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# Anticipating socio-technical tipping points

Franziska Mey [a,*], Diana Mangalagiu [b], Johan Lilliestam [c]

[a] Research Institute for Sustainability (RIFS) Helmholtz Centre Potsdam, Germany
[b] NEOMA Business School, France
[c] Sustainability Transition Policy Group, Friedrich-Alexander University Erlangen-Nürnberg, Germany

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ABSTRACT

The tipping point concept, widely recognized within the natural sciences, is experiencing a resurgence in social studies. The emerging field sees growing insights about characteristics and mechanisms of social system tipping; however, much disagreement remains. This includes whether social tipping points can be anticipated – determining its political relevance, as anticipation is essential for actions to intentionally trigger tipping. We address this disagreement and propose a framework which operationalises socio-technical tipping across subsystems and elements to anticipate tipping points, illustrated in two case comparisons. We show that whereas the transition to electric cars in Germany has started but is not about to tip, especially not regarding normative and regulatory regime factors, the same transition in Norway is about to tip, but still requires international car markets to tip before the sectoral transition is tipped and complete. Similarly, we show that the transition to a PV-based renewable power system in Germany has progressed strongly, both regarding technology and regime factors, but the system has not yet tipped: further efforts reforming infrastructure and regulation are essential. Hence, our findings emphasise the notion that while technological progress holds significance, it represents only one facet among several that must align for a system to undergo a tipping point.

## 1. Introduction

As global climate targets tighten, radical and disruptive changes become inevitable to accelerate fundamental societal transformation. In this context, the concept of social tipping points (STPs) receives growing attention, based on the notion of non-linear change, in which a small change may suddenly trigger a rapid systemic transformation (Milkoreit et al., 2018).

The concept of tipping points is used in several scientific disciplines, prominently in climate science (Lenton et al., 2019; Rockström et al., 2009; Schellnhuber, 2010). There, it describes the alteration of positive feedbacks within the climate system which enter new self-perpetuating states, possibly triggered by relatively small temperature increases (McKay et al., 2022). Consequences such as substantial sea level rise from collapsing ice sheets, dieback of biodiverse biomes such as the Amazon rainforest or warm-water corals, and carbon release from thawing permafrost are today strong concerns in both science and policy (Flores et al., 2024; Klose et al., 2024).

The tipping point concept has found resonance in social sciences, where a growing body of literature investigates social tipping points as means to expedite the transition to zero-carbon futures (Farmer et al., 2019; Geels and Ayoub, 2023; van Ginkel et al., 2020; Otto et al., 2020; Stadelmann-Steffen et al., 2021; Tàbara et al., 2018). In a concerted effort, researchers from both natural and social science have defined tipping points as “occurring when change in part of a system becomes self-perpetuating beyond a threshold, leading to substantial, widespread, frequently abrupt and often irreversible impact” (Lenton et al., 2023, p. 41). However, the view of tipping points in Earth systems being negative, triggering change into a worse system state than before, stands in contrast to the oftentimes *positive* tipping points *in technology, economy and society*. The latter is a relatively new concept focussed on the opportunities of change. Through coordinated strategic interventions *desirable changes* for climate change mitigation and a more sustainable trajectory are instigated legitimising the fundamental transformations required across all areas of life (Stadelmann-Steffen et al., 2021; Tàbara et al., 2021). Indeed, social-technical tipping points which manifest in the coupling of social and technological elements can be observed in the past, for example the transition from horses to cars in the global north, or introduction of the internet which had a profound and visible impact on the way we communicate, commerce and share information globally.

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* Corresponding author.
*E-mail address:* franziska.mey@rifs-potsdam.de (F. Mey).

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However, to effectively trigger social-technical tipping points, it is essential to understand how to anticipate such transformative changes.

Disagreement remains, and further research is needed to determine whether social tipping processes can be anticipated and thus intentionally induced (van Ginkel et al., 2020; Moser and Dilling, 2009; Tàbara et al., 2018; Winkelmann et al., 2020). Indeed, much hope is associated with the presence of human agency and particularly strategic policy interventions to create the enabling conditions to trigger positive social tipping in the context of climate change mitigation (Eder and Stadelmann-Steffen, 2023; Fesenfeld et al., 2022). Milkoreit (2022) and others warn to overrate the element of intentionality, because of the complexity and non-deterministic nature of social systems, so that social tipping points may only be observed ex post, but not ex ante. Other researchers suggest that although we cannot experience the future before it happens (Nuttall, 2012), we can sense something about the proximity of a system to a tipping point by observing reinforcing feedback loops and what controls them (Lenton et al., 2022). Since anticipation orients human action (Nuttall, 2012), it is possible to "appraise specific conditions and capacities" of a system which can lead to transformative change (Tàbara et al. 2018, p. 126).

We build on these arguments and propose that socio-technical tipping dynamics, and hence tipping points, can be identified not only ex post, but also ex ante – which is a prerequisite for the tipping point concept to be useful for policymaking. By observing changes in the sociotechnical system elements, we can meaningfully gauge progress towards tipping and anticipate socio-technical tipping points with sufficient precision to support near-term policymaking. To illustrate the feasibility of the proposed approach, we analyse two cases of socio-technical transitions at different stages and in different contexts: adoption of electric vehicles and solar PV.

## 2. Theoretical background

### 2.1. Elements of socio-technical transitions for positive tipping

Rapid transformations in sectoral systems such as energy and transport are crucial to accelerate decarbonisation (IPCC, 2022). These sectoral systems have been conceptualised as socio-technical systems and investigated in the field of sustainability transition studies (Geels, 2002, 2004; Köhler et al., 2019; Loorbach et al., 2017; Markard et al., 2020b; Van Den Bergh et al., 2011). A socio-technical transition is a complex and non-linear process, encompassing the realignment of elements of different types (e.g. technology and public norm) and at different spatial and organisational (e.g. local to global) and temporal scales (years to centuries), from one setting ideally tailored to a specific set of practices and technologies to another setting, tailed to fit entirely other practices and technologies (Fuenfschilling and Truffer, 2014; Markard et al., 2012).

These transition processes have been intensively studied through the lens of multi-level perspective (MLP) (Geels, 2004, 2005, 2011; Verbong and Geels, 2007), which discerns three main levels: the niche, where radical technical innovations develop; the regime, which represents the dominant practices and rules in a system; and the landscape, encompassing broader, external socio-economic and environmental factors. Transitions occur when pressures at the landscape level destabilize the regime, allowing niche innovations to break through and drive systemic change. Building on these theoretical considerations, we distinguish three overarching elements for our analysis: the technology (advanced from the niche level), material, and immaterial system elements (advanced from the regime level) which are further elaborated in Section 3, Fig. 1 and Table 1. We do not consider the landscape element, as it describes the broader exogenous setting and requires the niche and regime level to transition before.

The challenges to transition a socio-technical system to another requires changes in all elements (Geels, 2007) while overcoming the rigidity of already existing firmly institutionalised structures (Fuenfschilling and Truffer, 2014). While technological innovation can appear as a low-hanging fruit, changes in the regime elements – necessary for a transition to new technologies – are much harder to achieve as they require shifts in norms, rules and taken-for-granted assumptions or cultural beliefs. Indeed, institutional contexts influence (individual and collective) actors' cognition and values, ultimately constituting constraining or enabling conditions for change (DiMaggio and Powell, 1983; Meyer and Rowan, 1977; Powell and DiMaggio, 1991; Scott, 2014, 2005). Sticky institutional structures entrenched in path dependence can be disrupted by windows of opportunities enabling e.g. radical niche innovations or policy change (Köhler et al., 2019; Lenton et al., 2023).

