Research Policy 54 (2025) 105267

Contents lists available at ScienceDirect

Research Policy

journal homepage: www.elsevier.com/locate/respol

# From virtuous to vicious cycles – towards a life cycle model of technology deployment policies

Joris Dehler-Holland

*Institute for Industrial Production (IIP), Karlsruhe Institute of Technology (KIT), Hertzstraße 16, 76187 Karlsruhe, Germany*

ARTICLE INFO

*Keywords:*
Technology deployment policy
Policy feedback
Innovation systems
Technology life cycle
Sustainability transitions
Renewable energy

ABSTRACT

The management of sustainability transitions often includes action to accelerate technological change. Deployment policies are essential measures to increase the adoption of technologies and spur technological development. However, processes of technological development often follow non-linear pathways, and aligning policy and technological development is challenging. This paper links technological innovation systems (TIS) and their dynamics to the policy feedback framework based on the notion that policies shape future politics. Most significantly, the explicit consideration of TIS processes and progress allows for a more nuanced view of how policy effects turn into feedback and for assessing the co-evolution of TIS and policy over time. This framework is applied to study the case of the German Renewable Energy Act (EEG, 1999–2017). The case study provides evidence that the virtuous cycles of rapid TIS development also increase the odds of growing negative feedback based on rising policy costs, competition within sectors, and increasing technology side effects, opening up windows of opportunity for policy change. Based on these observations, this paper proposes an ideal-typical technology deployment policy life cycle model that describes how TIS, the focal policy, and their context co-evolve in a reciprocal process for the case of the EEG. The discussion sheds light on how deployment policies trigger search processes within the TIS that may encroach national borders to satisfy technology demand. Such search processes fuel political optimism. Rising policy costs and side effects, however, produce policy feedback limiting political leverage. The proposition of a model of how the linkages between policy and technology unfold over time contributes to understanding the timing of policies within sustainability transitions.

## 1. Introduction

Sustainability transitions have developed into an important field of scientific inquiry held together by diagnosing the need for substantial socio-technical change (Markard et al., 2012). Technology is a problem and solution to such transitions simultaneously: energy from renewable sources should replace fossil energy provision, and electric cars should replace combustion engines. As those admittedly blunt formulations suggest, sustainability is an inherently normative object, and political issues, directional decisions, and actors' struggles are at the core of such a transition (Meadowcroft, 2011). Consequentially, sustainability transitions are often a field of political intervention, and public policy is challenged to find ways to enable endurable change. Besides instruments directly focused on developing new technologies, such as R&D programs, researchers stress that demand for sustainable technologies is pivotal to reaching goals and changing innovation processes for the better (Mowery et al., 2010).

Demand is crucial in steering innovation "towards the right economic venues" (Di Stefano et al., 2012, p. 1291). Technology deployment policies (TDP) that spur demand for new technologies by providing financial incentives for adoption (e.g., tradable permits, deployment subsidies, feed-in tariffs, taxes, or public procurement) trigger the innovative output of industries (Peters et al., 2012). However, technology deployment policies come with specific challenges for policymakers regarding the non-linear market uptake and development of technologies. The diffusion of new technologies is often depicted as an "S-shaped" curve comprising a relatively long phase of low adoption, followed by a rapid acceleration of market uptake and subsequent saturation (Bass, 1969). Such dynamics demand a high degree of flexibility of deployment policies if structural bounds (Klein Woolthuis et al., 2005) or other instruments in a broader policy mix (Rogge and Reichardt, 2016) exist that call for close coordination of technology development, diffusion, and its environment. However, increasing coordination through regular policy revisions or monitoring schemes increases the possibility for stakeholders and interest groups to influence the policy process towards particular interests (Jordan and Matt, 2014,

*E-mail address:* joris.dehler-holland@kit.edu.

https://doi.org/10.1016/j.respol.2025.105267
Received 23 August 2021; Received in revised form 14 April 2025; Accepted 19 May 2025
Available online 26 May 2025

p. 237).

To understand the co-evolution of socio-technical systems and policies, sustainability transitions scholars increasingly have turned to theories of the policy process (Edmondson et al., 2019, 2020; Hoppmann et al., 2014; Kern and Rogge, 2018; Markard et al., 2016a; Rosenbloom et al., 2016; Schmid et al., 2019). While we have learned a great deal about the interdependencies between policy processes and socio-technical systems in general, the conceptualization of the relations between technological progress, technology adoption, and its policy implications remains weak. Therefore, the main contribution of this paper is the assessment of variations in the relations between policy systems, Technological Innovation Systems (TIS), and their context over time.

To this end, this paper proposes combining the policy feedback framework in socio-technical systems (Edmondson et al., 2019, 2020) with a more detailed description of feedback loops derived from the TIS literature. Based on these concepts, the German Renewable Energy Act (Erneuerbare Energien Gesetz; EEG) and the development of the German photovoltaic (PV) TIS are studied over the period from 1999 to 2017. The EEG supports the deployment of solar, wind, and biomass electricity generation by a feed-in tariff (later: feed-in premium) scheme, whose remunerations are distributed to electricity consumers through a surcharge on the electricity bill. This paper seeks to identify and describe temporal patterns of deployment policies from the case study results. Evidence for similar patterns in other cases is found in the literature.

The remainder of the paper is structured as follows. Section 2 discusses the theoretical foundations of policy feedback and the innovation system literature and synthesizes three stylized effect-feedback loops. Section 3 introduces the methods employed to assess the EEG and the related policy processes. Section 4 presents the EEG case study and seeks to abstract a model of an ideal-typical *technology deployment policy life cycle* from the results. Section 5 discusses the prospects of the TDP life cycle and points out possible directions for future research. Section 6 concludes the paper.

## 2. Theoretical background

Policies that incentivize the deployment of specific technologies are a widespread phenomenon. The adoption of renewable energy technologies in the electricity sector is supported in over 120 countries (IRENA et al., 2018). In the transport sector, electric vehicle adoption is incentivized broadly (Langbroek et al., 2016). Within the housing sector, energy efficiency measures and new heating systems are a vital concern of policymakers (Bertoldi, 2022; Rosenow et al., 2022).

In that regard, technology deployment policies are an essential measure to increase the uptake of technologies at the “middle of the experience curve” when technology costs have been brought down to the extent that niche adoption and initial market creation are possible (Breetz et al., 2018). It is only later, when technologies become competitive in the market, that policies such as carbon taxes or emission trading schemes “need to correct for externalities, ensure market access, and support complementary system-level changes” (Breetz et al., 2018, p. 498). Further following Breetz et al. (2018), each stage follows distinctive political logics and likely requires dedicated theorizing. Additionally, understanding technological processes in detail requires the application of rich theoretical concepts. This article, therefore, mainly focuses on deployment policies while being aware that they might be part of a larger policy mix (Rogge and Reichardt, 2016).

The literature on sustainability transitions increasingly considers policy process theories (Kern and Rogge, 2018). Authors have referred to advocacy coalitions (Markard et al., 2016a), discursive approaches (Rosenbloom et al., 2016; Smith and Kern, 2009), or the multiple streams framework (Normann, 2015) to assess the relations between policy processes and technology. Lately, several works have reflected on the impact of policies on subsequent technological and political change by considering policy feedback (Edmondson et al., 2019, 2020; Rosenbloom et al., 2019; Schmid et al., 2019). However, within this stream of literature, the consideration of socio-technical change remains under-conceptualized.

The Technological Innovation Systems (TIS) framework has been considered essential for analyzing innovation and change, providing detailed descriptions of TIS processes and dynamics (Weber and Truffer, 2017). Implicitly, the TIS literature has always considered policies as within its scope (Markard et al., 2015). Lately, Bergek et al. (2015) conceptualized the political context as part of a broader framework to analyze TIS context structures. Hoppmann et al. (2014) proposed a process of continuous refinement in the wake of upcoming issues in the political process (“compulsive policy-making”). However, the TIS framework has been criticized for relying solely on legitimation as the connecting element between TIS activities and politics and therefore requires a more detailed view of the policy process (Kern, 2015).

Therefore, there is potential to develop both literature streams by explicitly linking policy effects to TIS dynamics to explain change within the TIS induced by policy measures. Furthermore, linking TIS functions to emerging policy feedback can contribute to explaining policy change. To conceptualize full policy feedback loops, one must also take into account the embedding of a focal TIS into its contexts, such as sectors, and its relations to competing TIS or exogenous conditions. Edmondson et al. (2019) described feedback loops using socio-technical change as an aggregate of developments within the socio-technical system. By employing concepts from TIS dynamics to trace down how policy effects turn into feedback in detail, this study contributes to further disentangling effects and feedback. This allows us to understand in more detail how policy effects affect TIS-internal processes towards providing policy feedback.

Epistemologically, both concepts resonate well for three main reasons: (1) The concepts of self-reinforcing or undermining feedback are also an integral part of the TIS literature (Hekkert et al., 2007); (2) A critical analytical dimension of policy feedback and TIS are actors that support or oppose policy based on their vested interests (Jacobs and Weaver, 2015; Markard et al., 2015, p. 82; Oberlander and Weaver, 2015; Pierson, 1993); (3) The TIS literature acknowledges that TIS relations to its context structures such as political systems are essential to understand its development (Bergek et al., 2015). Therefore, combining both frameworks is well-suited to explore the links between policy and technology development.

From an analytical perspective, it is crucial to define the objects of analysis clearly and to delineate system boundaries. In the literature, it is common to delineate a TIS along national borders while acknowledging that the TIS might be part of a system transcending such borders (Bergek et al., 2015; Ulmanen and Bergek, 2021). This study focuses on the relations of a fixed policy (‘focal policy’) that fosters the deployment of a specific technology. As the locus of such deployment policies is usually national, focusing the analysis on the TIS constrained by national borders (‘focal TIS’) embedded into its (national) sectoral context makes sense. Therefore, global TIS development regarding the focal technology is considered as development in the context of the focal TIS (Bergek et al., 2015).

This section discusses the fundamental frameworks that guide the analysis of the co-evolution of a focal policy and a related focal TIS. We introduce the notion of policy feedback that governs the relationships between socio-technical systems and policy. Then, this section focuses on the TIS, concepts of dynamics, and the TIS context. This section closes by using the TIS framework to elaborate more detailed proposals of how policy effects influence the focal TIS and turn into policy feedback.

### 2.1. Policy feedback in socio-technical systems

One particularity of the politics of transitions is the importance of policy outcomes, i.e., the social or technological change induced by policy measures and its implications for subsequent policymaking. The policy feedback literature is built around the idea that policy outcomes influence future policy making, wherefore it was found a promising framework to assess the politics of sustainability transitions (Kern and Rogge, 2018). In the following, this section introduces some key concepts vital to analyzing transitional policies.

The key observation of policy feedback is that policy forms the base for further politics (Pierson, 1993). In other words, the outputs and outcomes of a policy process feed back onto subsequent policy processes: The enactment of a policy has *effects* on the socio-technical system, such as increased technology adoption. The political system observes policy outcomes within the socio-technical system (*feedback*) and reacts accordingly. Who it is that is affected by the deployment of a policy and how the policy changes the composition of actor groups are, therefore, critical questions of the policy feedback framework.

As important sources for policy feedback, the literature identified interest groups (e.g., Pierson, 1993) or the mass public (e.g., Campbell, 2012). The distribution of resources, providing benefits for specific groups while imposing losses on others, is an important example of policy effects on society, affecting the distribution of coalitions that may support the maintenance or termination of the focal policy (Pierson, 1993). The earlier literature has focussed on self-reinforcing feedback; however, recently, policy scholars extended the focus to include self-undermining feedback (Jacobs and Weaver, 2015; Patashnik and Zelizer, 2013; Weaver, 2010). Recently, the work on policy feedback has increasingly been applied in analyzing socio-technical transitions (Sewerin et al., 2020).

While policy feedback can be considered an important aspect of policy change, it must be acknowledged that it is not sufficient for changing policies (Oberlander and Weaver, 2015). Exogeneous conditions that the focal policy has not influenced play an essential role in amplifying policy feedback. Focusing events, international (economic) developments, elections, changes in government, or intervention from supra-national organizations may induce changes in the actors' constellations or exert additional pressure on policymakers that make policy change more likely (Edmondson et al., 2019).

For socio-technical transitions, Edmondson et al. (2019) proposed a framework delineating the policy feedback loop into a set of *effects* and *feedback* (Table 1). This framework will be the basis for the analyses undertaken in this study. The framework has proven useful in assessing the relationships between socio-technical and policy subsystems (Edmondson et al., 2020). However, how policy effects, such as the provision of resources to target groups, induce socio-technical change is not conceptualized sufficiently. Therefore, the following sections propose to link policy effects to TIS functions and the feedback emanating from induced socio-technical change.

