continue (Nykvist et al., 2019; BNEF, 2021).

Users (mid-2010s): Technological improvements, cost decreases, and expanding public charging infrastructure diminished user concerns and stimulated adoption [*feedback 2*], which in the UK increased significantly after 2015 (Valdez et al., 2019). This was also stimulated by purchase subsidies and positive public discourses [*feedback 4, 5*]. International markets also grew, with Chinese EV adoption increasing 266 % in one year, from 75,000 in 2014 to more than 200,000 in 2015 (IEA, 2022). This was important because China was an essential growth market that automakers wanted to target [*feedback 2*].

Firms (2015–2017): Company views of EVs substantially changed between 2015 and 2017, tipping their strategic orientation from hesitant engagement to strategic commitment (Bohnsack et al., 2020), as indicated by the quotes in Table 4. These cognitive and strategic changes were driven by learning processes and reflections on changing contexts, including technological and cost improvements in previous years (which were expected to continue), increasing consumer demand (including in major economies like China), and strengthening EV-oriented policies (especially in China and Europe) [*feedback 2, 3*].

An important negative pressure was the 2015 Dieselgate scandal, which revealed widespread emission test cheating by Volkswagen and other automakers. Volkswagen's subsequent strategic reorientation to EVs was at least partly a response to this scandal, which tarnished its reputation and legitimacy (Zhang et al., 2021). But since Volkswagen was one of world's largest automakers, its strategic reorientation galvanised other automakers, giving rise to an EV innovation race in subsequent years [*feedback 2*], which led companies to expand and diversify their EV models (Bohnsack et al., 2020; Campbell, 2022).

Despite these changing perceptions and innovation strategies, automakers and their industry associations also continued to use lobbying strategies to contest UK and EU climate legislation such as ICEV phase-out decisions (Laville, 2019; Jolly, 2021) to delay the pace of the EV transition.

Public attention and support (post-2015): Public attention increased substantially after 2015 (Fig. 13), as adoption expanded and

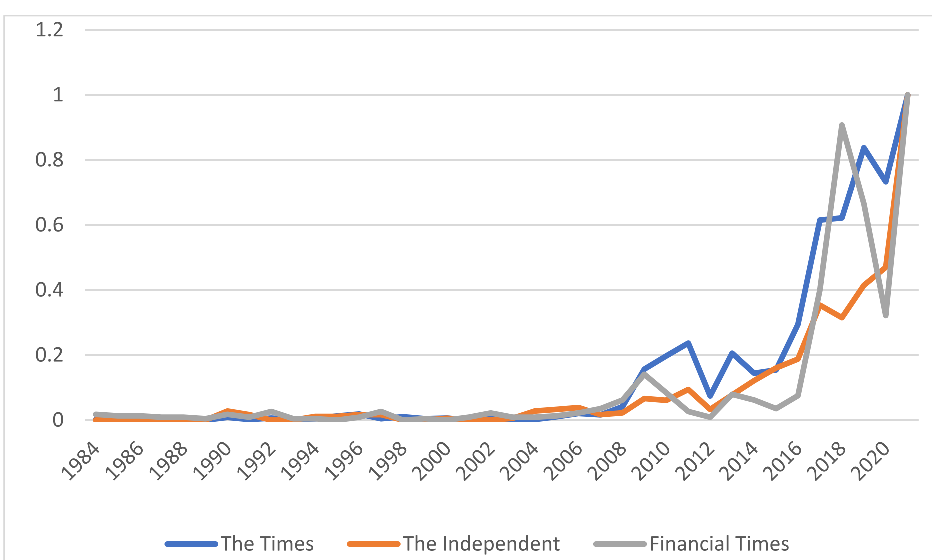

Fig. 13. Public attention for EV.
(Constructed using data the Financial Times, The Independent and The Times).

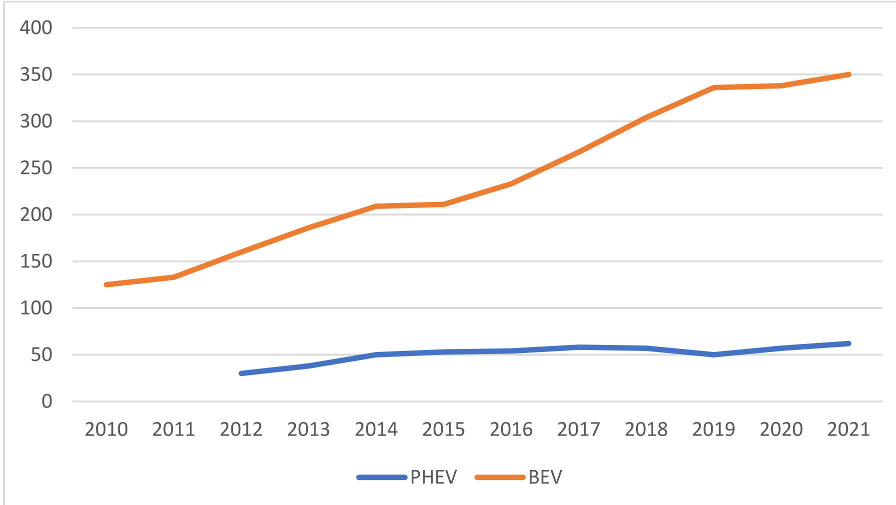

Fig. 14. Driving range (in km) of BEV and PHEV.
(Constructed using data from IEA, 2022).

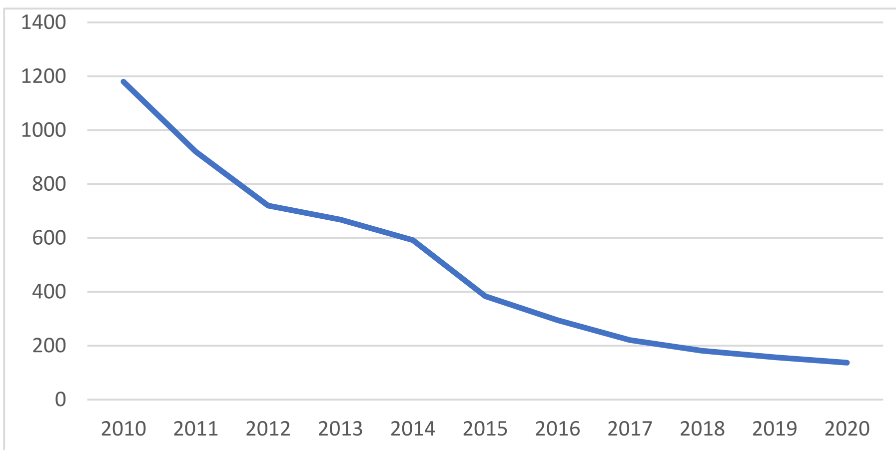

Fig. 15. Battery pack price in real 2020$/kWh.
(Constructed using data from BNEF, 2020).

new policies were introduced. Public EV discourses became increasingly positive, focusing on issues like economic growth, job creation, and clean air (Valdez et al., 2019). These positive discourses stimulated consumer interest [*feedback* 5] and legitimated further policy support [*feedback 7*].