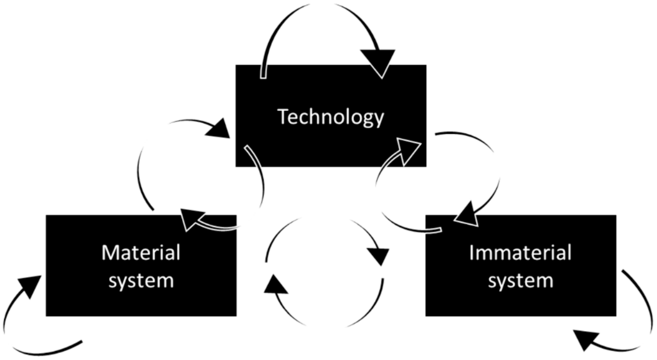

**Fig. 1.** State and change within and across system elements.

In both theoretical and empirical studies, researchers highlight that co-evolution and alignment of social and technical system elements typically result in incremental change: systems are not fixed, but internal feedback mechanism make them resist radical change. Yet, precisely such radical change – and fast, radical change at that – in socio-technical systems is required to transform the energy system to a net-zero state compatible with the Paris Agreement (Markard et al., 2020b). Such radical change has been conceptualised as positive tipping points whose impacts are predominantly beneficial by either reducing drivers of climate change (e.g. lowering GHG through shift to renewable energy) (Lenton et al., 2022; Meldrum et al., 2023) or/ and improving societal coexistence and well-being (e.g. different justice tenets) (Gupta et al., 2023; Rockström et al., 2023).

### 2.2. Identifying social-technical tipping points

The Global Tipping Point report decribes a socio-technical tipping point specifically arising because of the coupling of social and technical elements promoting the breakthrough of sustainability technologies and practices (Lenton et al., 2023). This aligns with the understanding of transformative change in transition studies which happens when all elements align, and the system has changed in a way that perfectly supports the functioning of a new technology that has matured and moved out of its niche to become dominant in the new system (Geels 2005).

However, researchers emphasise the challenges observing tipping in the complexity of social systems (Milkoreit, 2022; Nuttall, 2012; Winkelmann et al., 2020). They particularly highlight the process character of social tipping: transformative change is not indicated by one single indicator or point, rather than a dynamics across three phases of enabling, accelerating, and stabilising (Sharpe and Lenton, 2021; Stadelmann-Steffen et al., 2021).

A distinguishing characteristic in positive tipping dynamics is the human factor, and the abilities of individual and organised collective actors to intervene in a systems trajectory to enable desired change (Milkoreit, 2022; Winkelmann et al., 2020). This aligns with the socio-technical transitions perspective in which political action and policy making are considered decisive in shaping transition outcomes and pace (Kern and Rogge, 2016; Sovacool, 2016). Yet, Roberts and Geels (2019)

**Table 1**
Operationalisation of system elements to anticipate socio-technical tipping points.

| System elements | Specification | Analytical questions identifying positive feedback loop of state/ change of the element |
|---|---|---|
| Technology | | |
| Performance | The performance and maturity of a technological innovation, as a function of its own development (technological learning); also relative to incumbent technologies | What does it cost, also compared to competitors (absolute, trend)?<br>Is it more or equally *good* (e.g., reliable, efficient, easy to operate) as competing technology/ies?<br>Who experiences the improvement/deterioration of useability of the New?<br>Can the New live outside a policy niche, or does it require support? |
| Importance | The importance of a new technology; also relative to incumbent technologies | What is the market share of the New, relative to the Old (absolute, trend)?<br>What is the share of the New in new investment, deployment (absolute, trend)? |
| Immaterial | | |
| Policies & Regulations | The regulatory setting and its alignment for the New and/or against the Old | Have/are policies and/or regulations (e.g., market design; permission & licensing processes, incentive schemes) shifted/shifting to be supportive of the New? Does this make them less supportive of the Old? |
| Politics and agency | The influence and composition of political coalitions<br>Position and political norms and power/ preferences<br>Political acceptance | Who are the actors supporting the New and supporting the Old?<br>Influence of pro-New/pro-Old coalition? Formal power, incl. Government position? |
| Norms & Preferences | What is seen as appropriate and "right"<br>Market/ consumer perspective/ acceptance | Is the new technology (dominantly) seen as a problem or a solution, as appropriate or difficult?<br>What is the perception of "unsolved problems" of the New?<br>Who sees the new technology as a solution or problem?<br>Which shares of groups are relevant/ decisive? |
| Material | | |
| Infrastructure | The physical system supporting a technology | Are there perceived mismatches between existing infrastructure and the needs of the New?<br>Is the infrastructure changing to support the New? Are such changes detrimental to the Old? |
| Supply chain capacity | The companies active in the supply chain of a technology, their interests, capability and capacity | Does the New need a new industry base (e.g., component manufacturing, construction or operation) and is it emerging?<br>Does the industry for the New rely on the incumbent actors, or on new actors?<br>Can the industry for the New survive without continuous policy support? |

draw attention to the fact that policymakers are also bound by the broader political, economic, and societal contexts and timing (policies in earlier periods and their effects on technologies, business development, and public opinions) which influence their willingness to lead decisively. System change is determined by initial conditions, developments, and interactions among individual system elements such as technology price, industry performance and costumer behaviour creating push or pull factors (pressures and opportunities) for accelerating the diffusion of technologies. As change occurs across a range of elements and scales, spill-over effects are triggered, and initiate positive feedbacks of increasingly rapid sequential change processes and eventually a systemic shift.

Sectoral tipping points to new socio-technical trajectories appear easier to empirically validate than fundamental shifts in societal norms and behaviour (Geels and Ayoub, 2023). Indeed, indicators of technology breakthroughs (e.g. market adaption and penetration) can be already observed in different sectors (Meldrum et al., 2023). For example, in the electricity sector, renewable power sources of wind and solar stand for a remarkable success story. In 2010, solar PV was seven times more expensive and wind power twice as expensive as the cheapest fossil fuel-fired solution. In 2022, wind costs 29 % and solar 52 % less than the cheapest fossil fuel-fired solution in 2022 (IRENA 2024). Hence, Meldrum et al. (2023) find that significant elements in this socio-technical system have tipped (new wind/solar < new coal/gas), while others elements (e.g. network infrastructure) impend change (Meldrum et al., 2023). In other words, the socio-technical system of reference – the electricity system – has not yet tipped, and one must be clear when announcing such thresholds. Nonetheless, the interdependence across system elements may increase the tipping speed even more when closer to the tipping point, since feedbacks reinforce each other with increasing strength (Mey et al., 2024; Schmidt and Sewerin, 2017).