**Table 1**
Policy effects and feedback (Edmondson et al., 2019, 2020).

| Mechanism | Description |
|---|---|
| Resource Effects (RE) | Policy reallocates resources to target groups by policies that support technology development, e.g., knowledge creation, technology adoption, demonstration projects, or increasing costs for undesirable technologies, e.g., $CO_2$ taxes or surcharges; Reallocation of resources can affect the behavior of target groups towards more sustainable modes, but can also have unintended consequences. |
| Interpretive Effects (IntE) | Policies provide information that may create or change visions or expectations of actors; coherent policies and sufficient resources support the view of policymakers as dedicated to reaching targets and providing security, while the absence of such may lead to doubts about political will behind objectives related to higher uncertainty about future prospects. |
| Institutional Effects (InstE) | Policies interact with institutions, such as laws, rules, regulations, or unwritten norms, and the implementation of policies may foster changes in such institutions, or institutions might hinder policies from achieving their goals. |
| Socio-political feedback (SPF) | SPF comprises (1) cognitive, (2) constituency, or (3) agenda feedback. (1) occurs when a policy is perceived as successful or disastrous for achieving objectives by relevant groups or mass publics. (2) describes whether policy mobilizes supporters or opponents. (3) describes whether support or opposition leads to the consideration of incremental or substantial policy change. |
| Fiscal feedback (FF) | The policy's budget may raise concerns in financial ministries and agencies such as accountability or audit offices. Typically, financial ministries are potent actors within the government that control resource flows and, therefore, may limit the leverage of the focal policy. |
| Administrative feedback (AF) | Public bodies in charge of designing and implementing the policy may be weakened or strengthened by the policy, depending on whether it has achievable goals and whether the policy can be implemented without visible failures. |
| Exogenous conditions (ExC) | Changes beyond socio-technical systems such as catastrophic events or macro-economic trends may influence policy change |

### 2.2. Dynamics and change of technological innovation systems

While Edmondson et al.'s (2019, 2020) framework contributes to identifying the general patterns of policy feedback, it focuses less on conceptualizing the processes within socio-technical systems. Such a conceptualization, however, is essential when trying to understand how effects turn into feedback. This section introduces the technological innovation system framework to understand further how feedback emerges after the policy-triggered changes in the composition of the socio-technical system.

The TIS framework proposes a systemic view of structures involved in technology development, production, diffusion, and use. The systemic aspect contributes to the fact that innovation and technology development generally are difficult to influence and display high degrees of inertia, leading to lock-ins or path dependencies (Hekkert et al., 2007). The main components of a TIS are networks of actors and institutions that interact within a social environment or context (Carlsson and Stankiewicz, 1991). Notable contributions have addressed different dimensions of innovation systems, such as sectoral (Breschi and Malerba, 1997; Malerba, 2002), national (Freeman, 1995), and global (Binz and Truffer, 2017) innovation systems.

One of the key goals of this study is to understand technological change induced by policy measures. A classical approach to understanding TIS dynamics is that certain processes or functions are perceived as essential for the performance and development of a TIS (Bergek et al., 2008; Hekkert et al., 2007). In this study, we use Hekkert et al.'s (2007) list of functions: 1) Entrepreneurial activities; 2) Knowledge development; 3) Knowledge diffusion; 4) Guidance of the search; 5) Market formation; 6) Resource mobilization; 7) Creation of legitimacy. If such functions are performed successfully to a certain extent, virtuous cycles may drive TIS development (Negro and Hekkert, 2008). On the other hand, vicious cycles can prevent successful development. Such patterns have been observed to be alternating in some cases, while all system functions are important for TIS performance (Hekkert and Negro, 2009). Societal problems (such as environmental issues) can 'guide the search' and start the development of a TIS (Hekkert et al., 2007). Also, entrepreneurs who lobby for market formation or better economic conditions for a technology can start virtuous cycles of TIS development (Suurs et al., 2010). However, when it comes to the TIS' external environment, the framework has been criticized for its low degree of conceptualization of TIS relations to politics and its context in general (Kern, 2015; Markard et al., 2015).

In response, Bergek et al. (2015) developed a framework to analyze a TIS's contextual structures and interactions. Representing such a context structure, TIS scholars have focused on the impact of politics on the legitimation of new technologies. Also indirect effects on market creation and its influence on the direction of search have been acknowledged (Markard et al., 2015). Actors compete over institutional alignment and legitimation to gain access to resources (Bergek et al., 2015). On the other hand, the TIS also competes with its sectoral context over political legitimacy when the focal technology provides a service similar to incumbent technologies. However, recent scholarship has proposed that the strength of context relations depends on the stage of development of the focal TIS (Markard, 2020).

Therefore, based on the notion of life cycles in industry and technology development, Markard (2020) develops a life cycle model of technological innovation systems. Core dimensions for TIS development are the size of the TIS (measured by, e.g., sales figures), the institutional structure, and technology performance. The TIS life cycle proposes distinguishing four phases or stages in which the TIS forms, grows, reaches a mature level, and eventually declines. Across these stages, the relations of TIS and context tighten until they loosen during decline. Intensified political actions and lobbying might occur (Markard, 2020, p. 10). However, the TIS life cycle framework explicitly left the integration of TIS functions and life cycles for future research (Markard, 2020, p. 5). Therefore, we mobilize the work on 'motors of innovation'.

'Motors of innovation' contributed to understanding the successful emergence of TIS by identifying a set of reoccurring mechanisms that foster TIS development in a process of cumulative causation, supported by extensive case studies (Hekkert et al., 2007; Suurs, 2009; Suurs and Hekkert, 2009, 2012). A motor of innovation comprises a combination of system functions active at a particular time, linked by reinforcing feedback loops. Even more remarkable, Suurs (2009) proposed a sequential model of innovation based on the observation that the driving patterns follow each other in a generalizable manner. While the lack of uptake of the patterns of cumulative causation has been bemoaned in the literature (Köhler et al., 2020), we propose that they provide crucial information on functions particularly active throughout the phases of the TIS life cycle. For this study, the growth phase is particularly important, where all functions contribute to the TIS development, particularly market creation is essential, and TIS actors join forces to create advocacy coalitions and political support for the entire TIS, for example, through market formation policies ('system-building motor').

The following section combines policy feedback and aspects of TIS dynamics to propose three feedback loops to study how policy and TIS coevolve over time.

### 2.3. Three stylized feedback loops

This section aims to bring together the policy feedback literature with the different notions of TIS dynamics and development (i.e., TIS functions, motors of innovation, and TIS context structures). Arguably, that is a complex undertaking, given the number of variables introduced by the different frameworks (e.g., TIS functions, effects, and feedback). Therefore, this section focuses on sketching three stylized feedback loops that will later prove helpful in understanding the case study. I will refer to the three feedback loops as the *technology loop*, the *cost loop,* and the *side-effect loop* (see Fig. 1). The technology loop will make use of the understanding of TIS-internal dynamics provided by the motors-of-innovation framework. The cost loop builds more closely on the policy feedback literature, emphasizing the importance of the distribution of benefits of a policy in the wider society. Here, the context of a TIS plays an important role. Third, the side-effects loop addresses the relationship between technology and societal institutions, which play a role for policymakers in the pursuit of ambitious technology targets. With the growing maturity of the TIS, the three loops can be expected to be more or less pronounced over time during the coevolution of policy and the TIS life cycle.

Certainly, the three feedback loops depicted here are not the only possible mechanisms at play in the coevolution of policy and technology, nor are they meant to be deterministic. The reader is encouraged to further develop the implications of TIS dynamics and policy effects. As we shall see, the three feedback loops identified here are helpful to understand the case study further. The resulting framework enables a fine-grained analysis of the coevolution of technology and policy over time.

Before I detail the three feedback loops, I turn to discuss the orientation or directionality of feedback and effects. This helps to understand where policy and technology development are mutually supporting each other, or where technology development turns against policy maintenance.

#### 2.3.1. Virtuous and vicious cycles

This paper is particularly interested in periods of mutual reinforcement of policy and TIS. For that purpose, Edmondson et al. (2019) propose to consider feedback that strengthens the support for the policy as positive and feedback that weakens support as negative. While this is a relatively intuitive definition, the question of when policy effects are indeed positive is more tricky when considering the entire socio-technical system.

First, it is needless to say that policies do not affect all stakeholders in the same way. Policies often affect the distribution of resources, and therefore, their effects on one interest group are more intense than on another (Pierson, 1993). Therefore, the first step to identifying policy effects as either positive or negative is the proper differentiation of societal subgroups that are affected similarly by the policy. From this differentiation it also immediately follows that there may be different policy effects active at the same time, affecting fractions of the population in different or even opposing ways.

Therefore, second, the definition of positive and negative effects boils down to identifying an orientation for these interest groups. This research is particularly interested in the relationship between technological innovation systems and policies supporting technology deployment. An innovation system comes with a clear goal of inducing innovation processes (Suurs, 2009, p. 50). The performance of a TIS can be measured by analyzing the system functions (Hekkert et al., 2007). For this study, this implies that policy effects that contribute to strengthening TIS functions can be defined as *positive* policy effects. Conversely, policy effects that weaken TIS functions shall be defined as *negative* effects. This is the perspective that is applied majorly within this study.

Similarly, for the sake of understanding phases of mutual support of policy and socio-technical change, this study will evaluate effect orientation based on the self-interest of the relevant affected societal groups in the TIS context, similar to Burroughs (2017). Arguably, this definition based on self-interest will not enable this study to identify each effect as positive or negative (c.f. Campbell, 2012). However, fixing these orientations enables identifying situations in which positive policy effects leading to positive feedback largely align with the maintenance of a high policy support level (virtuous cycles), or negative effects largely align with decreasing support levels (vicious cycle). As argued above, positive and negative effects and feedback may exist at the same point in time. However, the distribution of their relative strengths may differ. The following sections will discuss how effects and feedback are linked in three different feedback loops.

#### 2.3.2. The technology – loop

When it comes to TIS development, the functional framework and the linkages between functions in the motors of innovations literature have contributed to understanding dynamics and change (Suurs, 2009; Suurs and Hekkert, 2009, 2012). This section draws onto these insights to sketch how policy affects TIS functions, and how that leads to policy feedback. It does so by assuming that the TIS already has reached a certain level of development[1] ('system-building motor') and that a deployment policy has been enacted (compare Fig. 1).

[1] In principle, the motors of innovations can be used to develop hypotheses on policy-TIS interactions also in other phases. For example, the 'entrepreneurial motor' can be used to understand the period before the introduction of relevant deployment policies. However, to further understand deployment policies that are employed at a stage when some development has already occurred, this case is most informative.

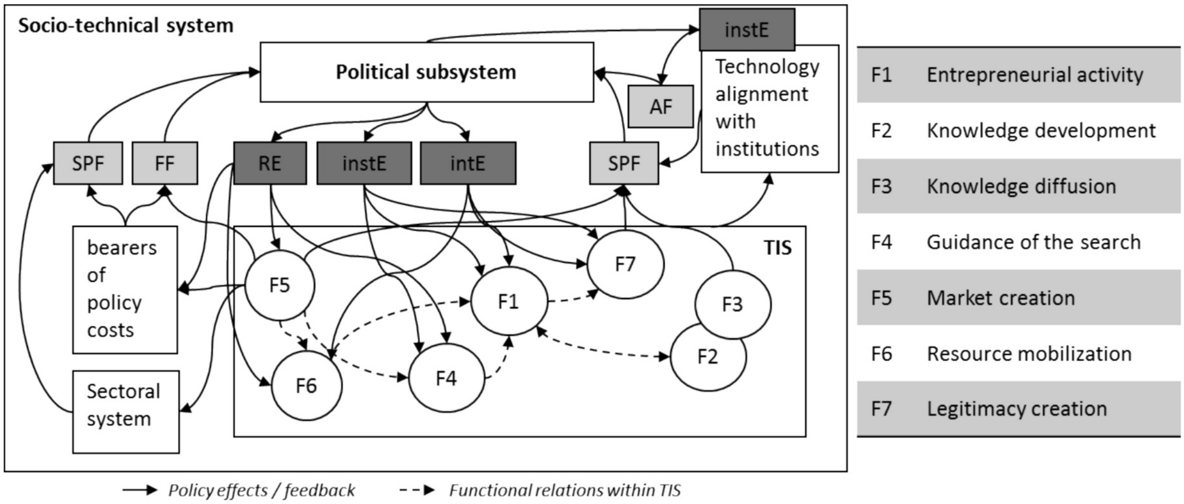


**Fig. 1.** Depiction of three feedback loops, and TIS functions relationships within the focal TIS according to the motors of innovation ('system-building motor'). Left: Cost loop; center-right: technology loop, upper-right: side-effects loop.

An immediate *resource effect* of deployment policies, if incentives are sufficient, is the increase of demand for the focal technology, or *market creation* in terms of TIS functions (e.g., Walrave and Raven, 2016). Increased demand in the following *guides the search* of the TIS towards the niche within which technology deployment is supported by the focal policy (Suurs, 2009, p. 223). Certainly, the interplay of the focal policy with existing regulations and laws additionally influences the search direction (*institutional effects*). Increased demand furthermore drives the *mobilization of resources*. Such a mobilization may occur either directly due to increased sales; or indirectly, as increased expectations towards market development also increase the attractiveness of the TIS to new investors. Subsequently, the TIS literature has found evidence that through increased resources, *entrepreneurial activity* is strengthened (Bergek et al., 2008; Suurs, 2009), where new actors are drawn into the TIS, and existing actors increase the scope of their activities. For these functions uncertainty about the prospects of the policy (*interpretive effects*) does play a major role (e.g. Marcus, 1981; Bhattacharya et al., 2017). TIS actors then actively search for ways to satisfy the increasing demand. Part of this search process can be an increase in TIS' innovative activities in terms of *knowledge development and diffusion* that was found to be affected by deployment policies (Costantini et al., 2015). Besides such explorative activities, earlier research found that deployment policies also increase the search for more efficient means to satisfy demand (Hoppmann et al., 2013). Growing TIS expand and fasten ties to their contexts, such as other TIS or sectors, or in geographical terms (Bergek et al., 2015; Markard, 2020). Where a TIS can increase its innovative activities, these activities become a political argument when the expansion of a TIS goes hand in hand with job creation and industrial leadership (*socio-political feedback*) (Fankhaeser et al., 2008; Lockwood, 2013; Stokes and Warshaw, 2017). Therefore, the TIS can *create legitimacy,* which is the basis of increasing positive socio-political feedback. Such policy feedback emanates from two relevant processes: on the one hand, TIS actors increase their political activities in terms of legitimation (e.g., lobbying). On the other hand, TIS activities are observed by its (political) context, and high activity within the TIS that contributes to industry or employment policy goals supports legitimacy creation.