Policymakers (post-2015): UK policymakers' perceptions and orientations also tipped between 2015 and 2017, as they came to see EVs as the core plank of transport decarbonisation and industrial policy. Public pressure, policy evaluation, and company lobbying led to a change in policies [*feedback 3, 4, 7*], which became more deployment-oriented, focusing on the creation of: a) charging infrastructures, b) mass markets, and c) industrial manufacturing and supply chains.

Government investments accelerated the expansion of a public recharging infrastructure after 2017 (Fig. 16), which also increased rapid charging devices that can charge EV-batteries from 0 % to 80 % in about 30 min (Geels and Turnheim, 2022).

The phase-out plans of petrol and diesel cars, first announced in 2017 and sharpened in 2020, created a trajectory towards mass markets, because all new vehicle sales from 2030 will be hybrid or pure electric.

The government's 2017 *Clean Growth Strategy* came to see EVs as important for industrial strategy, leading to new policy instruments such as capital grants and subsidies for automakers to build electric vehicle manufacturing plants [*feedback 3*]. Through the 2017 Faraday Battery Challenge, policymakers also invested £330 million to support R&D and manufacturing scale-up capability for batteries in the UK. This included the creation of the Faraday Institution and the UK Battery Industrialisation Centre. The 2018 *Automotive Sector Deal* further aimed to align industry and government in supporting and benefiting from the EV transition.

International policy pressure on firms also increased in the mid-2010s [*feedback 3*]. The European Commission in 2014 tightened fleet average new car emission regulations to 95 gCO_2/km by 2020, which would require some form of electrification, and in 2019 added stiff fines for companies that would miss the target, namely €95 for every gram over the limit, multiplied by the number of cars sold that year (Geels and Turnheim, 2022). In 2015, Beijing, and subsequently other major Chinese cities, relaxed license plate regulations for EVs. These regulations, which were introduced to combat local air pollution and congestion, thus mostly came to restrict ICEVs (Zhang et al., 2018). And in 2018, Chinese policymakers introduced a dual-credit scheme with steadily increasing quotas that reward carmakers with credits for producing more EVs, while forcing them to buy EV credits from other producers for the production of conventional cars (Anadon et al., 2022).

UK plants, jobs, and supply chain firms (post-2017): The EV

Table 4
Automaker's perceptions and strategic orientations towards electric vehicles in 2015–2017, evidenced by quotes from annual reports and press statements.

Mitsubishi (2015)[a]	"We are aiming to take the lead in benefitting from future changes in the product market by focusing on sales of eco-cars, including electric and clean diesel vehicles."
BMW (2015)[b]	"Innovations such as the BMW i3 and i8 in the field of electric mobility (…) provide excellent platforms for future growth."
Hyundai (2016)[c]	"The technological advancements will (…) allow us to begin a new era for the automotive industry. We will develop more green cars such as hybrids, electric vehicles and hydrogen fuel cells."
Volkswagen (2017)[d]	"Volkswagen wants to actively shape the current phase of technological transformation in the automotive industry. (…) The Volkswagen Group has launched a comprehensive electrification offensive in the form of Roadmap E, setting itself the goal of becoming one of the world's leading providers of battery-powered vehicles (BEV) by 2025. (…) We are therefore planning to invest more than €20 billion in industrializing e-mobility by 2030."
Ford (2017)[e]	"We continued to dramatically accelerate our electric vehicle plans with the formation of Team Edison, a dedicated global electric vehicle organization focused on bringing to market profitable, exciting electric vehicles and ownership experiences. (…) We announced a plan to increase our investment in electrification—expected to be over $11 billion by 2022—to substantially increase the number of battery electric vehicles we offer around the world."
General Motors (2017)[f]	"In October 2017 we announced our plans to launch more than 20 new Zero Emission Vehicles (ZEVs) in global markets by 2023, including two in the next 18 months. (…) We anticipate that electric vehicle sales will become increasingly important to our business."

[a] https://www.mitsubishimotors.com/content/dam/com/ir_en/pdf/anual/2015/annual2015.pd.
[b] https://www.bmwgroup.com/content/dam/grpw/websites/bmwgroup_com/ir/downloads/en/2016/hv/2015-BMW-Group-Annual-Report.pdf.
[c] https://www.hyundai.com/content/dam/hyundai/ww/en/images/about-hyundai/ir/financial-statements/annual-report/hw113210.pdf.
[d] https://annualreport2017.volkswagenag.com/servicepages/downloads/files/entire_vw_ar17.pdf.
[e] https://www.annualreports.com/HostedData/AnnualReportArchive/f/NYSE_F_2017.pdf.
[f] https://www.annualreports.com/HostedData/AnnualReportArchive/g/NYSE_GM_2017.pdf.

transition will require automakers to build new factories (or significantly retool existing plants) and involve major changes in supply chains, including new plants for producing batteries and electric motors. Since 2011, the EV sector in the UK has created 14,320 jobs (SMMT, 2022), including at Nissan's EV plant in Sunderland, opened in 2013. Since 2017, UK policymakers have tried to stimulate the building of new EV and battery plants with capital grants, subsidies and R&D support, but results have been mixed. Positive statements have come from Nissan, Vauxhall's new owner Stellantis, and Jaguar Land Rover. But other automakers perceived the UK as less attractive for locating EV and battery plants, due to industrial and policy contexts, including Brexit-related trade complications. In 2019, Honda announced the closure of its UK manufacturing plant in Swindon, as part of a wider global restructuring move. In 2019, Tesla chose Germany over the UK for its new Gigafactory (for batteries and cars). In 2020, Toyota postponed UK electric vehicle investments until 2027 (Jolly, 2020). And in 2022, BMW cancelled its earlier plans for a UK-produced electric Mini and moved production to China instead (O'Neill, 2022).