### 2.3. Anticipating tipping points

Whether social or sociotechnical tipping points can be anticipated is a hotly debated topic in the tipping community. A dominant view is that they cannot, and that "anyone claiming to know for sure when a particular tipping point will be reached should be treated with suspicion" (Nature, 2006), but there have been several approaches to address this issue. We identify three major strands in the literature. The first builds on natural system theories and the notion of "early warning signals" associated with the theory of "critical slowing down" indicating a system's loss of resilience, increasing stress and movements towards a tipping point. The hypothesis is that tipping points here are "not always unpredictable", instead could be detected using temporal, spatial, network methods and modelling techniques (Boulton et al., in Lenton et al., 2023, p.156). For example (Boers and Rypdal, 2021) detected positive melt-elevation feedbacks in Central Western Greenland ice cores, suggesting that this part of the ice sheet might be close to a tipping point.

The second strand refers to the early detection of natural tipping points applied in coupled socio-ecological contexts, suggesting that Earth system tipping points having impacts on socio-economic system conditions. For example (Fernández-Giménez et al., 2017) identify ecological and cultural tipping points in Mongolian pastoral social-ecological systems with feedbacks across land use conversion, loss of mobile pastoralism and livelihoods, rural migration and loss of pastoral culture leading to more land use conversion. Similarly, (Krishnamurthy et al., 2022) shows early warning signals for impending food crisis through Earth satellite observations of soil moisture. Here, authors stress that the human factor appears as the unpredictable element but also the enabling force for instigating interventions for tipping (Winkelmann et al., 2022, 2020).

A third strand of literature focuses (exclusively) on social contexts (political, economic, technological systems). This includes collective social dynamic concepts such as contagion and critical mass approaches, showing how the spreading of an action, behaviour or norm through a complex network may foster or hinder social tipping (Bentley et al., 2014; Ehret et al., 2022; Otto et al., 2020). For example, Andreoni, Nikiforakis, and Siegenthaler (2021), Centola (2010) and Centola et al. (2018) use prediction models to show social change triggered by critical group size. Within this strand, the socio-technical perspective focuses on the interaction between technology and social system elements highlighting the importance of actor interventions (Geels and Ayoub, 2023).

### *2.4. Positive feedbacks as transition drivers*

A determining mechanism for detecting tipping dynamics across natural and social science perspectives are system feedback processes. Sharpe and Lenton (2021) and Lenton et al. (2022) suggest that something can be said about the proximity of a system to a tipping point looking for reinforcing feedback loops and the factors that control them. As in natural systems, the determining mechanism in social tipping processes is ***positive feedback*** (Lenton et al., 2022). This is understood as self-reinforcing dynamic that drives change (Jones and Baumgartner, 2012). In Meadows (1999, p. 11)'s words: "the more it works, the more it gains power to work some more". This mechanism follows the notion that technological innovations, niche activities or minority groups can instigate self-amplifying responses towards wider deployment, diffusion, and public adoption (Pierson, 2004, 2000, 1993). The antagonist mechanism constitutes ***negative feedback,*** describing dampening processes in which "a disturbance is met with countervailing actions" to maintain the status quo (Jones and Baumgartner, 2012). Or in Meadows' (1999) words, "to keep the 'room temperature' fairly constant at a desired level". However, feedback loops usually cannot be observed directly but can instead be inferred from observing system variables and comparing them at two different points in time or in different contexts (Savaget et al., 2019).

As an example, Geels and Ayoub (2023) have identified specific feedback loops between techno-economic developments and core actor groups in the shift from small market niches to mass deployment. They demonstrated a particular sequence of these feedbacks in two cases – offshore wind in UK and electric vehicles (EVs) in UK and globally – and concluded that the deployment tipping point for the latter occurred 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.

However, the question of whether these dynamics can be anticipated ex ante or only observed ex post remains unresolved (Grimm and Schneider, 2011; Lenton et al., 2022; Tàbara et al., 2021; Fuchs and Thaler, 2017). Yet, the urgency to understand when, how and by whom positive tipping points may be reached, has increased in the context of contentious climate governance (Milkoreit et al. and Smith et al. in (Lenton et al., 2023)). Indeed, authors call for more research on the timing and sequencing of tipping point dynamics (Geels and Ayoub, 2023), as well as for reliable information and frameworks to assess the potential for, and proximity of, positive tipping opportunities (Smith et al. in Lenton et al., 2023). We aim to address these gaps in the following and contribute to the progression of the academic discourse on positive tipping.

### *2.5. Theoretical propositions*

In this paper, we make one central theoretical proposition: we propose that whereas the tipping point for an entire socio-technical system is difficult or possibly impossible to observe ex ante, the state and change in each single system elements can be observed. Therefore, by observing the key technological and regime elements and whether they have or are changing to become supportive of the new technology or practice, we can anticipate the socio-technical tipping point – and we can identify the system elements that have not yet tipped and still form barriers to the transition as a whole. This makes the tipping point concept politically useful: only if we can anticipate the tipping point, and only when we can identify the elements that still require change, can we design policies to trigger tipping. When all system elements have tipped and align with the needs of a new technology or practice can we consider the whole the socio-technical system as *tipped*.

In the following, for the remainder of this paper, we illustrate this theoretical proposition empirically by exploring and operationalising the to-tip system elements for the ongoing transitions to electric cars in Norway and Germany, and to the build-up of PV as a cornerstone of the transition to renewable electricity in Germany.

## 3. Methods and analytical framework

Building on these theoretical considerations, and to illustrate our theoretical proposition, we develop a conceptual framework which we apply using a comparative research design investigating two case studies during a specific period in two different contexts.

In our framework we conceptualise socio-technical systems comprising technology, material and immaterial system elements (see section 2.1. and Table 1). Changes may be observed in positive feedbacks within and between these system elements, representing a closed loop of causality amplifying changes in the system (Lenton et al., 2023). Hence, a tipping point is fuelled by these mechanisms triggering self-perpetuating change, becoming ultimately evident in the full penetration of a new technology with all elements changed into a new state. The tipping of each element represents an INUS condition: it is an ***I****nsufficient, but* ***N****ecessary part of an* ***U****nnecessary but* ***S****ufficient condition* for a system to pass a tipping point. Hence, the tipping of a single element is necessary but in itself it has no immediate effect on the transition (Lilliestam et al., 2016). The opportunity to anticipate a tipping dynamic arises in the time lag between different system elements shifting to new states. Consistent with our proposition (Section 2.5), we consider the system *tipped* and transitioned into a new, different state when all system elements have tipped and are aligned to support the new technology or practice.

We operationalise these elements in Table 1, breaking them down further into their components, and derive diagnostic questions to evaluate the state of change for each element. Some elements can be observed and measured as direct quantitative indicators, such as the cost of the new vis-a-vis the old dominant technology (Meldrum et al., 2023). For most elements, the analysis is particularly meaningful as a comparison of trends (i.e., over time) or across systems (e.g., progress in different countries).

This is the basis for our case study selection in which we specifically sought to investigate progressed transitions in developed country contexts. We selected the tipping state of the transition to PV in Germany (intertemporal comparison) and the state of the transition to EVs in Norway and Germany (cross-country comparison). Our choice was further guided by clear and explicit references in the literature to potential tipping dynamics in each of these cases (Geels and Ayoub, 2023; Sharpe and Lenton, 2021).