A prosperous TIS may provide positive administrative feedback and socio-political feedback alike. However, if context factors hinder the growth of a TIS or even lead to its decline, the ability to create legitimacy and positive feedback diminishes (Markard, 2020).

### 2.3.3. The cost – loop

One of the most prominent results of the policy feedback literature is the influence of the distribution of costs and benefits of a policy among political actors such as mass publics and different interest groups (e.g., Pierson, 1993). We have seen above how a deployment policy may affect processes within a focal TIS by increasing the benefits of adopting the technology to outweigh technology costs for a sizeable interest group. These benefits of one group are likely to be paid by another group or the state. The distribution of costs and benefits is a major policy design feature (Campbell, 2012; Edmondson et al., 2019; Larsen, 2018). For example, refinancing a feed-in tariff for renewable energies by a levy on the electricity price affects all electricity consumers directly, while refinancing it via the state's budget limits political engagement elsewhere or increases depts. Therefore, resource effects of a deployment policy can be expected also beyond market creation discussed above.

When considering deployment policies, likely, sectors that provide a service similar to the focal technology (e.g., the electricity sector in the case of photovoltaic energy generation) are affected by the focal policy, as the deployment policy impacts the service market. Therefore, sectors provide an important context structure to be observed when considering deployment policies.

Within the sector, service providers (e.g., electric utilities) or consumers may be affected in different ways. On the one hand side service providers face increased competition for the provision of services (e.g., Sensfuß et al., 2008). On the other hand side, consumers potentially bear price effects, depending on the nature of the deployment policy, or whether policy costs are redistributed by collective taxes.

Therefore, potential sources of fiscal or socio-economic feedback in the case of deployment policies range from financial ministries across different interest groups to mass publics in the case of large service markets (such as electricity). Particularly the perception of concentrated losses for mass publics or interest groups drives feedback (Oberlander and Weaver, 2015). Empirically, evidence for undermining feedback from sectors is widespread, as competition and threats to incumbent business models are likely[2] (Geels et al., 2014; Hess, 2014; Lee and Hess, 2019). However, synergies between sectors and new technologies also have been observed (e.g., Mäkitie et al., 2018).

### 2.3.4. The side-effects – loop

Understanding technology policies and the political feedback they cause calls for a detailed understanding of how and whether technology is supported or opposed by society or important societal groups (e.g., Alsheimer et al., 2025). In the analysis of socio-technical systems, these

[2] In fact, the socio-technical transition literature emphasizes struggles between niches and incumbent regimes (Geels, 2004).

interactions have been considered by including a detailed view of the institutional settings technologies encountered during market uptake. Here, the relationship between society, artifacts (technology), and institutions plays a key role in understanding how socio-technical systems evolve (Geels, 2004). The notion of 'regimes' describes the institutional settings against which novel technologies are deployed (e.g., Fuenfschilling and Truffer, 2014).

However, in the analysis of policy mix feedback in sustainability transitions, Edmondson et al. (2019) mainly focus their framework on structural institutions such as state agencies and the effects policy has on their constitution (*institutional effects)*. This narrow focus is all the more surprising, considering that policies that drive sustainability transitions often aim at a change in the use of technology towards a more sustainable mode (Markard et al., 2012). Therefore, to better understand the co-evolution of socio-technical systems and deployment policies, this paper adopts a broader concept of institutional effects, including societal norms and rules, shaped by artifacts and material conditions within the sociotechnical system (Geels, 2004).

In the literature, there is evidence that with policy-driven growing technology deployment, technology misalignment with existing institutions can become more prominent. For example, growing biogas production in Germany increasingly became misaligned with food farming (Markard et al., 2016b). Wind farms faced increasing opposition due to alleged environmental or health effects, and local resistance against wind projects slowed down development, causing legislation changes in veto rights for environmental organizations or action groups (Dehler-Holland et al., 2022). Generally, the literature on technology legitimacy and technology acceptance provides a detailed picture of the fragile relationship between technology and society (Alsheimer et al., 2025). Such misalignments are considered institutional effects in this study.

The example above (biogas energy) triggered a re-framing of the technology (*socio-political feedback*), leading to a reduction of biogas energy policy support (Markard et al., 2016b). Also the public perception of wind energy increasingly put alleged negative aspects of wind power into the foreground. Additionally, local administration was increasingly seen as notoriously slow in handling building permits (*administrative feedback*) (Dehler-Holland et al., 2022). In general, the transformation of the energy sector, considered one of the front runners of sustainability transitions, is loaded with institutional struggles (Reusswig et al., 2018). Therefore, sequences of institutional effects and socio-political or administrative feedback are considered as the side-effects loop.

Additionally, from the point of view of the focal TIS, such institutional effects affect the ability for *legitimacy creation*. When a technology is increasingly portrayed as having adverse side effects, positive externalities such as job creation or environmental benefits may be superimposed.

## 3. Methodology

To investigate the relationships between a focal TIS and a deployment policy, we chose the German Renewable Energy Act (Erneuerbare-Energien-Gesetz; EEG) and the German photovoltaics TIS because it represents an instance of a technology deployment policy from 2000 until today (2023), allowing for a longitudinal study of policy dynamics. The EEG stimulated considerable wind, solar, and biomass electricity generation investments and was amended several times. With its long history of political debates on renewable energy technologies, the perceived international leadership in renewable policies in the 1990s and 2000s, and its success in spurring the adoption of renewables, the EEG can be considered an 'extreme case' of technology-policy co-development (Schmidt et al., 2019). The selection of an extreme case is well-suited for exploratory studies that aim at formulating an initial set of hypotheses (Seawright and Gerring, 2008).

Prior research has conducted intense empirical research on the German EEG and the photovoltaics industry, focusing on different periods, data sources, and theoretical paradigms. Methodologically, this study primarily aims to accumulate this existing knowledge into a coherent narrative on the EEG's development. Such a line-of-argument synthesis (Noblit and Hare, 1988) "involves building up a picture of the whole (i.e. culture, organisation etc) from studies of its parts" (Barnett-Page and Thomas, 2009, p. 2) and has also been proposed for organizational research to advance knowledge in areas where separate field studies have produced scattered conclusions (Hoon, 2013). Most importantly, synthesis approaches to case studies include a step of translation, where different studies' results are made comparable to derive a bigger picture (Noblit and Hare, 1988). For translation, this study uses a combination of policy feedback and the TIS framework.

Synthesis approaches usually start by identifying a problem or phenomenon to orient the literature research (Hoon, 2013, 528f). Research on media accounts of the EEG over the period from 2000 to 2017 identified an attention cycle[3] pattern in newspaper coverage, where the framing of the EEG shifted from technology optimism to the perception of costs (Dehler-Holland et al., 2021). However, the politics leading to such phenomena are poorly understood (Gupta and Jenkins-Smith, 2015). The synthesis endeavor aims to derive an explanation for such patterns. The literature search focused, therefore, on three literature streams. By database research and snowballing, primary research studies on the photovoltaics TIS in Germany, the electricity sector, and renewable energy politics were identified. Important selection criteria for the studies were that studies observed phenomena during the observational period and built upon primary data.

For the photovoltaics TIS, the synthesis can draw on primary studies of entries and exits (Hipp, 2021), employment (O'Sullivan et al., 2018), patents (Huenteler et al., 2016; IRENA, 2021), business climate (BSW-Solar, 2019), research cooperations (Hipp, 2021), and technology deployment (AG Energiebilanzen e. V, 2019). Such data are particularly important to the study of TIS life cycles (Markard, 2020). Additionally, detailed studies using the TIS function framework are available (Dewald and Fromhold-Eisebith, 2015; Dewald and Truffer, 2011, 2012; Hoppmann et al., 2014; Jacobsson et al., 2004; Quitzow, 2015), as well as studies on lobbying activities (Seibt, 2015; Sühlsen and Hisschemöller, 2014). Several longitudinal studies focus on the main actors in the electricity sector, namely incumbent electricity suppliers and industry consumers (Borshchevska, 2016; Kungl, 2015, 2018; Kungl and Geels, 2018). For synthesizing processes in the policy subsystem, studies that focus on parliamentary debates (Hoppmann et al., 2014; Lauber and Jacobsson, 2016; Leipprand et al., 2017; Schmidt et al., 2019) and detailed political analyses covering either more extended periods or specific EEG amendments (Hirschl, 2008; Lauber and Jacobsson, 2016; Leiren and Reimer, 2018; Messing, 2020; Strunz, 2014; Strunz et al., 2016) were identified.

While the potential for synthesis from the studies identified is rich, different challenges need to be addressed. First, studies rarely cover the entire time frame of interest. Second, studies draw on different analytical frameworks, such as historical institutionalism (e.g., Leiren and Reimer, 2018), multiple streams (e.g., Messing, 2020), or organizational fields (e.g., Kungl, 2018). Dehler-Holland et al. (2021) proposed a phase segmentation based on media attention towards the EEG over time. These phases were used to systematically assess the literature base for contributions of original studies to understanding the underlying processes. For the second challenge, the policy feedback and TIS functions framework were used as translation vehicles into a 'common language' for the original studies. Therefore, events, actors' activities, or developments identified in the original studies were evaluated by whether they emit different kinds of policy effects or feedback. A particularity of synthesis approaches to case studies is that the findings and interpretations of original studies are sought to be preserved (Hoon, 2013, p. 527).

[3] Such issue attention life cycles have been introduced by Downs (1972)

Therefore, the inference of the original authors on causal mechanisms is retained from the original studies. For instance, a phrase like "German market development also enabled the growth of a number of German solar manufacturing start-ups, and by 2003 most of today's major German PV equipment suppliers had entered the market" (Quitzow, 2015, p. 131) is taken as evidence for resource effects of the EEG onto the PV TIS regarding the increase of entrepreneurial activities. This procedure resulted in Table 2 and Table A.2, where feedback and effects are identified, as well as external context factors in the political system and the electricity sector the original studies deemed important, along with significant changes in the EEG. The additional consideration of context factors serves to unravel the various possible exogenous conditions.

The final task is to make synthesis results intelligible to the scientific audience (Noblit and Hare, 1988). Therefore, a narrative from the synthesis results was written using the framework comprising policy feedback and TIS functional dynamics. Each phase is complemented by a comparative discussion highlighting key developments and comparing them to cases from the literature.

In addition to the case of the EEG and the photovoltaics TIS between 2000 and 2017, the above procedures were applied to the EEG's predecessor: the *Stromeinspeisungsgesetz (StrEG)* and the German wind power TIS. The StrEG was in force between 1991 and 2000 and triggered a rapid increase in wind power installations and TIS development. While space limitations did not allow for an additional detailed description, a summary table is provided in the Appendix (Table A.1), and the results showcase a pattern similar to the one presented with some notable differences. In Section 4, these results help to enrich the presented results towards the notion of a deployment policy life cycle, along with findings from other cases.

## 4. Case study and development of a TDP life cycle model

In this section, we use the framework developed in Section 2 to structure the analysis of the evolution of German EEG and the solar PV TIS. We divided the case study into five phases[4] (1999–2000; 2000–2004; 2005–2010; 2010–2014; 2014–2017). Policy feedback, effects, and critical variables are described in Table 2, sometimes in more detail than the body of text allows. Table A.2 in the Appendix shows an analysis of TIS functions. Additionally, each phase is followed by a discussion employing the stylized feedback loops (Section 2.3) as analytical tools. Additionally, similar cases from the literature are provided. The section is closed by proposing an ideal-typical model of the life cycle of technology deployment policies.

### *4.1. Preconditions*

#### *4.1.1. EEG case study (1999–2000)*

Between 1998 and 2000, the world market for solar panels was already growing (Jacobsson and Lauber, 2006). Additionally, the 100,000 roofs program and local feed-in laws supported the *market creation* function of the PV TIS (Jacobsson et al., 2004, p. 19). These market developments contributed to *resource mobilization*, also by "collective forms of project financing" (Dewald and Fromhold-Eisebith, 2015). At least two companies expanded their production capabilities in Germany (Jacobsson et al., 2004, p. 18), and increasing new entries in cell and module manufacturing (Hipp, 2021, p. 573) indicate increasing *entrepreneurial activities*. Also, *knowledge creation and diffusion* were active: German universities provided a solid knowledge base, and collaborations between industry and academia were established (Hipp, 2021; Jacobsson et al., 2004, p. 21), patenting activity increased (Huenteler et al., 2016). The 100,000 roofs program was already supported by the German solar industry association since 1996, and lobbying intensified for measures supporting national market creation (Jacobsson et al., 2004, p. 18). Also the success story of the wind power industry in Germany supported *legitimacy creation* of the PV TIS as renewable energy provision provided chances for industrial development and job creation (Bergek and Jacobsson, 2003).