In 2019, start-up company Britishvolt announced plans for a £3.8bn 38 GWh battery gigafactory, which received much attention and support. Since then, Britishvolt has struggled to secure sufficient funding, which caused delays and problems (Jolly, 2022). The UK thus appears to be falling behind in the global EV race, which would reduce industrial and job benefits of the transition (Campbell et al., 2019; Harding, 2022).

Although *potential* UK jobs by 2040 could be as high as 270,000 in EV manufacturing, 35,000 in battery Gigafactories and 65,000 people in the battery supply chain (Faraday Institution, 2022), it is presently doubtful that this potential will be realised as automakers find other countries more attractive for building EV and battery plants.

6. Discussion

Both case studies clearly show that accelerated diffusion was not only driven by techno-economic developments (such as learning curves, cost decreases, and technological improvements), but also by significant reorientations or 'tipping' in interpretations and strategic commitments of firms, policymakers, users, and wider publics. The cases thus confirm the basic point from our elaborated socio-technical perspective (summarised in Fig. 2) that techno-economic developments and significant actor reorientations causally interact in tipping point dynamics.

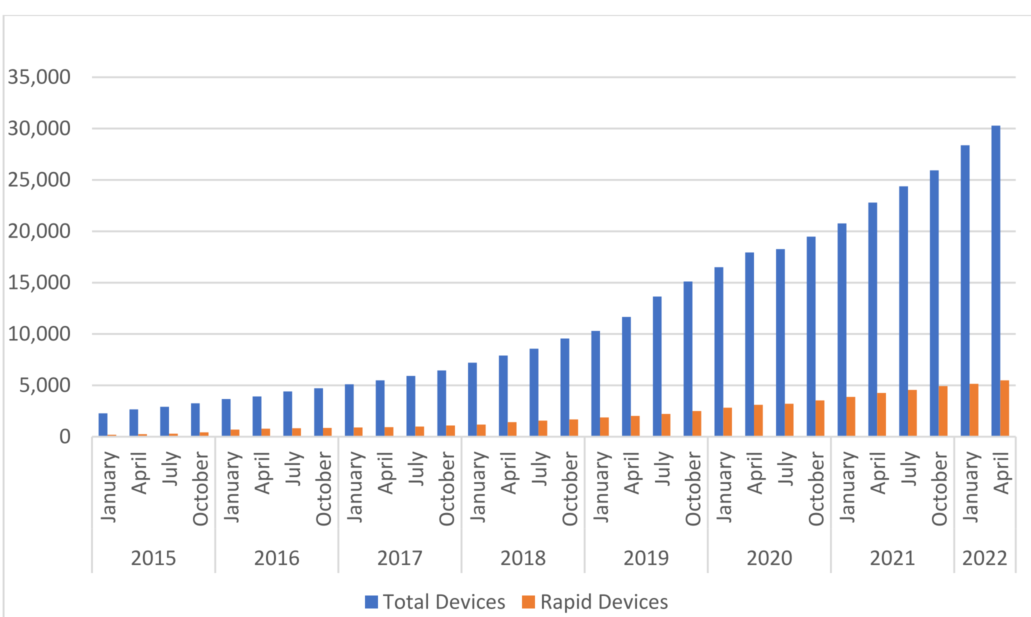

Fig. 16. Number of public charging points in the UK each quarter since 2015.
Source (Department of Transport: Electric Vehicle Charging Device Statistics Table EVCD_02).

The cases also showed that co-evolutionary interactions in tipping point dynamics had particular sequences, which unfolded in the space of a few years. In the offshore wind case, tipping dynamics had the following sequence of steps and significant reorientations that interacted through the feedback loops from Fig. 2:

1. Negative evaluations of the 2002 RO policy [*feedback 4*] and socio-political pressures related to the 2008 Climate Change Act [*feedback 7*] led policymakers to significantly reorient in 2009 and enact a major policy change (the amended Renewables Obligation with generous subsidies).
2. This policy change led to significantly increased public attention and positive debates about offshore wind that legitimated and supported the policy change [*feedback 6, 7*].
3. The policy change also significantly increased (subsidised) offshore deployment by supplier and user firms after 2009 [*feedback 3*].
4. Increased deployment, in turn, led to more learning-by-doing and learning-by-using processes, which enhanced the experiences, capabilities and confidence of supplier and user firms in the early 2010s [*feedback 2*].
5. Encouraged by these positive developments [*feedback 3, 4, 7*], policymakers made another significant reorientation in 2013, shifting from RO to Contracts-for-Difference instruments, which introduced price competition through auctions (in 2015, 2017, 2019, 2022) and attracted financial investors.
6. Learning processes improved technologies (such as turbines and complementary innovations), while scale economies and improvements in deployment and manufacturing significantly decreased costs after 2014 [*feedback 1, 2*].
7. Building on previous learning processes and convinced about further cost reduction potential [*feedback 1, 2*], user and supplier firms responded to the new policy by significantly reorienting their strategic actions and perceptions between 2015/17 (seeing a pathway to mass markets), leading to much cheaper offshore wind offers in auctions.
8. Positive economic results also attracted financial firms [*feedback 2*], which became significantly more involved after 2015, leading to more available finance at lower costs and more differentiated project developer coalitions.
9. Increased deployment and policy changes also stimulated the interest of domestic firms in supplying particular components [*feedback 2*], which increased UK-based jobs after 2015.
10. Increased deployment also enhanced public attention, leading to positive debates that increasingly framed offshore wind as solution to multiple issues, including climate mitigation, industrial growth, and jobs [*feedback 5, 6, 7*].
11. Enhanced policy targets in recent years and sector deals further locked offshore wind in as a core decarbonisation pathway [*feedback 3*].

In the EV case, tipping dynamics had the following sequence of steps and feedback loops.