The **technology system element** describes the performance and importance of a new technology (the *New*), over time (trend) and compared to incumbent technologies (the *Old*). As the new technology grows, its costs likely decrease, and it becomes more efficient and reliable (Grubb et al., 2021; Nemet, 2019; Rubin et al., 2015). Such learning processes are expected, to different degrees, for all new technologies, as they are initially immature. For the *New* to grow beyond its niche and become dominant, it must not necessarily be cheaper than the *Old*, but it must be competitive: it can be either cheaper or more performant, or both, than its competitors. When the *New* is competitive, it may live outside its policy niche, although further regulatory reforms (e.g., changes in market design, tax systems) may be needed (see below). The market share (or share of new deployment) of the *New* describes its current importance, whether it is already dominant or underway to possibly become dominant.

The **material system elements** constitute the physical properties required to support the deployment, development, and operation of the new technology. The central elements are infrastructure to support continuous deployment and efficiency operation of the new technology, and the industry base to produce components and units and continuously improve the technology. Technologies require infrastructure for working optimally or for working at all: a network of paved roads significantly enhance the utility of a car. As new technologies may be fundamentally different than the *Old*, they may require entirely new or substantially adapted infrastructure (Grubler, 1990). For example, solar power can be generated near (or by) the consumers, and the generation is weather-dependent – which requires a more local and flexible power grid than the centralized and dispatchable generation of fossil power stations. For the *New* to be deployed and become dominant, a supply chain for components and assets must arise and be able to supply the required size of production. Sometimes, this can be done by building on and adapting existing supply chains (e.g. the rise of nuclear power built on knowledge and companies experienced with nuclear submarines and weapons) (Markard et al., 2020a), but sometimes entirely new supply chains and industries are required (e.g. for wind power turbines or car batteries). A new industry will continuously improve the new technology, making it cheaper and/or more efficient, particularly if the industry actors are only/mainly active within the new and less/not within the old technology. When these factors align, the operation of the system based on the new technology become efficient, and the industry becomes capable of supplying and improving the new technology.

The **immaterial system elements** provide the non-physical characteristics and human factor in a system, including norms and preferences (incl. cultural and normative aspects), politics and agency, policies and regulations (incl. institutions and governance structures) involving power struggles transitioning from the Old to the New. The central aspect is the evolution of norms and the perception of the New as appropriate or problematic. A technology seen as “better” in the broadest sense, as solving more (societal) problems than it causes, will create a self-reinforcing dynamic of increasing legitimacy (Pierson 1993; Sewerin et al., 2020; Suchman 1995) and a steady development will trigger technological learning and generate supporters who call for more action, triggering more development, and so on (Schmidt and Sewerin, 2017). This in turn affects the politics of the transition, changing the influence and composition of pro-New and pro-Old actor coalitions. Any societal change, and especially if it is disruptive, will face resistance and active opposition from a variety of actors (e.g. incumbent industry, government, civil society actors), while consumer preferences as well as social movements can play a decisive role in shaping the transition pace and outcomes. Still, the first steps of creating the new system may generate supporters for the transition. As Geels (2004) points out individual and collective actors interact within the constraints and opportunities of existing structures, while they act upon and restructure these systems. Hence depending on their level of agency and political power, this process may take longer or shorter until positive feedbacks prevail (Winkelmann et al., 2020). A successful transition sees waning political support for the Old as the New gains supporters and eventually becomes the “system”, or a “new normal”. Over time, transition policies become increasingly entrenched, possibly forming the core of a new lock-in and, as part of the “new normal”, stop being seen as transition policies at all. This, finally, is accompanied by changing regulation, adapting the rules of the game to the needs of the New and to dominance of a new technology. This may hold issues like abandoning fossil fuel subsidies, or adapting power market designs to suit intermittent, weather-dependent technologies instead of dispatchable combustion generators. It may also hold adaptations to make the new system self-sustaining, such as reforming taxes from gasoline to taxing “fuel electricity” to finance road system maintenance after the transition to EVs. When these factors align, the New becomes a politically non-disputed “new normal”. For example, today’s transport system is motor-centred, and although many advocate for reduced car dependence, no one, irrespective of political colour, advocates for the horse. One measure for transition progress is thus whether the aim and the processes are politically contested, and may flip back if the government changes, or if the supporter side is becoming or is already stronger than the opponents.

In the next section we apply this framework by analysing two ongoing empirical transition cases: EVs in Norway and Germany, and PV in Germany. We assess whether each system has tipped or is about to tip by assessing the state and trends of each of the elements (see Table 1). Our analysis is based on techno-economic and deployment quantitative data, and on secondary qualitative data from governmental and energy agencies’ documents for the immaterial aspects. We utilize a binary coding system, indicating elements that *have* (green) or *have not tipped yet* (red).

## 4. Results

### 4.1. Electric vehicle transition in Norway and Germany

While the example of the EV transition is repeatedly employed to illustrate a tipped socio-technical system, or one about to tip (Lenton et al., 2022; Sharpe and Lenton, 2021), we show that whereas the Norwegian car sector is indeed tipping, the German sector is not. This illustrates both how anticipation of tipping – and identification of still-to-tip elements – is possible, especially in cross-country-case comparison, and how the element-by-element analysis helps identify remaining barriers to full system tipping.

#### 4.1.1. Norway

Norway is leading the way in the transition to EVs, and several studies conclude that the country has already surpassed the tipping point for its EV transition (Lenton et al., 2022; Sharpe and Lenton, 2021; Strauch, 2020). This is particularly argued from a technology point of view: EVs have reached an adoption rate with (so far unmatched) 82.4 % share of new registrations (93 % in January 2024) in the market and a total of 23.9 % of the total fleet in 2023 (Norsk elbilforening, 2024) (see Table 2). In contrast to many other past transitions much of the infrastructure (e.g. roads) and many needed regulations (e.g. traffic rules) already exist.

The success of EVs is attributed to the stable and long-term political support across all parties driven by a strong public pro-environmental discourse (IEA, 2023). Since the 1990 s, socio-political and economic incentives were implemented ranging from discounted road tolls for EVS to complimentary municipal parking and permission to use bus lanes which helped to increase market and community acceptance (Noel et al., 2020). A strong lever for public legitimacy was the existing high taxation on petrol vehicles (see Table 3 – difference of about 1000 Euro to EVs), which was reduced for electric vehicles making them attractive as a second car (Table 3). In 2017, the Parliament decided that all new cars sold by 2025 should be zero-emission (electric or hydrogen), ending

**Table 2**
Electric vehicle status in Germany and Norway in 2023.

| In 2023 | Germany | Norway |
|---|---|---|
| Total fleet (all cars) in million | 48.7 | 3.5 |
| Share of EVs in total fleet | 2.08 % | 23.9 % |
| EV share in new registrations | 18.4 % | 82.4 % (93 % in Jan 2024) |
| Policy targets | 7–10 million EVs by 2030 (14.1 % – 20.6 %)<br>EU regulation bans Internal Combustion Engine cars not running on synthetic fuels by 2035 | Only EVs or hydrogen based from 2025 on |

*Source: Kraftfahrt-Bundesamt 2023, https://www.kba.de The Norwegian Public Roads Administration, The Norwegian Road Federation (OFV). Alternative Fuel Observatory 2023.*

**Table 3**

Example of Volkswagen Golf versus E-Golf model costs in Norway in 2022.

| | Volkswagen Golf | Volkswagen e-golf |
|---|---|---|
| Import price | €22,046 | €33,037 |
| CO2 tax (113 g/km) | €4348 | |
| NOx tax | €206 | |
| Weight tax | €1715 | |
| Scrapping fee | €249 | €249 |
| 25 % VAT | €5512 | |
| Retail price | €34,076 | €33,286 |

Source: Norwegian Energy Agency 2022.

petrol and diesel car sales in Norway (Norsk elbilforening, 2024).