The electric utilities evaluated the liberalization of the electricity sector (Energy Industry Act; Energiewirtschaftsgesetz; EnWG, 1998) as a chance for growth and started to focus on and expand in the domestic market (Kungl, 2018, pp. 150–151). The engagement of the utilities in the political process of the EEG was relatively small, as they attributed higher importance to the nuclear phase-out discussions and focussed on the rapid market developments after liberalization (Kungl, 2018, p. 190).

Within the German industry, positions towards the EEG were ambiguous. While the "BDI [Bundesverband der Deutschen Industrie, Federation of German Industry] condemned the bill for exorbitant costs" (Lauber and Jacobsson, 2016, p. 151), the German Engineering Association (VDMA) supports the EEG in opposition to its parent organization BDI due to the interests of its members in the wind energy industry (Hirschl, 2008, p. 145).

After the elections in September 1998, a coalition of social-democrats and the green party came into government. The new government meant a change in the support coalition of renewables, as the Green Party had renewable energy expansion on its agenda since its foundation (Hake et al., 2015; Hirschl, 2008, p. 140). The greens forged an advocacy coalition of environmental groups, industry associations, and labor unions in favor of a profound reform of the Feed-In law (Jacobsson et al., 2004; Jacobsson and Lauber, 2006, p. 267). Social-democrats were hoping for job creation effects in the wind turbine industry that was perceived as endangered by decreasing feed-in tariffs due to market liberalization (Jacobsson and Lauber, 2006, p. 267). Conservatives and liberals opposed more substantial renewable support and argued against higher technology costs and adverse economic effects on the energy sector (Leipprand et al., 2017; Schmidt et al., 2019; Stefes, 2010). While the responsible ministry of economic affairs (BMWi) refused to propose a bill for the EEG, finally, a small group of members of parliament initiated a bill in parliament (Stefes, 2010). The new EEG, enacted in April 2000, introduced a fixed remuneration differentiated by renewable technologies.

#### *4.1.2. Comparative discussion*

The case of the EEG has shown that the solar TIS in Germany was already active. Notably, actors actively lobbied for deployment policies to support further growth. The fact that TIS activity and lobbying often precedes the introduction of dedicated market support measures was also observed in the TIS literature: In fact, Suurs (2009) sees the 'system building motor' of the TIS as contributing to the introduction of market stimulation programs, supported by extensive case studies on biofuels, hydrogen, and automotive natural gas. Typically, TISs in this stage are characterized by a relatively mature technology and already existing networks with growing political ties (Suurs, 2009, p. 222). Also Breetz et al. (2018) find deployment policies implemented when considerable technology learning has already occurred. However, when TIS actors, for example, can not form a clear common interest ('guidance of the search'), the implementation of market creation measures may also fail (Suurs, 2009, p. 221).

A further important characteristic of the EEG case was that incumbents in the sector initially appeared to underestimate the new technology and the related policy. Such underestimation by incumbents has also been found in the case of renewables in Italy (Prontera, 2021), in the case of the StrEG (Table A.1), and Stokes and Breetz (2018) found it a common characteristic in US technology policies ranging from renewables over electric cars to biofuels in the transport sector. The literature thus provides evidence that similar patterns can be found in other countries and sectors.

[4] Following Edmondson et al. (2020), we use abbreviations to refer to the conceptual components of the policy feedback framework: Resource effect **[RE]**, Interpretive effect **[IntE]**, Institutional effect **[InstE]**, Socio-political feedback **[SPF]**, Fiscal feedback **[FF]**, Administrative feedback **[AF]**.

**Table 2**
Summary of the main developments of the EEG divided into five phases.

| EEG | 0 (1999–2000) | I (2000–2004) | II (2004–2009) | III (2009-2014) | IV (2014–2017) |
|---|---|---|---|---|---|
| Socio-political Feedback [SPF] | - strong political networks of wind power industry, "prototype" of renewable energy industry [+SPF]<br>- Support coalition for EEG of environmental groups, industry unions, labor unions [+SPF]<br>- Liberalization keeps utilities busy and opens up opportunities [no -SPF]<br>- BDI opposes EEG due to expected costs [-SPF], but VDMA supports proposal [+SPF] | - Growth of solar TIS, creation of jobs [+SPF]<br>- Growing PV market with a high number of diverse investors [+SPF]<br>- Utilities press for market integration of renewables [-SPF]<br>- Industry associations lobby for surcharge exemptions [SPF] | - Growing employment in the solar industry [+SPF]<br>- Increasingly professional solar industry associations [+SPF]<br>- A high number of beneficiaries of the EEG [+SPF]<br>- VDEW and utilities oppose EEG and fan fears of "deindustrialization" due to high costs [-SPF] | - Solar industry loses political leverage due to low international module prices, dropping employment [-SPF]<br>- Ties of PV industry to federal states mitigate stronger cutbacks [+SPF]<br>- Utilities seize rising surcharge as argument [-SPF]<br>- Pressure of utilities on BMWi in favor of auctions [SPF]<br>- BDI active opponent of EEG surcharge [-SPF] | - Auctioning scheme criticized for adverse effects on smaller investors<br>- Limited influence of stakeholders on the policy process |
| Fiscal Feedback [FF] | - BMWi refuses to propose bill due to expected costs [-FF] | - BMWi demands to lower remuneration [-FF] | | - Rösler (economic affairs minister) presses for substantial reductions and a cap for solar power [-FF] | |
| Administrative Feedback [AF] | | | | - BDI criticizes threats to the security of supply and the poor coordination of the 'Energiewende' [-AF]<br>- Responsibilities for energy policy bundled at BMWi in 2013 | - Slow grid expansion and conflicts with Bavaria |
| Resource Effects [RE] | - 100,000 roofs program implemented for PV [+RE]<br>- EEG implemented [+RE] | - EEG remuneration differentiated by technology [+RE]<br>- 100,000 roofs program expired [−RE] | - Cap on solar power installations removed [+RE]<br>- Increased remuneration for solar power [+RE]<br>- Increasing EEG surcharge [−RE]<br>- Increasing impact of renewables on wholesale power prices [−RE] | - Various adjustments of the solar remuneration [−RE]<br>- Strongly increasing EEG surcharge [−RE]<br>- Increasing impact of renewables on wholesale power prices [−RE] | - Target corridor for all technologies [−RE]<br>- Stagnant EEG surcharge [−RE] |
| Interpretive Effects [intE] | | - Fixed EEG remuneration and long-term perspective increase investment security [+intE]<br>- By 2003, discourse on amendments decreases expectations [−intE] | - Removal of solar cap increases security [+intE] | - Societal and business expectations in solar decrease due to changing political framework and international competition [−intE]<br>- No protection of national solar industry [−intE] | |
| Institutional effects [instE] | - EEG and 100,000 roofs program well-aligned [+instE]<br>- EU DG energy and competition oppose bill [−instE] | - BMWi advisory board proposes to terminate EEG due to potential conflicts with EU ETS [−instE]<br>- State-aid inquiries of EU [−instE] | - Decreased conflict between BMWi and BMU due to positive TIS development [+instE] | - Increasing conflict between BMWi and BMU; debate on 'Strompreisbremse'<br>- Increasing misalignment with grid infrastructure<br>- European Commission inquiry based on state-aid guidelines [-AF/−instE] | - Amendment of state-aid guidelines, emphasis on market instruments<br>- Responsibilities for energy policy bundled at BMWi |
| TIS development (see also Table A.2 for additional information) | - Wind TIS has grown, German industry second-largest in the world<br>- The world market for PV already growing, expanding production in Germany | - German solar TIS grows, and new entrants | - Strong market development, installed capacity grows fast<br>- Module prices decrease due to technological learning<br>- High R&D expenditure | - German PV module producers lose market shares, entrepreneurial activity decreases<br>- After 2011, several German manufacturers file for bankruptcy<br>- Employment decreases, and expectations turn negative<br>- Slowdown of market development from 2012 | - Solar TIS stabilizes: Employment and business climate |
| Sectoral change | - Liberalization promises profits for conventional plants | - Liberalization promises profits for conventional plants | - High profits of utilities due to ETS and alleged market power | - Economic crisis, reduced electricity demand, increased competition from renewables | - Utilities restructure and split up or sell conventional power assets and renewables |

(*continued on next page*)

**Table 2** (*continued*)

| EEG | 0 (1999–2000) | I (2000–2004) | II (2004–2009) | III (2009-2014) | IV (2014–2017) |
|---|---|---|---|---|---|
| | - Renewables share 2000: 6.3 % of electricity consumption | - Renewables share 2004: 9.4 % of electricity consumption | - Expansion of conventional power plant fleet<br>- Utilities lose legitimacy<br>- Utilities diversify and invest in renewables, but only outside of the home market<br>- Renewables share 2010: 17 % of electricity consumption | - Nuclear phase-out increases pressure<br>- Wind offshore as a business opportunity<br>- Value adjustments of utilities<br>- Renewables share 2014: 27.4 % of electricity consumption | - Offshore auctions offer investment options for large-scale investments<br>- Renewables share 2017: 36 % of electricity consumption |
| Exogeneous Conditions [ExC] | - EnWG enacted in 1998<br>- Agreement on nuclear phase-out in 2000 | - Nuclear phase-out becomes law | - The first trading period of EU ETS starts in 2005<br>- Changes of the EnWG and introduction of a regulatory authority for electricity markets (Bundesnetzagentur)<br>- Shortage of silicon on the world market<br>- Financial crisis in 2008 | - Financial crisis<br>- Increasing worldwide production of PV modules; dropping silicon prices<br>- Nuclear incidents in 2011 in Fukushima, Japan, and German nuclear phase-out until 2022 | |
| Policy change (focus on solar) | - 100,000 roofs program<br>EEG enacted 2000:<br>- Technology-specific remuneration of renewable electricity for 20 years<br>- Cap for installed PV capacity<br>- Fixed annual degression<br>- Remuneration is added to electricity bills via the EEG surcharge | 2004:<br>- "Solarstrom-Vorschaltgesetz" initiated by the parliamentary factions of social democrats and greens<br>- Cap on PV capacity removed, remuneration increased | 2009:<br>- Dynamic degression of remuneration depending on annual installed capacity<br>- Support of self-consumption | 2010:<br>- One-time degression of remuneration in July and October<br>- Increased regular annual degression of solar remuneration<br>2011:<br>- Adjustments of degression rates due to high solar deployment<br>2012:<br>- Introduction of (voluntary) market premium<br>- Increase of industry exemptions<br>- Monthly degression of solar remuneration if target corridors exceeded<br>- Cap for funding of a maximum of 52 MW installed solar capacity<br>2014:<br>- Pilot phase for auctions for ground-mounted solar<br>- Obligatory market premium for all technologies<br>- Monthly degression for all technologies | 2017:<br>- Introduction of auctions for all technologies<br>- "Netzausbaugebiete" should limit wind expansion with high curtailment from 2017 |
| Policy subsystem change | - Social democrats and greens form a coalition (1998)<br>- BMWi responsible (minister Müller) but reluctant to propose the bill<br>- Members of parliament propose bill | - Social democrats and greens reelected (2002), shift weights towards greens<br>- Responsibility for EEG passed to BMU<br>- Conflicts between BMU and BMWi | - Conservatives and social democrats form coalition 2005 (Chancellor Merkel)<br>- Solar power is increasingly seen as costly in parliamentary debates | - Conservatives and liberals form coalition 2009 (Chancellor Merkel)<br>- Conservatives and social-democrats form coalition 2013 (Chancellor Merkel)<br>- Responsibility for EEG passed from BMU to BMWi after elections in 2013<br>- Influential actors/ministers: Rösler (economic affairs, 2011–2013), Röttgen (environment, 2009–2012), Altmaier (environment, 2012–2013), Gabriel (economic affairs, 2013–2017)<br>- Secretaries of state: Baake | |

### 4.2. *Phase I - post-enactment and interaction with existing institutions*

#### 4.2.1. *EEG case study (2000–2004)*

The new EEG, enacted in April 2000, introduced a fixed remuneration differentiated by technologies. The EEG promised a remuneration of 50,6 Cent/kWh for 20 years for electricity generated by solar PV. However, the support for PV was initially capped at a maximum amount of 350 MW of installed capacity.

In the phase after enactment, the EEG's alignment with existing institutions was put into question by various circumstances. High uncertainties arose from the state-aid inquiries of the European Commission **[−instE]**, which the European court of justice finally resolved in 2001 (Hirschl, 2008, p. 149). Later within this period, the EEG came into conflict with the planned introduction of the European emission trading scheme, where the scientific advisory board of the economics ministry even proposed to terminate the law altogether due to its possible interactions with the trading scheme in Europe **[−instE]** (Hirschl, 2008, pp. 157–162), increasing uncertainty on the maintenance of the EEG **[−intE]**.

Despite these uncertainties, the EEG was able to support PV *market creation* **[+RE]** (Fig. 2) together with the earlier introduced 100,000 roofs program **[+instE]**. The EEG *mobilized resources* that drew in new entrants along the whole value chain into the TIS, and networks within the TIS tightened **[+intE, +RE]** (Quitzow, 2015, p. 131). Households, farmers, citizen cooperatives, and green ventures could now produce electricity for economic and ideological reasons (Dewald and Truffer, 2011; Mautz et al., 2008, pp. 93–95), and *entrepreneurial activity* increased. In 2003, most large module producers had entered the market (Quitzow, 2015, p. 131). Within this phase, *knowledge development and diffusion* accelerated with patenting activity increasing (Fig. 3) and a higher level of R&D collaboration (Hipp, 2021, p. 575). New entrants and the broad actors base also strengthened solar industry associations (Jacobsson et al., 2004, p. 21), increasing the potential for *legitimacy creation* **[+SPF]**.