1. In the late 2000s and early 2010s, automakers had mostly negative perceptions of EVs but defensively engaged in R&D in response to new entrants and first movers and diffuse policy pressures [*feedback 2*].
2. In response to public pressures, EU and UK policymakers developed outline visions of EV decarbonisation pathways [*feedback 7*] and offered tentative support through R&D subsidies and purchase subsidies [*feedback 3*], Chinese policymakers in the early 2010s more strongly stimulated the production and use of EVs for industrial policy reasons.
3. Public debates at the time highlighted both positive and negative aspects of EV use [*feedback 6*], which legitimated policy support [*feedback 7*].
4. Public debates also galvanised early adopters [*feedback 5*] to purchase EVs.
5. The resulting real-world user experiences and concerns led automakers to focus on technological improvements (in battery capacity, driving range, charging times) and cost reductions [*feedback 2*], which continued throughout the whole period, gradually improving EV attractiveness to wider user groups.
6. These techno-economic improvements and growing Chinese demand, which increased rapidly after 2014 due to policy support, led to significant reorientations in the perceptions and strategies of automakers between 2015 and 2017 [*feedback 1, 2*], which was also stimulated by the Dieselgate scandal.
7. Policy orientations also significantly changed between 2015 and 17, leading to a focus on direct infrastructure investment (to enable widespread use), mass market creation (through ICEV phase-outs and restrictions), and support for battery and EV plants [*feedback 3, 4*].
8. These policies were supported and legitimated by significantly increasing public attention and positive debates about climate mitigation, clean air, industrial growth and jobs [*feedback 6, 7*].
9. The positive cultural meanings, cost reductions, technical improvements, policy support and emerging infrastructure prepared the ground for deployment tipping points after 2019/20 [*feedback 1, 2, 5*].

These sequencing summaries not only demonstrate the interacting feedbacks between techno-economic developments and actor reorientations, but also show an important sequencing difference: the deployment tipping point for offshore wind around 2009 *preceded* significant actor reorientations, while the deployment tipping point for EVs in 2019 (UK) and 2020 (globally) *followed* significant actor reorientations between 2015 and 2017.

One reason for this sequencing difference is that a significant early policy reorientation, which provided generous long-term subsidies, enabled accelerated deployment of offshore wind after 2009, even though firms still had doubts about the economic viability of offshore wind, which was still relatively expensive. The increased subsidised deployment did, however, set in train many learning processes and cost reductions, which in subsequent years strengthened the capabilities and confidence of actors, culminating in *later* reorientations in perceptions and strategies (of firms, users, and policymakers, especially) which then subsequently sustained further diffusion. In the EV case, policymakers also offered early support (e.g., R&D, purchase subsidies), but this was more tentative and did not immediately boost large-scale deployment. Acceleration in the EV case thus involved the more gradual alignment and reinforcement of multiple feedbacks and processes (in technology, cost, adoption, firm strategies and public debates), which significantly changed orientations of multiple actors (especially firms, policymakers, and wider publics) between 2015 and 2017, which was *before* mass diffusion.

Another reason for the sequencing difference is that diverse user preferences and cultural meanings played a greater role in the EV case because the car adopter population is large and diverse and because cars are consumer goods with high emotive powers (while offshore wind turbines are capital goods deployed by firms). Because of the user diversity, firms could find some consumers (wealthy men with an interest in innovation and sustainability) who were willing to pay more for EVs and act as user 'innovators' in Rogers's adopter categorisation (Fig. 17). Cultural meanings of EVs as modern, clean, and technologically-advanced motivated these consumers to buy EVs in early stages, when they were still expensive. This small but early adoption then galvanised learning processes and interaction mechanisms between firms, users, policymakers and wider publics *before* widespread diffusion and cost

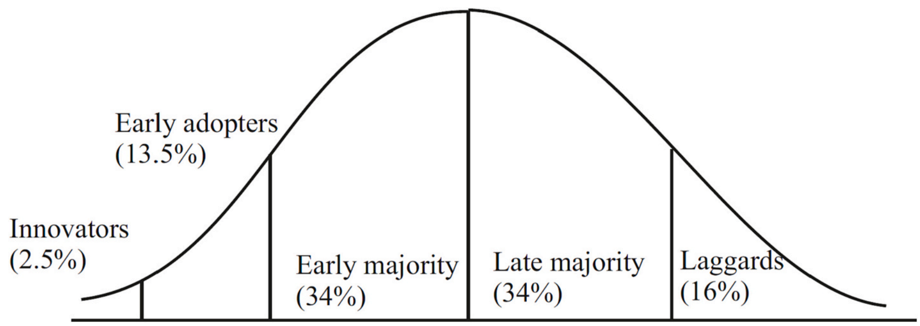

Fig. 17. Adopter categories in a population of adopters (Rogers, 1996).

reductions.

Cultural considerations were less salient for offshore wind, where the users were firms that deploy financial cost-benefit calculations to inform their adoption decisions. These adopter firms were also fewer in number and less diverse than EV buyers, which means there were fewer adopters willing to act as user 'innovators' to set in train early learning processes and interaction mechanisms.

A third reason is that offshore wind turbines were mostly technological replacements in upstream electricity production, while EVs involved both technical and wider system changes, including in recharging infrastructure, user practices, supply chains, and factories. While the deployment of modular technical changes like offshore wind can be pushed early and decisively by policymakers, this is less the case for systemic transitions like EVs that require development, alignment, and learning processes on multiple dimensions *before* accelerated mass diffusion can occur (Geels and Turnheim, 2022).

In terms of the causal feedback loops from Fig. 2, these considerations imply that offshore wind acceleration was triggered by societal and political feedbacks (3, 5, 6, 7), which then subsequently activated the economic feedback loops (1,2), which in turn further strengthened the societal and political feedbacks (3, 4, 5, 6, 7). In the EV acceleration, in contrast, the feedback loops interacted in a more dispersed and gradually reinforcing way, because there were early policies and societal debates (which activated socio-political feedbacks) as well as early users and firm investments (which activated economic feedbacks).

Another important difference between the cases was that the political lobbying feedback from firms was negative in the EV case and positive in the offshore wind case. The reason for this difference is that energy and turbine companies were new entrants in electricity production, which lobbied for stronger climate policies, while most automakers (except Tesla) were incumbent firms that had sunk investments in ICEV manufacturing, which they tried to protect by politically delaying the transition, while simultaneously preparing for the transition through innovation strategies.