However, some challenges remain. A study conducted in 2022 indicates an unbalanced distribution of EVs ownership that concentrates on the wealthiest (Qorbani et al., 2024). Similar to other countries the socioeconomic status of households plays a role for EV ownership (Abotalebi et al., 2019; Chen et al., 2020; Fevang et al., 2021) showing that some issues for an accelerated transition of the entire car fleet have to be addressed.

A large barrier persists with the charging infrastructure including a lack of standards (fragmented system of charging stations including apps for location and payment) and the growing electricity demand from an increasingly diversified EV driver demographic in Norway (Békés et al., 2023). Since the 1990 s, government incentives supported deployment of charging station grid with presently (July 2023) 21,600 public charging points (EAFO, 2023) across the country, corresponding to 28 vehicles per public charging point. Home charging plays a major role, as 73 % of EV owners live in single-family homes (Figenbaum and Nordbakke, 2019). A “charging right” for people living in apartment buildings was established in 2017 and the creation of network of fast charging stations progressed. The latter is particularly important as fast charging smooths the experience for consumers who do not have reliable access to private charging or face time constraints (e.g., a taxi driver between fares, a family on a long-distance trip, or a delivery person between stops), and ultimately encouraging EV adoption across wider swaths of the population (IEA, 2023). In 2023, 252 super-fast chargers (DC Level 2) and more than 6,000 DC chargers operate mainly in the urbanised regions Norway (EAFO, 2023). Moreover, the absence of a domestic car manufacturing industry and the associated jobs did not require a transition. Hence, there was no public bias towards a local car manufacturer; instead, models were introduced from available markets such as the Japan or US.

As confirmed by other studies (Geels and Ayoub, 2023; Lenton et al., 2022; Sharpe and Lenton, 2021), we find that the individual transport system, with some few aspects, mainly related to international processes

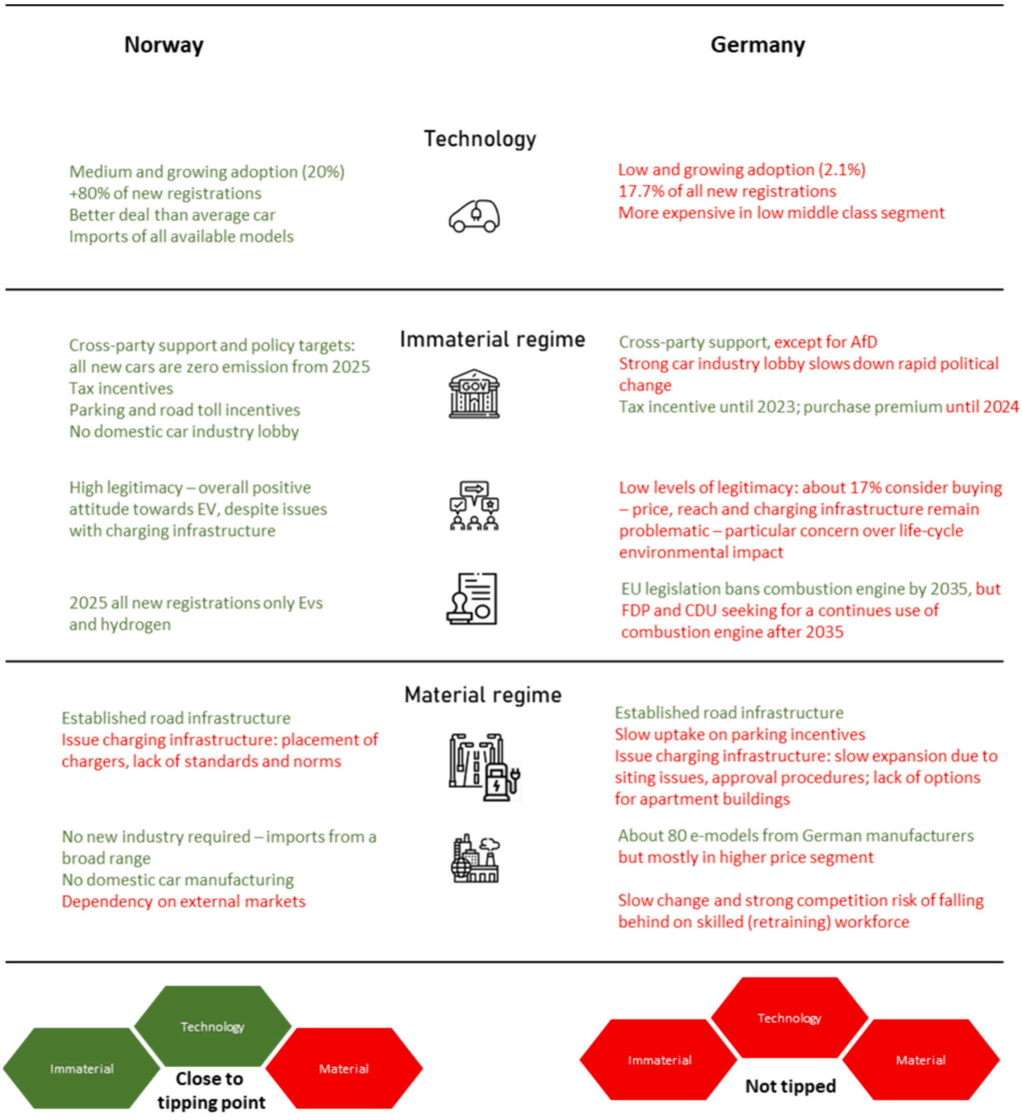

**Fig. 2.** EV system tipping status in Norway and Germany 2023.

(e.g. international charger standards), has not yet fully tipped. More specifically, we show that all system elements in Norway have entered positive feedback loops resulting in a difficult to reverse and fundamental change of the entire system. Yet, one uncertainty remains: the absence of domestic car manufacturing leaves the country dependant on EV imports and consequently progressing transition in other countries (e.g., US) to cater their local market, which may even be counteracted by Norway's oil exporting industry.

#### *4.1.2. Germany*

In Germany, the EV transition started later than in Norway, and most of its system elements have not yet entered positive feedback loops (see Fig. 2). In stark contrast to Norway, the technology adoption is much lower, with EVs only constituting a low fraction of the German car fleet (2.1 %) and slower growth with new registrations at 17.7 % in 2023 (up from 14 % in 2021) (KBA, 2023).

While similarly to Norway the technology deployment was pushed by governmental financial incentives, yet they did not trigger a similar growth. The prices of EVs are still comparatively high specifically in the lower- and middle-class segments of cars (referring the size and cost) which constitutes about half the market (KBA, 2023). Consequently, this makes EVs compared less attractive than fossil fuel cars for many Germans, especially in lower income brackets. This is quite the opposite of the situation in Norway. In the German small-car segment, for example, the purchase price of the petrol car Opel Corsa (German manufacturer) is EUR20,300, whereas the same model in the electric version costs 50 % more (Opel 2024). Despite declining costs, an average price difference of EUR4,500 still exists between petrol and electric cars in 2024 (ADAC, 2024). This also applies to the second-hand EV market, which is only slowly gaining traction in Germany (AutoScout24, 2024).