On the other hand, utility companies lobbied against the feed-in priority granted to renewable energies in the forerun of the EEG 2004 amendments. They promoted the market integration of renewable electricity, knowing that the technologies were not competitive enough in the wholesale market **[-SPF]** (Kungl, 2018, pp. 191–192). The energy industry association mainly drove campaigns. However, utilities were not united in their opposition, as EnBW turned to the EEG supporter group due to their interest in installing hydro plants **[SPF]** (Kungl, 2018, p. 192). At the same time, utilities did not engage in renewable investments due to their return expectations and the risk of increasing competition for their power plants in an oversupplied market (Kungl, 2018, pp. 197–198). During the elections in 2002, the aluminum industry and industry associations lobbied for exemptions for energy-intensive industries **[SPF]** (Hirschl, 2008, p. 156).

Within the government parties, solar, wind, and biomass were generally evaluated positively in the debates on the amendments of 2004 (Seibt, 2015, pp. 181–183). An essential theme of parliamentary debates was the market creation and the chances to create jobs in a growth industry **[+SPF]** but also costs for society and particularly industry entered the discussions (Hoppmann et al., 2014, pp. 1427–1429). The broad actor base made representatives more susceptible to lobbying by renewable energy associations as local initiatives and citizens increased pressure **[+SPF]** (Seibt, 2015, p. 180).

#### 4.2.2. Comparative discussion

The phase after enactment of the EEG was shaped by the increasing development of the TIS and the solar market, but also by frictions of the EEG with existing laws and regulations. Thus, the unfolding of the technology loop is hampered by policy uncertainties influencing resource mobilization by interpretive effects. Such institutional struggles have been described in the policy feedback literature after enactment (Patashnik and Zelizer, 2009) and in the classical policy cycle (Jann and Wegrich, 2017, pp. 51–53). These struggles may contribute to the uncertainty of actors about whether the policy will be maintained and contribute to administrative feedback. Often, early deployment policies come with caps on the degree of deployment or temporal limitations (Stokes and Breetz, 2018), similar to the German EEG. As for the case of the EEG, Stokes and Breetz (2018) observe that increasing industry feedback helps to extend support. In the case of the EEG, this process was contested by sectoral actors such as utilities, who were unable to form a ‘closed industry front’ due to diverging interests.

### 4.3. Phase II - enthusiasm, growth, and realization of costs

#### 4.3.1. EEG case study (2005–2009)

The EEG amendment 2004 increased the remuneration for solar PV and removed the cap for installed PV capacity. After the amendment was passed and with the solar industry’s ongoing success, political conflicts around the EEG decreased for the moment **[+instE]** (Lauber and Jacobsson, 2016, p. 151).

The TIS functions show a high activity level driven by the EEG (Table A.2). The EEG supported the *market creation,* and demand for solar modules increased sharply **[+RE]** (Fig. 2). Removing the solar capacity cap additionally signaled a political commitment to solar energy **[+intE]** (Quitzow, 2015). *Entrepreneurial activity* increased, and a high number of new entries entered the market (Hipp, 2021, p. 573). Employment within the industry increased sharply (Fig. 4). Also *knowledge development and diffusion* accelerated, patent activity (Fig. 3) and R&D collaboration (Hipp, 2021, p. 575) increased, and private R&D expenditure soon surpassed public spending (Quitzow, 2015). Q-Cells

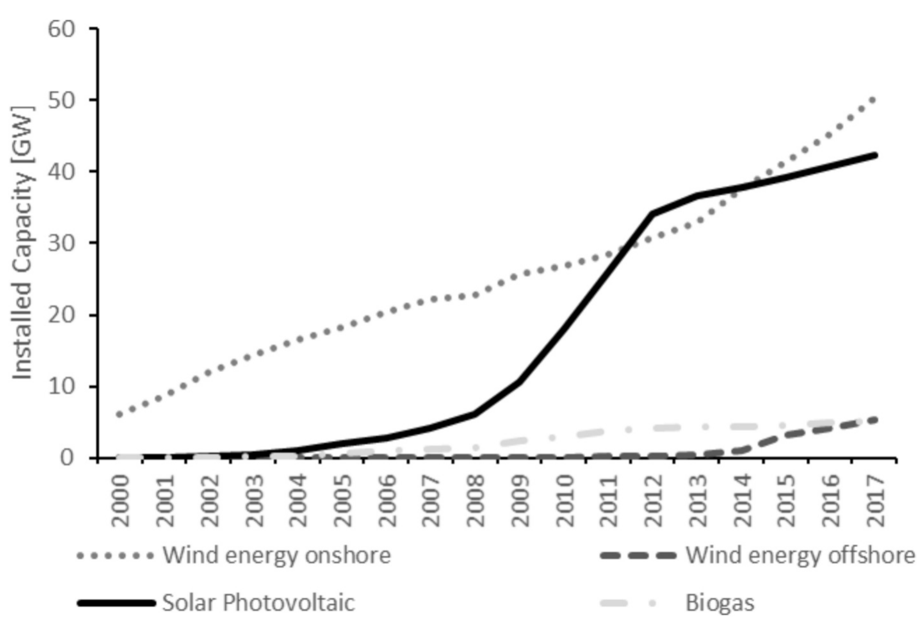


**Fig. 2.** Cumulative installed capacity of renewable energy technologies in Germany (2000–2017) (AG Energiebilanzen e. V, 2019).

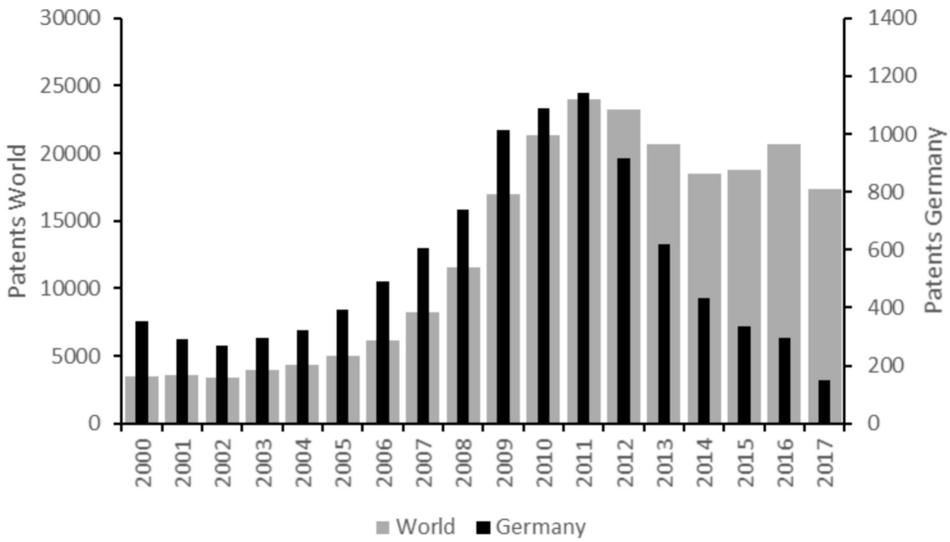


**Fig. 3.** Patents for solar technologies worldwide and in Germany (IRENA, 2021).

and Solarworld emerged as important actors while additional equipment suppliers entered the German market. However, high prices for silicon at the world market **[ExC]** limited the expansion of module production in Germany (Quitzow, 2015, p. 134), and supply constraints of German module producers increased ties to pioneering companies in China via OEMs and joint ventures. These interactions increased trust in the quality and opened the German market for Chinese products (Quitzow, 2015). The solar industry association (Bundesverband Solarwirtschaft; BSW) increased lobbying activities (Seibt, 2015). Job creation and international industry leadership became core arguments for *legitimacy creation* **[+SPF]** (Quitzow, 2015, p. 133). However, with growing deployment, the integration of PV into the electricity grid became an issue **[−instE]** (Hoppmann et al., 2014), the EEG surcharge increased (Fig. 5), and therewith the costs imposed onto the population and industry **[−RE]**.

The large incumbent utilities expanded their conventional capacities and built new coal and gas power plants. The recently introduced carbon trading scheme increased the profits of their power plant fleet, as certificate prices are endogenized into electricity prices (Kungl, 2018, p. 225). While incumbents focused on their core business in the beginning, their opposition towards the EEG grew, referring to a possible "deindustrialization" of the German economy, "when the threat to the incumbents' vision of the field coming from the expansion of renewables became more and more apparent" by the end of this phase **[-SPF]**

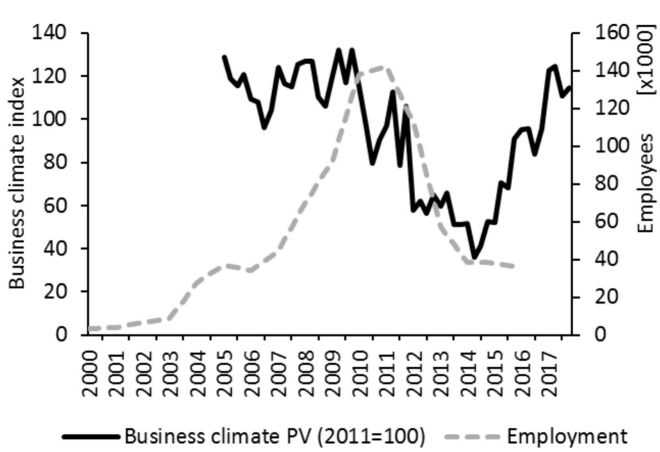


**Fig. 4.** Business climate index of the PV industry in Germany (BSW-Solar, 2019) and employment in the PV industry (O'Sullivan et al., 2018).

(Kungl, 2015, p. 18). However, between 2006 and 2008, utilities founded subdivisions for investment in renewables (Kungl, 2018, 244ff). The new subdivisions primarily invested in projects beyond the German borders, as investments within Germany would have meant increasing competition for their own assets (Kungl, 2018, p. 309).

The fast development of the solar TIS "led to an unprecedented excitement among politicians of all parties. In many debates, the EEG was praised as a success story *[…]*. Even the FDP, which was the only party that favored 'market-based instruments', such as tradable green certificates over a FIT, urged measures to support the export of German PV technology" (Hoppmann et al., 2014, p. 1429). However, module prices declined further by the end of this phase, also attributable to an expansion of module production worldwide (particularly in China (Quitzow, 2015)). Windfall profits of investors and increasing policy costs contrasted the previous positive image of PV within parliamentary debates **[−RE - > -SPF]** (Hoppmann et al., 2014; Seibt, 2015, pp. 181–182). To reduce PV windfall profits and limit costs borne by consumers, the EEG amendment of 2009 introduced a 'dynamic degression' that made remuneration dependent on the installed capacity in the previous year (Hoppmann et al., 2014, pp. 1429–1430).

#### 4.3.2. Comparative discussion

In this phase, TIS development and focal policy produce a virtuous cycle of mutual reinforcement. The technology loop unfolds its full potential, when resource effects spur market development, while policy uncertainty and hampering interpretive effects are reduced. Positive externalities from the technology loop provide strong policy support.

Particularly in the electricity sector, evidence for the effect of local value creation in renewable energy technologies on policy ambition is strong (Eicke and Weko, 2022). For example, renewables were reframed in China as vital to economic growth and competitiveness and experienced increased political support in the early 2000s (Mori, 2018). However, evidence beyond the electricity sector of such virtuous cycles may be found in the Swedish biofuel programs, where a vigorously active TIS contributed to the introduction of more stringent market stimulation policies (Suurs, 2009, p. 134). Despite its mixed results, Jänicke (2012) refers to improving energy efficiency as a case of successful virtuous cycles in Germany, Japan, and the UK.[5]

Ironically, the virtuous cycle inducing TIS expansion nourishes the

[5] However, one must acknowledge that the UK zero carbon homes program was dismantled after the financial crisis in 2008 (Edmondson et al., 2020).

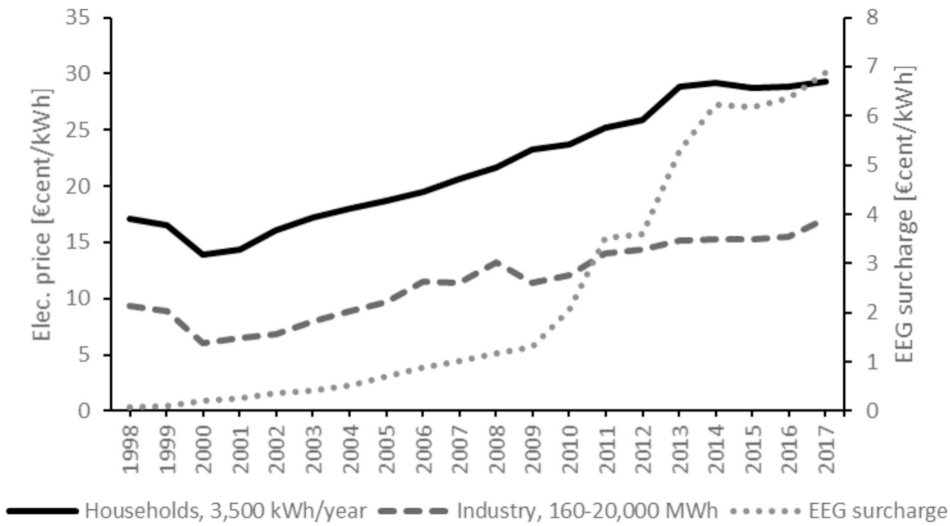


**Fig. 5.** Development of electricity prices and the EEG surcharge (BDEW, 2021).

roots of subsequent vicious cycles. Strong market creation in Germany also attracts increasing competition from abroad. Renewable generation depresses electricity wholesale prices,[6] policy costs redistributed by the surcharge became more prominent within the policy process of the EEG, and utilities and industry mobilized against the EEG. Already in this early stage, the cost loop starts to unfold, starting to interfere with the positive feedback generated by the technology loop.