Another reflection is that both cases saw *two* significant policy changes and reorientations. In the offshore wind case, the first policy reorientation was the strong early commitment in 2009 (to stimulate deployment with attractive long-term subsidies) and the second was a reorientation around 2013/15 towards attracting financial investors and stimulating competition to reduce costs. In the EV case, the first reorientation was a shift towards tentative early support (R&D support and adoption subsidies) and the second reorientation was towards much stronger commitment around 2015/17 (to create infrastructure, mass markets, and new plants). This underlines not only the importance of policymakers in low-carbon tipping points but also the role of policy learning, confidence building, and business and public support (feedback loops 3, 4 and 7), which led to significant policy adjustments halfway through the process.

Finally, we note that some actor orientations changed gradually rather than suddenly, for example public attention for offshore wind (Fig. 4). We should thus not assume that social tipping is likely or necessary for each actor group in accelerated transitions (see also Milkoreit, 2023). Feedback loops from wider publics, in particular, are important to support or legitimate substantial actions by policymakers, firms, and users, but this effect can also occur through gradual increases in public attention and pressure.

7. Conclusions

To overcome the dichotomy in the positive tipping point literature, the article developed a socio-technical transition perspective, which accommodates the importance of both techno-economic improvements and significant actor reorientations. Building on recent contributions with similar aims, we made a next step by elaborating and advancing socio-technical transitions theory by more precisely articulating social, political, business and techno-economic feedback loops in the shift from small market niches to mass deployment. This new perspective on positive tipping points goes beyond existing approaches that use diffusion curves to identify single inflection points, drawing attention instead to multiple actor reorientations and techno-economic developments that together accelerate the diffusion of low-carbon innovations in the span of a few years. This means that a purely techno-economic analysis of tipping points is too narrow and potentially misleading.

As a second contribution we empirically analysed the temporality of co-evolutionary interactions in tipping point dynamics in our cases, showing that patterns differed significantly. Accelerating techno-economic deployment *preceded* significant actor reorientations in offshore wind, while *following* them in the EV case. We offered reasons for these differences, which indicate that co-evolutionary sequences are context- and case-specific.

We further conclude that policy support was essential in both tipping point cases, although early support was stronger in the offshore wind than in the EV case. Policy support in both cases changed twice due to policy learning and increasing emphasis on mass deployment and cost reduction in later stages.

Future research could fruitfully focus on further elaborating co-evolutionary interaction loops between social and technical tipping points, doing more real-world case studies (to expand empirical groundings and move beyond the wishful thinking that characterizes part of the literature), and further investigating co-evolutionary patterns in the temporality and sequencing of tipping point dynamics, which is important and interesting as our two cases showed.

Future research could also address limitations of this paper. One limitation relates to conceptual framework, which we qualified as a first step. We already noted that the 'firm' category in Fig. 2 was too limited to capture empirical complexities, which is why our case studies added supply chains, employees, and financial firms. Future research could thus elaborate the conceptual framework by including more types of actors with regard to both firms as well as policy, civil society, and users. As a trade-off, such conceptual broadening would, however, multiply the number of feedback loops and complicate empirical research.

Another limitation is that the paper focused on the endogenous dynamics and co-evolutionary feedbacks in emerging niche-innovations and thus ignored the role of regime destabilisation (or landscape shocks) in tipping points. The EV case did, however, refer to Dieselgate, which suggests that de-legitimisation and erosion of the ICEV regime was important. Future research could thus try to develop a broader MLP-based understanding of tipping points, which would address endogenous niche-innovations, regime destabilisation and exogenous shocks. Socio-technical transitions research of positive tipping points can thus progress along various promising avenues.

CRediT authorship contribution statement

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

Data availability

Data will be made available on request.