The phasing out of the government subsidy in late 2023 has further diminished cost parity and contributed to a market stagnation. Only solar homeowners have an additional cost benefit with reduced charging costs (Spiegel, 2023). But most Germans rent their homes (renters: 53.5 %, homeowners: 46.5 % (destatis, 2023)), while in Norway the home ownership share is comparatively high (80.8 % (statista, 2023)).

Furthermore, a lack of information or conflicting information about the benefits of EVs have characterized the German public debate for years (Dambeck and Nefzger, 2019; Ehlerding, 2018; Gomoll, 2021; Agora Energiewende, 2019; Kämper et al., 2020; Lang, 2021). A particular discourse over the life cycle assessment and environmental impact of battery-powered versus combustion engine cars, which places a strong focus on (potentially) negative impacts of manufacturing and material sourcing of the batteries fuelled public reluctance. The much lower levels of public resonance also stem from perceived barriers regarding battery life length and charging infrastructure availability. This scepticism reflects in public polls: in 2022 about 24 % of Germans would consider buying an electric vehicle, while in 2023 only 17 % consider it (Wolf and Fischer, 2023). Following the abrupt cessation of state subsidies in 2023, the already waning interest in electromobility decreased further (ADAC, 2024). Sceptical sentiments are also spread through the growing populist right-wing movement, framing EVs as a symbol of climate activists and the green party (Büchling et al., 2023; Prengel, 2024).

Political interventions have not been coherent either. Although the German government introduced EV support in 2009 aiming for 1 million EVs by 2020, and higher ambitions with the target of at least 15 million electric cars by 2030, the existing purchase bonus is already scaled back and was terminated in December 2023. In addition, the Government party FDP in charge of the national transport ministry has intervened in EU negotiations for ending the usage of combustion engines from 2035 Budras and Mussler, 2023; Schmutz, 2023). Concessions to the German interventions are to allow exceptions for the use of e-fuels, which means failing to prioritize EVs and respective infrastructure needs. The position of the largest opposition party CDU questioning the end of the combustion engine and contributing to the right-wing narratives over fears for the competitiveness of the Germany car industry also fuels doubts about a swift transition (Der Spiegel Online, 2024; Tagesspiegel, 2024).

Indeed, Germany is globally known for its car industry which yields political power as the most important industry branch securing approx. 2.2 million jobs (direct: 780,000; indirect: 1,42 million), accounting for around 7 % of the socially insured jobs in Germany (BMWK, 2023).. Yet, German companies were late to start manufacturing, the first generation of EVs emerging e.g. at BMW in 2013 and Volkswagen only in 2020. Both companies have targets, with BMW aiming to sell 50 % zero-emission cars by 2030 (BMW Group, 2023) and Volkswagen planning to produce only electric cars in Europe from 2033 (Volkswagen, 2023). Presently, however, German car manufacturers have concentrated mainly on producing EVs in higher price segments and only started producing more affordable models in 2023 (Lang, 2023; Tagesschau Online, 2023). In addition, workforce retraining and qualification are crucial step in the process and necessitate a substantial commitment from car manufacturers (Agora Energiewende, 2019).

In the German public discourse, the Achilles heel is the charging infrastructure. Although the pace of public charging infrastructure expansion has increased – in January 2024, there were 100,000 normal and 25,000 rapid chargers (Bundesnetzagentur 2024)) – it seems unlikely that Germany will meet the national target of one million charging stations by 2030, but likely that charger growth will not keep up with the planned growth of the EV market (15 million by 2030), or even with recent moderate growth (Bundesministerium für Digitales und Verkehr, 2022). In addition, the charging infrastructure expansion must go hand in hand with the expansion of the grid infrastructure and its digitalization. However, this remains one of the largest challenges in Germany also impairing the electricity transition.

Hence, positive feedback loops in Germany are still weak, with largest barriers being high costs and mixed political signals stemming from interventions of strong incumbent car manufacturers and a reluctant customer base. With further falling cost of batteries (a determining factor of the cost of the car) and performance improvements faster change appears possible. But the tipping point for EVs in Germany may be anticipated for only after 2035.

### *4.2. Solar PV transition in Germany*

The example of the solar PV adoption in Germany illustrates how system elements tip, one by one, through global technological progress but also national policy action, and how system-wide tipping is getting closer (Fig. 3): here, we show this by comparing the status of the transition to PV in German electricity in 2000 s and 2022. The expansion of renewable power in Germany is often referred to as a great success story with global impact (Mey et al., 2022). Indeed, the introduction of the Renewable Energy Resource Act in 2000 (RES Act; German: Erneuerbare Energien Gesetz, EEG) created a market for wind and solar in Germany (Bechberger, 2000), which led to substantial deployment that triggered very strong learning effects, and the decreasing costs made both technologies attractive also to other countries, until renewables entered a virtuous cycle of self-reinforcing market growth and global cost improvements (Jacobsson and Lauber, 2006; Kungl and Geels, 2016).

In the case of PV, policy interventions have been and continue to be a strong driver of the transition. **In 2000,** the German government introduced the RES Act which provided significant funding to trigger PV deployment. This was bolstered by high public legitimacy stemming from decades of conflict about nuclear power and growing public environmental awareness about the negative impacts of coal (Lipp, 2007; Schweizer-Ries et al., 2010; Zoellner et al., 2008). Photovoltaics had moved from a special purpose niche (satellite technology, calculators, and used by enthusiatsts, especially in the anti-nuclear movement) to become an innovative energy alternative (yet only) maintained by policy support (Rosenbaum and Mautz, 2011). The market share was 114 MW, which remains almost negligible with 0.01 % in the context of the country's total electricity generation. At this stage, the technology