Evidence from various cases indicates increasing opposition towards support schemes with increasing technology penetration and competition (Gürtler et al., 2019; Mori, 2018; Prontera, 2021; Stokes and Breetz, 2018). Particularly in Europe, the economic crisis of 2008 was an additional exogenous driver of increasing opposition, as it also affected electricity demand (Gürtler et al., 2019; Prontera, 2021). However, also the StrEG faced increasing opposition from utilities in 1996 in the absence of an economic crisis (Table A.1). The cases above primarily rely on schemes that distribute the costs towards consumers (resource effects), for example, via surcharges to the electricity bill, and therefore emit socio-political feedback due to the imposition of costs towards a significant fraction of population and industry. However, when costs are borne by state budgets (resource effects), fiscal feedback may arise from financial ministries or treasury (e.g., Edmondson et al., 2020).

Besides policy costs and competition, institutional effects can become a source of growing negative feedback with increasing deployment. For example, biogas and biofuel production brought along increasing concerns about the competition with food cultivation (Markard et al., 2016b; Pilgrim and Harvey, 2010; Suurs and Hekkert, 2009), and wind power in Germany was challenged increasingly by acceptance issues (Dehler-Holland et al., 2022).

### *4.4. Phase III - political struggles and increased uncertainty*

#### *4.4.1. EEG case study (2009-2014)*

Shortly after the EEG amendments in 2009, it became clear that remuneration reductions were insufficient to reduce the pace of PV market uptake due to rapidly plummeting module prices driven by a rapid expansion of international PV production capacities **[+RE]** (Fig. 2). Therefore, remuneration was further reduced in 2010 and the beginning of 2012, until in 2012, a target corridor for PV between 2.5 and 3.5 GW was introduced and a monthly degression of remuneration in case the corridor was exceeded. At the same time, the EEG surcharge that was collected from households and industry via the electricity bill increased further **[−RE]** (Fig. 5). Furthermore, renewable energy production increasingly depressed electricity wholesale prices, reducing revenues of electricity generators **[−RE]**. Additionally, grid stability and power intermittency risks entered political debates and showcased the possible technological issues to align expanding renewables with existing infrastructure **[−instE]** (Hoppmann et al., 2014).

The difference between feed-in remuneration and PV module costs further drove *market creation* in Germany. However, Chinese imports that could compete with European quality standards and leverage the advantages of low-cost, large-scale production capacities increasingly covered the demand **[RE]** (Quitzow, 2015). German module producers' ability to mobilize resources decreased, and *entrepreneurial activity* decreased with increasing exit rates (Hipp, 2021, p. 573) and dropping employment (Fig. 4). Consequently, *knowledge development and diffusion* regarding R&D collaborations (Hipp, 2021, p. 575) and patenting activity (Fig. 3) declined. Concerning rising Chinese competition and import duties on Chinese products, the solar industry was split between profiteers (e.g., installers of cheap modules) and losers (e.g., module manufacturers) of an increasingly internationalized supply chain (Meckling and Hughes, 2018). Despite the loss of legitimacy of the German solar TIS in terms of costs and performance and increasingly divided interests regarding Chinese imports, the industry association BSW was regarded as successful in preventing stronger EEG cutbacks **[+SPF]** (Seibt, 2015, p. 197). The ties of the TIS to the governments of the states in Eastern Germany also contributed to safeguarding benefits **[+SPF]** (Lauber and Jacobsson, 2016; Quitzow, 2015; Strunz et al., 2016).

Utilities faced external pressures from declining market shares due to increased renewable capacities, lower power demand due to the financial crisis, and decreasing power prices due to renewables and dropping commodity prices (Kungl and Geels, 2018, p. 12). However, until 2011, those external pressures did not strongly affect utilities (Kungl and Geels, 2018). They continued their defensive strategies concerning the EEG, but their activities regarding nuclear lifetime expansion and carbon capture and storage prevailed (Kungl, 2015, p. 261).

After the nuclear accidents in Japan, the conservative-liberal government decided on a rapid nuclear phase-out, which immediately affected utilities' power plant portfolios and profit expectations. External pressures on utilities and their conventional power plants increased **[ExC]** (Kungl and Geels, 2018). Concerning the EEG, utilities supported a stronger market integration **[SPF]** (Kungl, 2018, p. 356) and put BMWi under pressure favoring auctions for renewables (Leiren and Reimer, 2018, p. 37). While they now, in principle, accepted the Energiewende, their arguments changed from the general technological

[6] This is referred to as the merit-order effect (Sensfuß et al., 2008).

and economic infeasibility of renewables to threats to supply security and the support scheme's costs (Kungl, 2018, p. 356). Utilities seized the rising EEG surcharge (Fig. 5) as an argument against the EEG and its increasing burden on (vulnerable) households **[-SPF]** (Kungl, 2018, pp. 360–361).

From 2011, policy costs became a key topic politically **[SPF]** (Leiren and Reimer, 2018). Media framing of the EEG shifted towards emphasizing its costs **[-SPF]** (Dehler-Holland et al., 2021). The increasing EEG surcharge (Fig. 5) was seen as dangerous for the competitiveness of the German industry **[-SPF]**. Particularly the powerful federation of German industry (*Bundesverband der Deutschen Industrie, BDI*) increased its activities between 2009 and 2015 **[SPF]** (Borshchevska, 2016, p. 103). Its main arguments were 1) the risk to the security of supply, 2) poor management of the energy transition leading to unpredictable policymaking **[-AF]**, and 3) the rising EEG surcharge bearing competitive disadvantages for the German industry (Borshchevska, 2016). The extensive political activity of the energy-intensive industries goes in line with further exemptions of the EEG surcharge for large electricity consumers (Strunz et al., 2016).

In the forerun of the elections of September 2013, all major German parties agreed that reforms were necessary (Messing, 2020, p. 172) due to the increased costs of renewables (Leiren and Reimer, 2018, p. 37). The new government introduced a pilot phase for PV auctions with the target to introduce auctions for wind power and PV by 2017.

#### 4.4.2. Comparative discussion

The preceding phase has strengthened the political position of the focal TIS and, at the same time, increased the array of opponents' arguments. The solar TIS in Germany struggled with intense international competition, dropping module prices and rapidly reducing market support for PV as a consequence of negative feedback from the cost loop.

Similarly, renewable support in various European countries has seen retrenchments and even termination supported by pressure from utilities in the aftermath of the financial crisis of 2008 (Gürtler et al., 2019; Prontera, 2021). Also the StrEG was faced with initiatives proposing to dismantle the law around 1996; however, the wind power lobby successfully defended it (Table A.1, Bergek and Jacobsson, 2003). Additional examples of deployment policies in the US transport sector for biofuel and electric vehicles witnessed increasing opposition with progressing diffusion and subsequent retrenchments due to increasing policy costs (Stokes and Breetz, 2018). Interestingly, these examples also provide evidence for a stage of political uncertainty over the future of programs.

With growing diffusion, also institutional effects of technology deployment become apparent. In the case of solar energy in Germany, grid integration and security of supply increase in political salience. The side-effects loop is triggered by adverse institutional effects that further contribute to undermining positive feedback from the technology loop.

Similar dynamics have been observed in the support of biogas electricity generation in Germany, which was reduced significantly due to land use conflicts (Markard et al., 2016b), as were biofuel targets in Europe (Purkus et al., 2019). Furthermore, Germany witnessed intense discussions on increasing the mandatory distance of wind turbines to dwellings with growing local acceptance issues (Dehler-Holland et al., 2022).

The ability of the German solar (and earlier, wind power) TIS to prevent stronger cutbacks despite increased competition from abroad and declining legitimacy is worth further discussion. The cases presented by Gürtler et al. (2019) (Spain, Czech Republic) and Prontera (2021) (Italy) represent cases in which renewable energy support has been terminated completely, or at least market development has come to a halt. In contrast, the cutbacks perceived in Germany did not wholly stop development (Fig. 2), and support for deployment was maintained at a lower level. We argue that these differences may be related to the lobbying of a TIS active along the whole value chain of technology creation and the related framing of renewable energies having positive societal and economic effects such as industry and job creation. Prontera (2021) emphasizes that Italy did not have a comparable photovoltaics industry, and neither did the Czech Republic. In the case of Spain, a comparative media analysis found that the framing of photovoltaics in terms of its economic benefits did not occur (Kriechbaum et al., 2017). In the German case, a growing wind TIS in 1996 could fend off policy retrenchments, and a struggling but well-connected PV TIS between 2010 and 2014 prevented stronger policy cutbacks. In that respect, this study contributes to the literature on sustainability transitions highlighting the importance of creating strong advocacy coalitions to prevent early dismantling, as observed in the case of zero-carbon homes in the UK (Edmondson et al., 2020; O'Neill and Gibbs, 2020).

### 4.5. Phase IV - political consolidation, loss of interest, reorientation

#### 4.5.1. EEG case study (2014–2017)

After the elections in 2013, the new government introduced a pilot phase for a tendering scheme for PV into the EEG, intending to introduce auctions for all renewable technologies by 2017. Since 2012, the feed-in remuneration for solar electricity has been lower than the household electricity price,[7] wherefore the business model for household PV changed towards self-consumption of electricity (Dehler et al., 2017). Together with target corridors, a cap on the target for installed capacity of PV, and reduced remuneration, these developments limited the potential for *market creation* in Germany. Additionally, the increase of the EEG surcharge came to a halt (Fig. 5), decreasing immediate pressure on policymakers. *Entrepreneurial activities* stabilized on a lower level with almost no new entries in cell and module manufacturing (Hipp, 2021, p. 573) and a stable number of employees in the industry (Fig. 4), focussing on installation and production equipment. *Knowledge development and diffusion* remained at a low level (Fig. 3). In preparation for the final introduction of auctioning in the EEG amendments 2017, the economics ministry implemented platforms to discuss details of the reforms with various stakeholders; however, the critical points of the reform were not up for discussion, and renewable energy associations were perceived as having little influence in the debate (Messing, 2020, p. 158). A critical subject of debate was how small investors such as citizen cooperatives could be incentivized, as the auctioning scheme was seen as problematic for investors who cannot diversify investment risks with a higher number of bids (Messing, 2020, p. 145). Additionally, missing electricity grid capacities were addressed in the discourse (Messing, 2020, p. 174). The attention of energy transition policy increasingly turned to the phase-out of coal electricity generation (Leipprand and Flachsland, 2018).

#### 4.5.2. Comparative discussion

Within the fourth phase, the attention of all actors towards the EEG and feedback declined. Resource provision to the TIS was moderate and adapted to the growth corridors, the EEG surcharge did not grow further, and in 2017, tenders were finally introduced in a process that left little space for debate. The contradicting feedback of the three different loops has been balanced in political discourse, resulting in a temporal relief of political tensions.

Similar phases have been observed in the literature on political attention after the intense realization of costs (Downs, 1972). The PV TIS activities stabilized, albeit on a lower level. The results of this phase depend on the relative strength of the three different feedback loops. For example, after policy dismantling in Spain, the Czech Republic, and Italy, markets for renewable energy collapsed when policy costs increased and have not been balanced by an equally strong technology loop (Gürtler et al., 2019; Prontera, 2021). Similarly, German biogas deployment was reduced drastically, when side effects regarding food production became prevalent (Markard et al., 2016b).

[7] A condition often termed *grid parity*.

### 4.6. Towards a life cycle model of technology deployment policies

The previous sections have shown how policy effects and feedback relate to the developments of the German EEG and the solar TIS in Germany. These empirical results underpin the recent identification of an attention-cycle pattern of German news media coverage (Dehler-Holland et al., 2021) with a detailed description of technology and policy processes that drive the emergence of such patterns. A comparative discussion of similar cases from the literature contrasted the empirical results.

Building upon these findings, this paper proposes a stylized representation of main policy effects and feedback (Fig. 6Fig. 6, Table 3). The activity level of the three feedback loops conceptualized in Section 2.3 influences the development of the cycle. For instance, in the discussion of phase IV (Section 4.5.2), the hypothesis was developed that the policy output of the life cycle crucially depends on the relative strength of the three loops (Fig. 6 b).

Since its first inception by Downs (1972), the phenomenon of attention cycles has aroused high academic interest, and the basic patterns were identified in various domains (Gupta and Jenkins-Smith, 2015). However, the processes behind these attention patterns are poorly understood. The results presented in Section 4 provided insights into the mechanisms driving political and societal debates in the case of the German EEG. Particularly, positive media coverage of the PV industry indeed went along with high innovative activity in the German TIS. Increasing prevalence of costs in the media indeed followed an increasingly harsh political and societal debate. The next section will discuss the prospects of the development of the three feedback loops in more detail.