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References

Aldersey-Williams, J., Strachan, P.A., Broadbent, I.D., 2020. Validating the "seven functions" model of technological innovations systems theory with industry stakeholders—a review from UK offshore renewables. Energies 13 (24), 6673.
Anadon, L.D., Jones, A., Peñasco, C., 2022. Ten Principles for Policymaking in the Energy Transition: Lessons From Experience. Report From the Economics of Energy Innovation And System Transition Project.
Andreoni, J., Nikiforakis, N., Siegenthaler, S., 2021. Predicting social tipping and norm change in controlled experiments. Proc. Natl Acad. Sci. USA 118 (16), e2014893118. https://doi.org/10.1073/pnas.2014893118.
Argyris, C., 1976. Singe-loop and double-loop models in research on decision-making. Adm. Sci. Q. 21 (3), 363–375.
Arthur, W.B., 1989. Competing technologies, increasing returns, and lock-in by historical events. Econ. J. 99 (394), 116–131.
Axsen, J., Orlebar, C., Skippon, S., 2013. Social influence and consumer preference formation for pro-environmental technology: the case of a UK workplace electric-vehicle study. Ecol. Econ. 95, 96–107.
Barr, P.S., Stimpert, J.L., Huff, A.S., 1992. Cognitive change, strategic action, and organizational renewal. Strateg. Manag. J. 13, 15–36.
BEIS, 2019a. Investment Trends IN UK REnewable Electricity Landscape. Department for Business, Energy & Industrial Strategy, London.
BEIS, 2019b. Energy Innovation Needs Assessments: Offshore Wind Sub-theme Report. Department for Business, Energy & Industrial Strategy, London.
BEIS, 2022. Energy Trends: March 2022. Department of Business, Energy and Industrial Strategy, London.
Bennett, A., Checkel, J.T. (Eds.), 2015. Process Tracing: From Metaphor to Analytic Tool. Cambridge University Press, Cambridge.
BNEF, 2020. Battery Price Survey. Bloomberg New Energy Finance.
BNEF, 2021. Zero-emission Vehicles Factbook: A Bloomberg NEF Special Report Prepared for COP26. Bloomberg New Energy Finance.
Bohnsack, R., Kolk, A., Pinkse, J., Bidmon, C., 2020. Driving the electric bandwagon: the dynamics of incumbents' sustainable product innovation. Bus. Strateg. Environ. 29 (2), 727–743.
Brand, C., Anable, J., Tran, M., 2013. Accelerating the transformation to a low carbon passenger transport system: the role of car purchase taxes, feebates, road taxes and scrappage incentives in the UK. Transp. Res. A Policy Pract. 49, 132–148.
Bunce, L., Harris, M., Burgess, M., 2014. Charge up then charge out? Drivers' perceptions and experiences of electric vehicles in the UK. Transp. Res. A Policy Pract. 59, 278–287.
Burnstein, P., 2003. The impact of public opinion on public policy: a review and an agenda. Polit. Res. Q. 56, 29–40.
Campbell, P., 2022. Carmakers embrace greener vision in wake of Dieselgate. In: Financial Times, 5 May 2022.
Campbell, P., Pfeifer, S., Pooler, M., 2019. How the UK is falling behind in the global electric car race. In: Financial Times. March 25, 2019.
Carbon Trust, 2020. Policy, Innovation And Cost Reduction in Offshore Wind. London.
Centola, D., Becker, J., Brackbill, D., Baronchelli, A., 2018. Experimental evidence for tipping points in social convention. Science 360 (6393), 1116–1119.
David, P.A., 1985. Clio and the economics of QWERTY. Am. Econ. Rev. 75 (2), 332–337.
Eder, C., Stadelmann-Steffen, I., 2023. Bringing the political system (back) into social tipping relevant to sustainability. Energy Policy 177, 113529.
Edmondson, D.L., Kern, F., Rogge, K.S., 2019. The co-evolution of policy mixes and socio-technical systems: towards a conceptual framework of policy mix feedback in sustainability transitions. Res. Policy 48 (10), 103555.
Falleti, T.G., 2016. Process tracing of extensive and intensive processes. New Polit. Econ. 21 (5), 455–462.
Faraday Institution, 2022. UK Electric Vehicle And Battery Production Potential to 2040. Didcot.
Farmer, J.D., Hepburn, C., Ives, M.C., Hale, T., Wetzer, T., Mealy, P., Rafaty, R., Srivastav, S., Way, R., 2019. Sensitive intervention points in the post-carbon transition. Science 364 (6436), 132–134.
Geels, F.W., 2010. Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective. Res. Policy 39 (4), 495–510.
Geels, F.W., 2019. Socio-technical transitions to sustainability: a review of criticisms and elaborations of the multi-level perspective. Curr. Opin. Environ. Sustain. 39, 187–201.
Geels, F.W., 2020. Micro-foundations of the multi-level perspective on socio-technical transitions: developing a multi-dimensional model of agency through crossovers between social constructivism, evolutionary economics and neo-institutional theory. Technol. Forecast. Soc. Chang. 152, 119894.
Geels, F.W., 2022. Causality and explanation in socio-technical transitions research: Mobilising epistemological insights from the wider social sciences. Res. Policy 51 (6), 104537.
Geels, F.W., Turnheim, B., 2022. The Great Reconfiguration: A Socio-technical Analysis of Low-carbon Transitions in UK Electricity, Heat, And Mobility Systems. Cambridge University Press, Cambridge.
Geels, F.W., Verhees, B., 2011. Cultural legitimacy and framing struggles in innovation journeys: a cultural-performative perspective and a case study of Dutch nuclear energy (1945–1986). Technol. Forecast. Soc. Chang. 78 (6), 910–930.
Geels, F.W., Kern, F., Fuchs, G., Hinderer, N., Kungl, G., Mylan, J., Neukirch, M., 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). Res. Policy 45 (4), 896–913.
George, A.L., Bennett, A., 2004. Case Studies And Theory Development in the Social Sciences. The MIT Press, Cambridge Mass.
Greve, H.R., 2003. Investment and the behavioral theory of the firm: evidence from shipbuilding. Ind. Corp. Chang. 12 (5), 1051–1076.
Gunderson, L.H., 2000. Ecological resilience: in theory and application. Annu. Rev. Ecol. Syst. 31 (1), 425–439.
GWEC, 2021. Global Offshore Wind Report. Global Wind Energy Council, Brussels.
Hall, P.A., 1993. Policy paradigms, social learning and the state: the case of economic policy making in Britain. Comp. Polit. 25 (3), 275–296.
Hall, S., Foxon, T.J., Bolton, R., 2017. Investing in low-carbon transitions: energy finance as an adaptive market. Clim. Pol. 17 (3), 280–298.
Harding, R., 2022. Electric vehicles accelerate China's looming dominance as a car exporter. In: Financial Times, 2 June 2022.
Heptonstall, P., Gross, R., Greenacre, P., Cockerill, T., 2012. The cost of offshore wind: understanding the past and projecting the future. Energy Policy 41, 815–821.
Howlett, M., Ramesh, M., Perl, A., 2009. Studying Public Policy: Policy Cycles And Policy Subsystems. Oxford University Press, Canada.
Howlett, M., McConnell, A., Perl, A., 2017. Moving policy theory forward: connecting multiple stream and advocacy coalition frameworks to policy cycle models of analysis. Aust. J. Public Adm. 76 (1), 65–79.
Hughes, T.P., 1994. Technological momentum. In: Smith, M.R., Marx, L. (Eds.), Does Technology Drive History? The Dilemma of Technological Determinism. The MIT Press, Cambridge, Mass., pp. 101–113
IEA, 2022. Global EV Outlook 2022: Securing Supplies for an Electric Future. International Energy Agency, Paris.
IRENA, 2021. Renewable Power Generation Costs in 2020. International Renewable Energy Agency, Abu Dhabi.
Jolly, J., 2020. Toyota will not invest in electric cars in UK until after 2027. In: The Guardian, 7 December 2020.
Jolly, J., 2021. Car industry lobbied UK government to delay ban on petrol and diesel cars. In: The Guardian, 15 March 2021.
Jolly, J., 2022. Huge UK electric car battery factory on 'life support' to cut costs. In: The Guardian, 12 August 2022.
Kern, F., Smith, A., Shaw, C., Raven, R., Verhees, B., 2014. From laggard to leader: explaining offshore wind developments in the UK. Energy Policy 69, 635–646.
Kern, F., Rogge, K., Howlett, M., 2019. Policy mixes for sustainability transitions: new approaches and insights through bridging innovation and policy studies. Res. Policy 48 (10), 103832.
Klitkou, A., Bolwig, S., Hansen, T., Wessberg, N., 2015. The role of lock-in mechanisms in transition processes: the case of energy for road transport. Environ. Innov. Soc. Trans. 16, 22–37.
Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemaade, F., Avelino, F., Bergek, A., Boons, F., et al., 2019. An agenda for sustainability transitions research: state of the art and future directions. Environ. Innov. Soc. Trans. 31, 1–32.
Kolb, D.A., 1984. Experiential Learning: Experience as the Source of Learning And Development. Prentice-Hall, Englewood Cliffs.