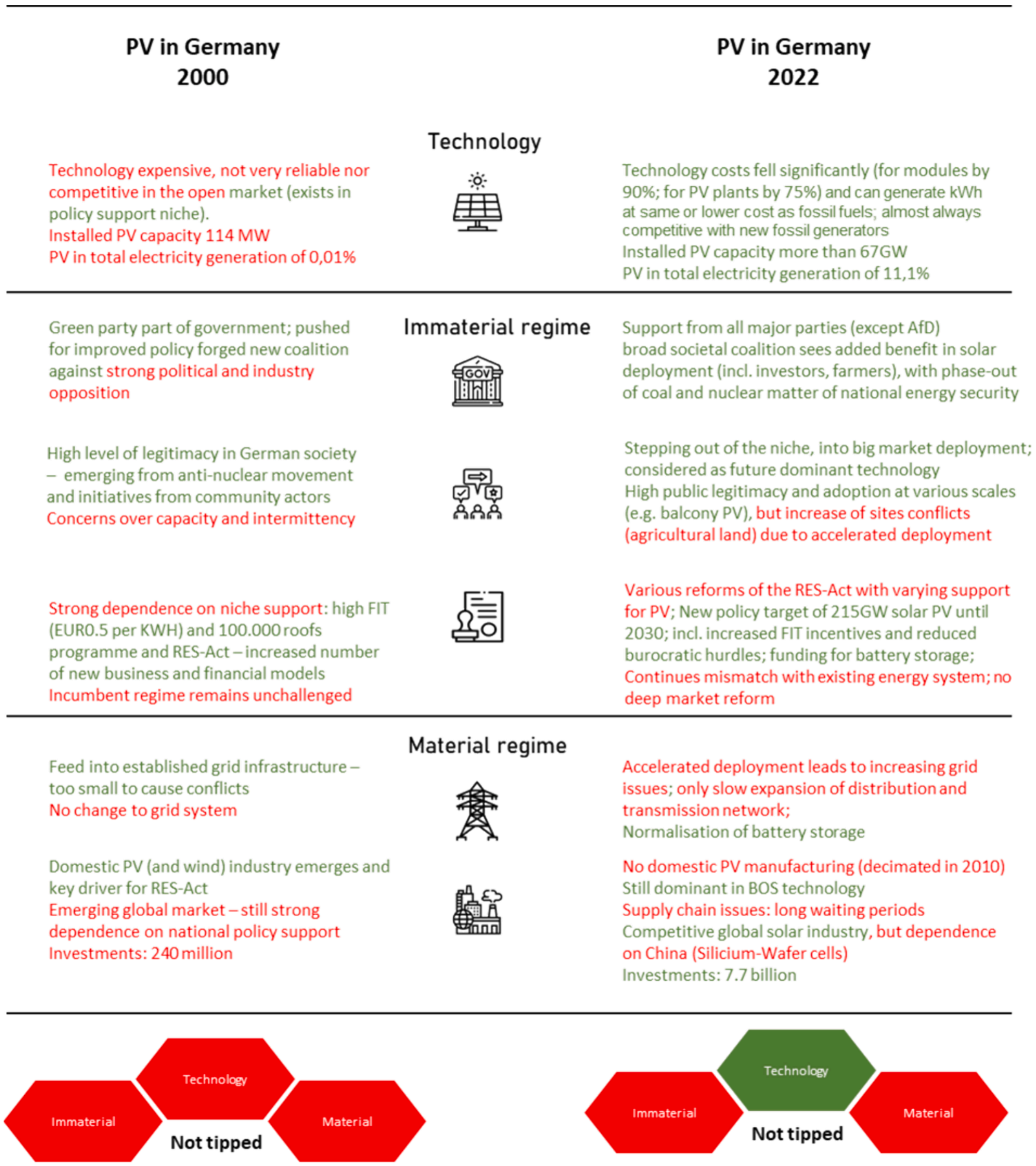

**Fig. 3.** Comparison of the status of solar PV transition Germany in 2000 and 2022.

was still very expensive (Fuchs, 2019). With the introduction of a feed-in tariff support scheme (EUR0.5 per kWh in 2000) as well as the 100,000 rooftop programm, actors outside the traditional energy industry, in particular homeowners, commerce and small- and medium-sized enterprises and farmers entered the market and established them as a new group of supporters for the technology (Jacobsson and Lauber, 2006; Lauber and Mez, 2004). This new coalition was led by the Green party and its proponent. As the Greens entered the government in 1998, they immediately sought to establish renewables as an alternative energy source to enable the phase out nuclear power – and immediately faced strong opposition from the incumbent actors, and also from parts of the Social Democrat coalition partner, with traditionally close ties to the coal industry (Geels et al., 2016; Jacobs, 2012; Kungl and Geels, 2016).

Changes in the incumbent material system were not immanent. Even the regulated priority grid access did not cause substantial disruptions with the incumbent actors since the deployment remained small compared to the system size. However, the domestic PV industry leveraged on the policy interventions and strengthened the sector's position in the market (Fuchs and Wassermann, 2008).

For the year 2000, we find that none of the system elements had changed, except for a high level of public legitimacy. Nonetheless, significant policy interventions were established to shape technology and industry development. However, at this point, no projection had anticipated the global success of the technology (David and Gross, 2019), confirming that a tipping point was not in sight.

**In 2022,** the situation shifted in all system elements. The technology has already tipped indicated by significant drops in technology costs. From 2010 to 2020, PV module prices plummeted by 90 %, and PV power plant costs saw a reduction of over 75 % since 2006, owing mainly to technological advancements and economies of scale (see Fig. 4). The levelized costs of electricity (LCOE) of new PV (without battery: between EUR0.031 per kWh and EUR 0.11 per kWh and with battery: between EUR0.05 per kWh and EUR0.19 per kWh) has become cheaper than potentially newly built coal-fired power plants (hard coal and lignite: EUR0.1 per kWh), whose costs have risen due to increased CO2 certificate prices (Kost et al., 2021) (see Fig. 5). The cost reduction significantly supported the increase in market share to more than 67GW in 2022 accounting for 11.1 % of the total installed electricity generation. A policy target of 215GW until 2030 and accompanied policy measures (e.g. reducing bureaucracy and incentivising household

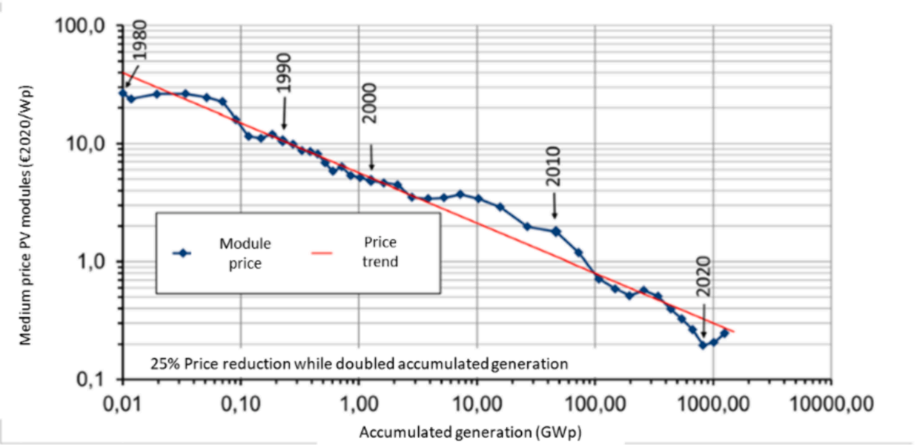

**Fig. 4.** Price of solar modules in relation to accumulated production (GWp) over time. .
Source: Slightly adapted from ISE 2022

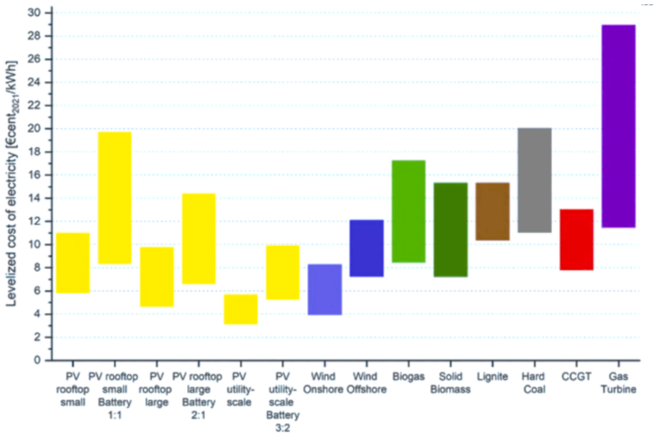

**Fig. 5.** LCOE of electricity production for renewable and conventional energy sources in 2021 in Germany. .
Source: Slightly adapted from ISE 2021

uptake) is further accelerating the deployment (BMWK 2024).