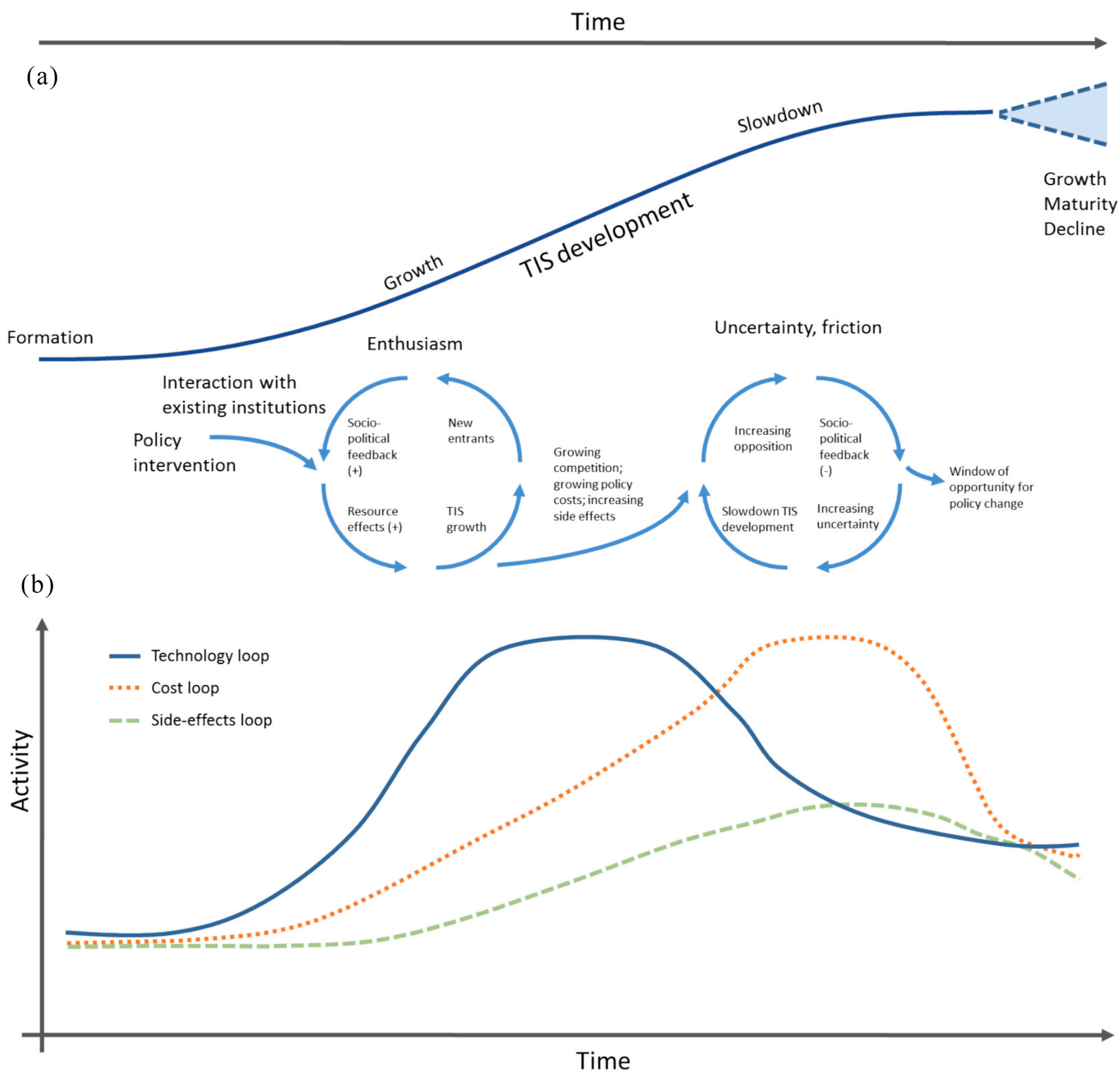


**Fig. 6.** (a) Illustration of the technology deployment policy life cycle model. (b) Stylized activity levels of the three different feedback loops for the case of the German EEG and PV.

**Table 3**
A technology deployment policy life cycle model for the case of the German EEG.

| Phase | Characterization | TIS stage | Effects | Feedback mechanisms | Feedback loop |
|---|---|---|---|---|---|
| 0 | *Pre-enactment* | Formative, early growth with emerging political networks | • Policy not yet enacted | • Initial support from the TIS<br>• Underestimation of incumbents<br>• Issue attention to certain societal problems | – |
| I | *Post-enactment and interaction with existing policy and institutions* | Formative or early growth | • InstE due to embedding of focal policy into existing institutional arrangements<br>• RE due to the focal policy<br>• intE: uncertainty whether the policy will be maintained | • AdF<br>• FF less likely; low costs<br>• -SPF from incumbents, closed industry fronts against technology<br>• +SPF increasing political ties of TIS | • Technology loop begins to provide positive feedback, yet hampered TIS development by interpretive effects hampering resource mobilization |
| II | *Technology and policy enthusiasm and realization of costs* | Growth | • +RE due to the focal policy<br>• -RE due to increasing policy costs for public or national budget; increasing competition in the sector<br>• intE: Policymakers appear committed to technology and policy<br>• instE: policies well-aligned<br>• TIS actors actively search for ways to efficiently satisfy growing demand | • +SPF: Industry associations and TIS actors increase political ties<br>• Increased positive externalities: job creation, technology leadership<br>• -FF/-SPF: policy costs increase | • Strong positive feedback by the technology loop; positive externalities support legitimacy creation<br>• Cost loop starting to provide negative feedback, undermining TIS legitimacy creation by feedback from the TIS context |
| III | *Political struggles and increased uncertainty* | Shakeout/ decline | • intE: increasing uncertainty about whether the policy will be maintained or changed<br>• Reduced RE for TIS<br>• -RE due to policy costs<br>• Increasing instE due to technology alignment | • Stage of the TIS determines continued or decreasing +SPF<br>• -FF/-SPF: High policy costs<br>• -SPF: incumbents seize policy costs as an argument; shape policy to meet their demands<br>• -AdF is possible due to technology side effects | • Technology loop weakened by TIS competition and national decline, lower potential for legitimacy creation<br>• Cost loop and side-effect loop superimpose technology loop |
| IV | *Political consolidation, loss of interest, reorientation* | Maturity | • intE uncertainties resolved<br>• RE depending on the previous phase<br>• instE: adaption of institutional arrangements towards technology | • Low attention to policy, feedback declined<br>• Sensitive to events that rekindle attention | • Activity of feedback loops balanced by political action to consolidate feedback |

## 5. Discussion

The previous sections analyzed the co-evolution of the German EEG and the photovoltaics TIS and identified three major drivers of developments. This section discusses the three feedback loops and identifies policy implications of the identified mechanisms. Furthermore, possible avenues for future research and methodological limitations are addressed.

First, the case study showcased how the EEG was able to create strong incentives for the deployment of PV. The activities within the TIS during the expanding technology feedback loop can be described as a search process in which actors try to find ways to meet increasing demand by expanding innovative activities and searching for solutions within the TIS's context. This extensive search process induces enthusiastic political discourse on positive economic externalities of TIS development, such as job creation or industry leadership. Surprisingly, in Germany, the demand for PV modules could not be met by the growing German TIS alone, which therefore triggered the search for alternative supply chains; German suppliers actively entered collaborations with Chinese cell producers. In the following, fast developments in China led to expanding production capacities, decreasing module costs, and ultimately to the decline of the German solar TIS. The positions of the German solar TIS were divided into winners and losers of the ongoing internationalization, which affected its potential for legitimacy creation and policy feedback. The literature has shown that the potential for the allocation of different parts of the supply chain depends on the characteristics of the focal technology and national innovation systems (Quitzow et al., 2017; Schmidt and Huenteler, 2016). When innovation regarding a technology largely comprises its manufacturing and products are easy to transport, TIS actors are likely to face global markets and competition (Schmidt and Huenteler, 2016). On the other hand, the discussed cases of wind and biomass electricity generation did not suffer similar allocation struggles. Both technologies require more exchange between deployers and manufacturers than PV for innovation. Therefore, technology complexity and the geographical context of a TIS must be considered when developing deployment policies.

From a national perspective, policymakers might be inclined to shield national deployment policies from external entries. However, the welfare gains of global supply chains compared to a restriction on national suppliers are substantial (Helveston et al., 2022). Alternatively, national deployment policies could be complemented and balanced with more support for the supply side, such as increased R&D support to maintain the competitiveness of national TIS (Nuñez-Jimenez et al., 2022). Such additional measures in a broader policy mix could help guide the search in more favorable directions in political terms.

Second, the case study showed how the distribution of increasing costs grew into a feedback loop superimposing the perceived positive effects of job creation and industrial leadership. The negative feedback concerning policy costs arises from sectoral competition and the distribution of costs within the public or the state's budget. Such feedback appears to ignore the long-term benefits of emission reductions and that external costs have not been sufficiently internalized in electricity prices from conventional sources (Lauber and Jacobsson, 2016). For policymakers, the cost feedback implies a dilemma of maintaining sufficient support so that technology deployment is not stalled while responding to increasing opposition. The literature has discussed the ability of policies to adapt to changes by design under the labels of *robustness* or *resilience* (Capano and Woo, 2017). Procedural measures included in policy design, such as regular monitoring intervals, planned policy revision, or (semi-)automatic adjustment mechanisms, can help to make policies more adaptive and may contribute to limiting undermining feedback (Howlett, 2019; Jordan and Matt, 2014). In the case of the EEG, the German government opted for redirecting policy costs from consumer electricity bills to the state's budget. While such a decision may reduce the visibility of policy costs to the public, it may expose the policy to budget cuts due to austerity plans.

Third, the side-effects loop has been less prevalent in the case of PV. Issues such as power grid stability and security of supply have entered the debate only marginally. This does not mean, however, that such institutional issues can have a decisive effect on policy decisions. Cases that we discussed above show, that institutional struggles between technology characteristics and alleged adverse effects of its deployment can lead to changes in support policies (e.g., Dehler-Holland et al., 2022; Markard et al., 2016b). It therefore remains important to consider possible conflicts such as local acceptance early within the policy cycle.

The abstraction of feedback loops undertaken in this paper should not hide the fact that at the core of policy feedback, political actors, interest groups, and vested interests and their agency are drivers of political discourse. For instance, at the climax of the EEG cost narrative, German policymakers started to discuss the phase-out of coal electricity generation. Here, I argue that this discourse was partly driven by the increasing perception of the policy costs of renewable energies and the realization that a successful transition cannot be driven by deployment policies alone against increasing regime resistance. On the one hand, this points to a limitation of this study, where I focused on a single policy instrument instead of a policy mix.

On the other hand side, there is some potential in the identification of the three feedback loops and the TDP life cycle, which provides a sense of timing, when policy mixes must be taken one step further to actively undermine forces of regime inertia when the wave of technology euphoria has passed, and negative feedback dominates. This observation links the described life cycles to broader policy mixes (Rogge and Reichardt, 2016) and points to avenues for future research. Breetz et al. (2018) suggested that policy measures and logics change along the technology learning curve. The TDP life cycle model could be the starting point of the description of the co-evolution of policy mixes and technology along the temporal axis.

Methodologically, this study built upon a synthesis of existing studies on the case of the Renewable Energy Act in Germany. Such a synthesis approach may have weaknesses. First, a synthesis approach can only be followed for a case with a substantial research base. This was the case for the German EEG. However, as the observational period spans a considerable period (1999–2017), coverage of the case towards the end of the period becomes thinner (as can be observed in Table A.1). This can be explained by the increasing proximity of the observational period to the point in time the research was conducted. The decreasing attractiveness for research of the latter stages of the German solar TIS may also contribute to this issue. Second, a synthesis approach primarily relies on the interpretation of the original studies. Therefore, heterogeneous perspectives and methods from these studies must be translated into a common framework, and the quality of the results also depends on the quality of primary studies.

Additionally, this study followed an inductive approach to theory building. The inductive way of reasoning bears the risk of overgeneralization. This risk was mitigated by an additional triangulation of the resulting model with cases from the literature, and a closer analysis of the StrEG in Germany (Table A.1). Many studies focus on renewable energy policies in different jurisdictions; however, this study could also provide evidence from other sectors, particularly transportation. This might be because deployment policies are more common within these sectors or transitions have already advanced furthest.

## 6. Conclusions

This paper employed policy feedback and concepts from the literature on technological innovation systems to assess the dynamic relationships between technology deployment policies, relevant industries, and their contexts. Three feedback loops were distinguished whose activity levels relate policy output to policy outcomes. A case study of the German Renewable Energy Act and the PV TIS brought to light a temporal pattern whose characteristics were summarized in the proposal of an ideal-typical *technology deployment policy life cycle*.

The proposed model makes a step further in understanding the politics of sustainability transitions, particularly concerning the co-evolution of technology and policy (Edmondson et al., 2019; Hoppmann et al., 2014). Specifically, the model suggests that policy feedback may not be equal at different cycle stages and that different feedback loops compete with each other. Even more noteworthy, it indicates that phases of rapid TIS growth (virtuous cycles) can also increase negative feedback and induce vicious cycles of reduced policy support that ultimately open up windows of opportunities for retrenchment and possible breaches in transformation processes. Intense previous growth phases and prosperous TIS may increase the likelihood of policy maintenance or succession.