Lam, A., Mercure, J.-F., 2022. Evidence for a global electric vehicle tipping point. Working paper series number 2022/01, Global Systems Institute, University of Exeter. https://www.exeter.ac.uk/research/gsi/research/workingpaperseries/.
Latour, B., 1992. Where are the missing masses? The sociology of a few mundane artefacts. In: Bijker, W.E., Law, J. (Eds.), Shaping Technology/Building Society. MIT Press, London, pp. 225–258.
Laville, S., 2019. Carmakers among key opponents of climate action. In: The Guardian, 10 Oct 2019.
Lenton, T.M., 2020. Tipping positive change. Philos. Trans. R. Soc. B 375 (1794), 20190123, 1-8.
Lenton, T.M., Held, H., Kriegler, E., Hall, J., Lucht, W., Rahmstorf, S., Schellnhuber, H.J., 2008. Tipping elements in the earth's climate system. Proc. Natl Acad. Sci. USA 105 (6), 1786–1793.
Lenton, T.M., Benson, S., Smith, T., Ewer, T., Lanel, V., Petykowski, E., Powell, T.W.R., Abrams, J.F., Blomsma, F., Sharpe, S., 2022. Operationalising positive tipping points towards global sustainability. Glob. Sustain. 5, e1.
Leventon, J., Abson, D.J., Lang, D.J., 2021. Leverage points for sustainability transformations: nine guiding questions for sustainability science and practice. Sustain. Sci. 16 (3), 721–726.
Lie, M., Sørensen, K.H. (Eds.), 1996. Making Technology our Own: Domesticating Technology Into Everyday Life. Scandinavian University Press, Oslo.
Lindberg, M.B., Kammermann, L., 2021. Advocacy coalitions in the acceleration phase of the European energy transition. Environ. Innov. Soc. Trans. 40, 262–282.
Lockwood, M., 2022. Policy feedback and institutional context in energy transitions. Policy Sci. 55, 487–507.
Lounsbury, M., Glynn, M.A., 2001. Cultural entrepreneurship: stories, legitimacy, and the acquisition of resources. Strateg. Manag. J. 22 (6–7), 545–564.
MacKinnon, D., Karlsen, A., Dawley, S., Steen, M., Afewerki, S., Kenzhegaliyeva, A., 2022. Legitimation, institutions and regional path creation: a cross-national study of offshore wind. Reg. Stud. 56 (4), 644–655.
Mahoney, J., 2000. Path dependence in historical sociology. Theory Soc. 29 (4), 507–548.
Meckling, J., 2019. Governing renewables: policy feedback in a global energy transition. Eviron. Plann. C. Gov. Policy 37 (2), 317–338.
Meckling, J., Kelsey, N., Biber, E., Zysman, J., 2015. Winning coalitions for climate policy. Science 349 (6253), 1170–1171.
Mercure, J.-F., Sharpe, S., Vinuales, J.E., Ives, M., Grubb, M., Lam, A., Drummond, P., Pollitt, H., Knobloch, F., Nijsse, F.J.M.M., 2021. Risk-opportunity analysis for transformative policy design and appraisal. Glob. Environ. Chang. 70, 102359.
Milkoreit, M., 2023. Social tipping points everywhere? Patterns and risks of overuse. WIREs Clim. Change 14 (2), e813.
Milkoreit, M., Hodbod, J., Baggio, J., Benessaiah, K., Calderon-Contreras, R., Donges, J. F., Mathias, J.-D., Rocha, J.C., Schoon, M., Werners, S.E., 2018. Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review. Environ. Res. Lett. 13 (3), 033005.
Morton, G., Anable, J., Nelson, J.D., 2017. Consumer structure in the emerging market for electric vehicles: identifying market segments using cluster analysis. Int. J. Sustain. Transp. 11 (6), 443–459.
Nehls, G., 2021. GE Renewable Energy to open new offshore wind blade manufacturing plant. Press release, March 10, 2021. https://www.ge.com/news/press-releases/ge-renewable-energy-plans-open-new-offshore-wind-blade-manufacturing-plant-teesside-uk.
Newig, J., 2004. Public attention, political action: the example of environmental regulation. Ration. Soc. 16 (2), 149–190.
Nissan, 2009. Annual Report 2009: Nissan, Enriching People's Lives. Nissan, https://www.annualreports.com/HostedData/AnnualReportArchive/n/OTC_NSANY_2009.pdf. https://www.annualreports.com/HostedData/AnnualReportArchive/n/OTC_NSANY_2009.pdf.
Noonan, M., Smart, G., 2017. The Economic Value of Offshore Wind Benefits to the UK of Supporting the Industry. Report From the Offshore Renewable Energy Catapult. London.
Nyborg, K., Anderies, J.M., Dannenberg, A., Lindahl, T., Schill, C., Schlüter, M., Adger, W.N., Arrow, K.J., Barrett, S., Carpenter, S., Chapin III, F.S., Crépin, A.-S., Daily, G., Ehrlich, P., Folke, C., Jager, W., Kautsky, N., Levin, S.A., Madsen, O.J., Polasky, S., Scheffer, M., Walker, B., Weber, E.U., Wilen, J., Xepapadeas, A., De Zeeuw, A., 2016. Social norms as solutions. Science 354 (6308), 42–43.
Nykvist, B., Sprei, F., Nilsson, M., 2019. Assessing the progress toward lower priced long range battery electric vehicles. Energy Policy 124, 144–155.
O'Neill, S.Z., 2022. BMW to axe UK production of electric Mini and relocate to China. In: Financial Times, 15 October 2022.
Otto, I.M., Donges, J.F., Cremades, R., Bhowmik, A., Hewitt, R.J., Lucht, W., Rockström, J., Allerberger, F., McCaffrey, M., Doe, S.S.P., Lenferna, A., Morán, N., Van Vuuren, D.P., Schellnhuber, H.J., 2020. Social tipping points for stabilizing Earth's climate by 2050. Proc. Natl Acad. Sci. USA 117 (5), 2354–2365.
Penna, C.C.R., 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. Res. Policy 44 (5), 1029–1048.
PFI, 2022. Project Finance International Yearbook 2022. https://edition.pagesuite-professional.co.uk/html5/reader/production/default.aspx?pubname=&edid=c3bdaaba-d89f-496a-ae40-a178495132e4.