Today there is a broad political majority in Germany in favor of PV deployment (except for right-wing Alternative for Germany (AfD)), especially after the Russian invasion of Ukraine. The benefits of solar deployment are widely acknowledged across ideological divides and party affiliations. Solar PV, alongside wind energy, is considered one of the key future technologies for Germany's electricity supply (see Fig. 5), supported by a strategic package of measures to accelerate the transition (BMWK 2023). Despite significantly reduced support, PV still receives support (feed-in tariffs for rooftop solar, auctions for large-scale PV), and several bureaucratic hurdles were alleviated in 2022 (BMWK, 2023). However, with the increasing demand for land and its impacts, the concerns of local communities and nature conservation organizations have grown (Neumann and Frobel, 2022). Utility-scale projects can now be developed on various new land categories, such as peatland PV and agri-PV on grassland, made possible by changes in the RES-Act of 2022 (Bundesamt für Naturschutz, 2022).

Although the solar PV market is still bolstered by strong policy support (BMWK, 2023), it is also attracting substantial investments (EUR7.7 billion see Fig. 3) and gaining momentum outside of support schemes with. For instance, the 187 MW solar farm EnBW Solarpark Weesow-Wilmersdorf stands as one of the pioneering large-scale projects built without government funding since 2020 (EnBW, 2023).

The continuous expansion of PV also enabled progress in the material system. A domestic solar industry was established with a workforce of over 150,000 employees at its peak in 2011 (Statista, 2023; UBA, 2023). However, curtailed policy support and increasing international competition decimated the industry in in the following years (Podewils, 2013), indicating that the tipping point was not within reach. Today, Germany still holds notable shares of the global market for inverter manufacturers, silicon manufacturer Wacker and several manufacturers of production equipment (Wirth, 2023). The new geopolitical context has further spurred the discussion of re-establishing a local solar industry, while funding support for small- and large-scale projects was reinvigorated in the RES-Act reform 2022 (Spinnler, 2023).

Like the EV transition, PV faces several challenges in the transformation of the material system, particularly the adaptation of required infrastructure. Here, the transmission grid is a primary bottleneck. The current planning horizon of 10–15 years for grid expansion is significantly outpaced by the rapid growth of renewables (Bundesnetzagentur 2024). For example, the north–south grid expansion (Tennet, 2024) has been much delayed, leading to increased curtailment of renewable energy generation and requiring more redispatch measures to manage grid constraints (Tagesschau, 2023). However, progress is being made. In 2023, approvals were issued for nearly 1,400 km of grid lines, and in 2024, the goal is to complete the approval process for up to 2,400 km. This represents a nearly fourfold and sevenfold increase, respectively, compared to 2021 (BMWK, 2024).

Despite these challenges, in contrast to 2000, the tipping point for solar PV generation in Germany is within reach and can be anticipated within the next decade. We find that positive feedback loops have been triggered across all system elements while remaining challenges are being addressed.

## 5. Discussion and conclusions

In this article, we propose that socio-technical tipping points can be anticipated if we observe not only the whole system but the single elements making up the sociotechnical system. We provide a framework for doing this, and illustrated its usefulness in two case studies. We show that not only is it possible to anticipate tipping points – the nearness or remoteness of them for a specific sector – but it is also possible to elaborate actionable recommendations from this analysis, as we identify the still non-flipped elements for full sectoral tipping. We thus find that socio-technical tipping points can indeed be identified ex ante with some precision, although not predict their exact timing.

Empirically, our case studies illustrate that whereas technological dynamics are essential for tipping, this is not sufficient for sectoral tipping. For EVs, our findings oppose those of several other studies, claiming that either the EV sector as a whole (Geels and Ayoub, 2023) or even the EV segment in Norway (Lenton et al., 2022; Sharpe and Lenton,

2021) has tipped. We agree that EV technology has progressed immensely, and in certain regulatory settings – such as the Norwegian tax system – EVs are economically competitive with combustion engine cars. The Norwegian transition started earlier than the German one, arguably because Norway had no incumbent car industry opposing it, and has progressed far, both regarding EV deployment and infrastructure adaptation. This does however not constitute tipping: even in Norway, chargers are still scarce in many places, and without continued efforts – which are underway, but not yet done – the system may still fall back into the old system. In Germany, many elements are still missing, both with the charging infrastructure and, especially, within the immaterial system element: the EV legitimacy is still low among the population, fuelled by entrenched norms of "what a car is" and should be capable of. Our view of tipping as the accumulation of system's wide positive feedback suggests that tipping remains remote, but as some system elements start to flip, feedbacks increase the likelihood of further system elements flipping in a cascading manner (see (Sharpe and Lenton, 2021)). Hence, Norway is close to a tipping point, especially because the successful tipping in most system elements creates pressure for the last ones to tip as well, whereas Germany still has a long way to go, particularly in the acceptance and normative aspects of the EV transition.

In the PV sector, we show how most system elements have flipped over the last two decades, so that a tipping point into a PV-based power future is discernible, although it has not yet happened. The enormous technological progress has made PV among the cheapest technologies available, but this is insufficient for sectoral tipping, especially due to a misfit with existing fossil fuels-based markets and regulations and that redesign and expansion of transmission and distribution grids is not happening at the needed pace. Hence, the misfit of PV with the existing material and immaterial is growing with increasing PV deployment. If the transmission grid is upgraded, the sector is likely to tip, but if change is slow or insufficient, PV deployment will likely hit hard boundaries which may take years to overcome. The transition to PV is not a done deal although technology has sufficiently improved.

Hence, it is premature to announce a global tipping point for the EV sector (Geels and Ayoub, 2023), but in specific places it is or will soon be justified. For PV, we show that although the technology is mature and arguably the cheapest kWh available, the *system* has not yet tipped. As widely acknowledged in the socio-technical systems literature, technology is only part of the equation (Krupnik et al., 2022). Indeed, we showed that the technology element of the system has the greatest potential to tip rapidly; possibly, it *must* tip first to create transition pressure and a sense of direction for subsequent system changes. However, the material element change appears much slower, and the immaterial element even slower, at least in the cases we studied.

Our study has several limitations, which could be addressed in future research. First, the analysis of systems and elements change may need further development, including more detailed data allowing for more fine-grained evaluation criteria, beyond tipped/non-tipped. This could also include more standardised variables, making cross-country analysis easier and faster, and to the extent possible based on quantitative "objective" variables. Such approaches are being developed (e.g. Velten et al., 2023). It would be particularly important to generate theory-led frameworks, to complement existing empirically-led ones (e.g. RIFS, 2023). Second, we see our main contribution in illustrating that tipping points can be anticipated with relatively simple means, but do not claim our framework to be complete or the ultimate one. Hence, further work to refine and update it, and to expand it for further cases, thereby improving and validating (or invalidating) its usefulness will be needed. Finally, we acknowledge that predicting the future is difficult, especially for non-linear transformation processes, and we do not claim to predict tipping points, their timing or effects, but simply provide a heuristic lens for charting the still new waters of social and socio-technical tipping point research.

## CRediT authorship contribution statement

**Franziska Mey:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Diana Mangalagiu:** Conceptualization, Methodology, Writing – review & editing. **Johan Lilliestam:** Conceptualization, Data curation, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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