Pinkse, J., Groot, K., 2015. Sustainable entrepreneurship and corporate political activity: overcoming market barriers in the clean energy sector. Entrep. Theory Pract. 39 (3), 633–654.
Poole, M.S., Van de Ven, A.H., Dooley, K., Holmes, M.E., 2000. Organizational Change And Innovation Processes: Theory And Methods for Research. Oxford University Press, New York.
RMI, 2022. Peaking: A Theory of Rapid Transition: How Patterns of Peak, Plateau, And Decline Point to Fossil Fuels' Accelerating End. Rocky Mountains Institute, Colorado.
Roberts, C., Geels, F.W., 2018. Public storylines in the British transition from rail to road transport (1896–2000): discursive struggles in the multi-level perspective. Sci. Cult. 27 (4), 513–542.
Roberts, C., Geels, F.W., 2019. Conditions for politically accelerated transitions: historical institutionalism, the multi-level perspective, and two historical case studies in transport and agriculture. Technol. Forecast. Soc. Chang. 140, 221–240.
Roberts, C., Geels, F.W., Lockwood, M., Newell, P., Schmitz, H., Turnheim, B., Jordan, A., 2018. The politics of accelerating low-carbon transitions: towards a new research agenda. Energy Res. Soc. Sci. 44, 304–311.
Rogers, E., 1996. The Diffusion of Innovations, Fifth edition. Free Press, New York.
Scheffer, M., Carpenter, S.R., Lenton, T.M., Bascompte, J., Brock, W., Dakos, V., Van de Koppel, J., Van de Leemput, I.A., Levin, S.A., Van Nes, E.H., Pascual, M., Vandermeer, J., 2012. Anticipating critical transitions. Science 338 (6105), 344–348.
Schellnhuber, H.J., 2009. Tipping elements in the Earth system. Proc. Natl Acad. Sci. USA 106 (49), 20561–20563.
Schmidt, T.S., Sewerin, S., 2017. Technology as a driver of climate and energy politics. Nat. Energy 2, 17084.
Schmidt, V.A., 2008. Discursive institutionalism: the explanatory power of ideas and discourse. Annu. Rev. Polit. Sci. 11 (1), 303–326.
Schot, J.W., Geels, F.W., 2008. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda and policy. Tech. Anal. Strat. Manag. 20 (5), 537–554.
Seto, K.C., Davis, S.J., Mitchell, R.B., Stokes, E.C., Unruh, G., Urge-Vorsatz, D., 2016. Carbon lock-in: types, causes, and policy implications. Annu. Rev. Environ. Resour. 41, 425–452.
Sharpe, S., Lenton, T.M., 2021. Upward-scaling tipping cascades to meet climate goals: plausible grounds for hope. Clim. Pol. 21 (4), 421–433.
Skeete, J.-P., 2019. Concentration of power: a UK case study examining the dominance of incumbent automakers and suppliers in automotive sociotechnical transitions. Glob. Trans. 1, 93–103.
Smith, A., Raven, R., 2012. What is protective space? Reconsidering niches in transitions to sustainability. Res. Policy 41 (6), 1025–1036.
Smith, S.R., Christie, I., Willis, R., 2020. Social tipping intervention strategies for rapid decarbonization need to consider how change happens. Proc. Natl Acad. Sci. USA 117 (20), 10629–10630.
SMMT, 2022. Plugging the Gap. Society of Motor Manufacturers and Traders, London.
Sovacool, B.K., Enevoldsen, P., Koch, C., Barthelmie, R.J., 2017. Cost performance and risk in the construction of offshore and onshore wind farms. Wind Energy 20 (5), 891–908.
Stadelmann-Steffen, I., Eder, C., Harring, N., Spilker, G., Katsanidou, A., 2021. A framework for social tipping in climate change mitigation: what we can learn about social tipping dynamics from the chlorofluorocarbons phase-out. Energy Res. Soc. Sci. 82, 102307.
Strauch, Y., 2020. Beyond the low-carbon niche: global tipping points in the rise of wind, solar, and electric vehicles to regime scale systems. Energy Res. Soc. Sci. 62, 101364.
Tàbara, J.D., Frantzeskaki, N., Hölscher, K., Pedde, S., Kok, K., Lamperti, F., Christensen, J.H., Jäger, J., Berry, P., 2018. Positive tipping points in a rapidly warming world. Curr. Opin. Environ. Sustain. 31, 120–129.
Thomas, J.B., Clark, S.M., Gioia, D.A., 1993. Strategic sensemaking and organizational performance: linkages among scanning, interpretation, action, and outcomes. Acad. Manag. J. 36, 239–270.
Turnheim, B., 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.
Valdez, A.M., Potter, S., Cook, M., 2019. The imagined electric vehicle user: insights from pioneering and prospective buyers in Milton Keynes, United Kingdom. Transp. Res. D 71, 85–95.
Way, R., Ives, M.C., Mealy, P., Farmer, J.D., 2022. Empirically grounded technology forecasts and the energy transition. Joule 6 (9), 2057–2082.
Wind Europe, 2020. Financing And Investment Trends: The European Wind Industry in 2020. Brussels.
Winkelmann, R., Donges, J., Smith, E.K., Milkoreit, M., Eder, C., Heitzig, J., Katsanidou, A., Wiedermann, M., Wunderling, N., Lenton, T.M., 2022. Social tipping processes towards climate action: a conceptual framework. Ecol. Econ. 192, 107242.
Zhang, M., Atwal, G., Kaiser, M., 2021. Corporate social irresponsibility and stakeholder ecosystems: the case of Volkswagen Dieselgate scandal. Strateg. Chang. 30 (1), 79–85.
Zhang, X., Bai, X., Zhong, H., 2018. Electric vehicle adoption in license-plate controlled big cities. J. Clean. Prod. 202, 191–196.

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