Future research will show whether similar patterns can be observed for other technologies and in other countries. A first comparison with reported cases provided reasons to believe that the identified three feedback loops and their relative activity levels have some explanatory value in assessing technology deployment policies.

I think the technology deployment policy life cycle model will be useful to scholars and policymakers. It provides a step towards outlining the possibilities of future policy change when deployment policies are enacted and points to critical policy design issues and the timing of regime destabilization measures in policy mixes.

## CRediT authorship contribution statement

**Joris Dehler-Holland:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, 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.

## Acknowledgments

JDH thanks Nicolas Schmid and Anthony Britto for helpful comments on earlier versions of the manuscript, Kira Schumacher for stimulating discussions, and three anonymous reviewers for constructive feedback.

## Appendix A. Appendix

**Table A.1**
Summary of the main developments of the StrEG (1990–2000) and wind power in Germany, divided into five phases. Compiled from (Bergek and Jacobsson, 2003; Geels et al., 2016; Hake et al., 2015; Jacobsson and Lauber, 2006; Lauber and Mez, 2004; Renn and Marshall, 2016; Stefes, 2010).

| StrEG | I (before 1991) | II (1992–1993) | III (1993–1995) | IV (1996–1997) | V (1997–1999) |
|---|---|---|---|---|---|
| Socio-political Feedback [SPF] | - Utilities underestimate feed-in law (StrEG) [no -SPF]<br>- Renewable associations propose feed-in law [+SPF] | | - Increased political leverage of wind power associations [+SPF]<br>- Opposition rises based on rising electricity costs; utilities support local initiatives against wind power and PR campaigns [-SPF] | - Utilities and VDEW increase pressure, file lawsuits against StrEG [-SPF]<br>- Protests against planned remuneration cutbacks by associations and citizen groups [+SPF] | |
| Fiscal Feedback [FF] | - Estimated low costs of the feed-in law and distribution of the expenses via electricity bills lower the potential for [FF] | | | - BMWi proposes to lower remuneration due to increasing costs [-FF] | |
| Administrative Feedback [AF] | | | | | |
| Resource Effects [RE] | 1989:<br>- Introduction of support programs (1000 roofs program, 100 MW program)<br>- Introduction of the focal StrEG in 1990 [+RE] | - Continued [RE] based on the combination of StrEG and additional programs | | - StrEG remains unchanged despite pressures; government proposal does not pass parliament<br>- Support reduced in some regions [−RE] | - Introduction of the 100,000 roofs program in 1999 |
| Interpretive Effects [intE] | | - Feed-in law reduces risk and uncertainty for investors | | - Political struggles increase uncertainty for investors [−intE] | - Uncertainties for investors are resolved when cutbacks do not pass parliament |
| Institutional effects [instE] | | - Feed-in law well-aligned with other market development programs [+instE] | - Importance of adjacent programs ceases, and StrEG becomes a major instrument [instE] | - Alleged conflict with European state-aid guidelines and StrEG | |
| Exogeneous Conditions [ExC] | - Increased public concerns about climate change and environment, nuclear safety<br>- German reunification challenges the energy sector and integration of East German power plants necessary | | | | - Introduction of EnWG<br>- Social democrats and greens elected |
| TIS development | - Initial development of wind TIS based on R&D support for renewables since the 70s and initial market development programs | - Initial wind market growth and TIS development due to increased [RE] | - Strong wind market development, increased learning, increased entries, specialization | - Rapid market expansion slows down, lower number of installations (Fig. A.1). | - Market expansion increases |
| Sectoral change | - Eastern and Western German electricity systems are merged<br>- Renewables share 1991: 3.1 % of electricity consumption | - Renewables share 1993: 3.8 % of electricity consumption | - Renewables share 1995: 4.7 % of electricity consumption | - Renewables share 1997: 4.1 % of electricity consumption | - Liberalization of the electricity sector by the EnWG increases competition and causes market consolidation<br>- The “Big Four” utilities emerge<br>- Renewables share 1999: 5.2 % of electricity consumption |

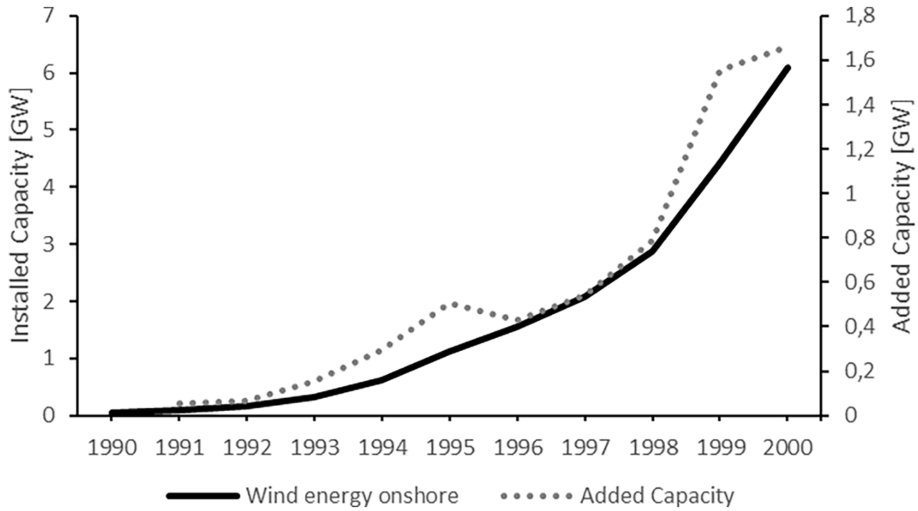


**Fig. A.1.** Installed wind energy capacity and yearly added capacity in Germany (1990–2000) (AG Energiebilanzen e. V, 2019).

**Table A.2**
Analysis of TIS functions of the German solar TIS.

| Function | Phase I (1999–2000) | Phase II (2000–2004) | Phase III (2004–2009) | Phase IV (2009-2014) | Phase V (2014–2017) |
|---|---|---|---|---|---|
| TIS Life cycle phase | Early growth | (Early) growth | Growth | Shakeout/Decline | Maturity |
| Entrepreneurial activities | - Increasing new entries in cell and module manufacturing (2000) (Hipp, 2021, p. 573)<br>- Increasing production capacities in Germany (Jacobsson et al., 2004, p. 18) | - Steady new entries, higher level in cell and module manufacturing (Hipp, 2021, p. 573)<br>- Incumbents leave the market, medium-sized companies dominate (Dewald and Fromhold-Eisebith, 2015)<br>- Slow increase in employment<br>- Firm entries and capacity extension could not keep pace with demand development (Quitzow, 2015, p. 132)<br>- Capacity expansion not as large as in Japan and the US (Quitzow, 2013) | - Increased level of new entries, and low exits in cell and module manufacturing (Hipp, 2021, p. 573)<br>- Ineffective in reducing costs; Capacity expansion only when silicon shortage over (Quitzow, 2015, p. 134)<br>- Strong increase in employment<br>- First signs of decline in 2009, lower investments, financial crisis (Quitzow, 2015, p. 139) | - Exits exceed entries, and almost no new entries in cell and module manufacturing (Hipp, 2021, p. 573)<br>- Collapse of employment<br>- Decline and insolvency of producers (Dewald and Fromhold-Eisebith, 2015)<br>- Still strong in production equipment (Dewald and Fromhold-Eisebith, 2015) | - Exits exceed entries, and almost no new entries in cell and module manufacturing (Hipp, 2021, p. 573)<br>- Stabilization of employment |
| Knowledge development | - Dominant design already emerged in the early 1990s, increase in patents (Huenteler et al., 2016)<br>- Strong knowledge base in German universities (Jacobsson et al., 2004, p. 21) | - Patents slightly decrease (Fig. 3) | - Patents increase fast (Fig. 3)<br>- Increased private and public expenditure (Quitzow, 2015, p. 134) | - Patents drop after 2011 (Fig. 3) | - Patents still drop (Fig. 3) |
| Knowledge diffusion through networks | - R&D collaboration increases (Hipp, 2021, p. 575)<br>- Collaboration of industry and universities (Jacobsson et al., 2004, p. 21) | - R&D collaboration at higher level (Hipp, 2021, p. 575)<br>- Intense collaborations between industry and research (Dewald and Fromhold-Eisebith, 2015) | - R&D collaboration increases steadily (Hipp, 2021, p. 575)<br>- Close collaboration between manufacturers and equipment suppliers (Quitzow, 2015, p. 134) | -R&D collaboration drops sharply (Hipp, 2021, p. 575) | -R&D collaboration low (Hipp, 2021, p. 575) |
| Guidance of the search | - "High growth potentials of solar cells" (Jacobsson et al., 2004, p. 23)<br>- 100,000 roofs program guides the search towards rooftop systems<br>- Wind power as an example of success | - FiT, however, caps for maximum solar capacity<br>- 100,000 roofs program | - High business climate index, starting to drop<br>- High silicon prices encourage development of thin-film technologies (Quitzow, 2015)<br>- Increasing uncertainty due to industry and market developments and policy goals (Quitzow, 2015, p. 143) | - Dropping business climate index<br>- Dropping societal expectations (Kriechbaum et al., 2017)<br>- Guidance towards production equipment | - Stabilization of business climate |

(*continued on next page*)

**Table A.2** (*continued*)

| Function | Phase I (1999–2000) | Phase II (2000–2004) | Phase III (2004–2009) | Phase IV (2009-2014) | Phase V (2014–2017) |
|---|---|---|---|---|---|
| TIS Life cycle phase | Early growth | (Early) growth | Growth | Shakeout/Decline | Maturity |
| Market formation | - 100,000 roofs program<br>- Local feed-in laws (Jacobsson et al., 2004, p. 19) | - Increased adoption<br>- FiT remuneration<br>- New market segments: rooftop, roof integration (Jacobsson et al., 2004, p. 19)<br>- Industry very vulnerable to market decline (Jacobsson et al., 2004, p. 21) | - Guidance towards production equipment<br>- Increased adoption<br>- FiT remuneration even higher<br>- Entry of ground-mounted system market segment (Dewald and Truffer, 2011, pp. 296–297)<br>- High business climate index, but dropping by the end of the phase | - Extreme increased adoption and slowdown<br>- FiT remuneration high, and cutbacks<br>- Dropping business climate index | - Linear path of adoption<br>- FiT remuneration adapted to growth<br>- Stabilization of business climate |
| Resource mobilization | "Collective forms of project financing (citizen solar plants – Bürgersolaranlagen)" (Dewald and Fromhold-Eisebith, 2015)<br>100,000 roofs program<br>Local Programmes in states/ by companies (Jacobsson et al., 2004, p. 18) | "Collective forms of project financing (citizen solar plants – Bürgersolaranlagen)" (Dewald and Fromhold-Eisebith, 2015)<br>EU promotion of solar cluster in Eastern Germany (Dewald and Fromhold-Eisebith, 2015) | "Collective forms of project financing (citizen solar plants – Bürgersolaranlagen)" (Dewald and Fromhold-Eisebith, 2015)<br>Half of installations profited from low-interest loans (KfW), Commerzbank, local banks, state-owned banks (Quitzow, 2015, p. 133)<br>Public investment subsidies available, but not used excessively, moderate growth of supply-side investment (Quitzow, 2015, pp. 134–135)<br>- Ineffective in reducing costs; Capacity expansion only when silicon shortage over (Quitzow, 2015, p. 134) | | |
| Creation of legitimacy | - Lobbying intensified for national market creation (Jacobsson et al., 2004, 18f) | - BSW: lower number of employees in 2004 compared to later<br>- Strengthened industry associations by new entrants (Jacobsson et al., 2004, p. 21)<br>- Industry and jobs strong argument for amendment in 2003 (Quitzow, 2015, p. 133) | - Seibt 143: Increase of employees of BSW, 151: Increase employment for lobbying and PR; 157: increased press releases; fusion of UVS and BSi in 2006 (Seibt, 2015)<br>- Support of eastern states governments prevents stronger cutbacks (Quitzow, 2013, p. 20)<br>- Strong industry increases political weight (Quitzow, 2015, 133&135) | - Seibt 143: Increase of employees of BSW until 2012, 151: Increase empl. For lobbying and PR, 157: increased press releases, 197: BSW most successful, can use high public acceptance, despite critique (Seibt, 2015)<br>- Fragmented value chain undermines common position of solar industry (Meckling and Hughes, 2018) | |

## Data availability

No data was used for the research described in the article.

## References


AG Energiebilanzen e. V, 2019. Auswertungstabellen zur Energiebilanz für die Bundesrepublik Deutschland 1990 bis 2018. https://ag-energiebilanzen.de/10-0-Auswertungstabellen.html.

Alsheimer, S., Schnell, T., Chlebna, C., Rohe, S., 2025. Competing terms for complementary concepts? Acceptance and legitimacy. Renew. Sustain. Energy Rev. 207, 114960. https://doi.org/10.1016/j.rser.2024.114960.

Barnett-Page, E., Thomas, J., 2009. Methods for the synthesis of qualitative research: a critical review. BMC Med. Res. Methodol. 9, 59. https://doi.org/10.1186/1471-2288-9-59.

Bass, F.M., 1969. A new product growth for model consumer durables. Manag. Sci. 15 (5), 215–227.

BDEW, 2021. BDEW-Strompreisanalyse Januar 2021. https://www.bdew.de/media/documents/BDEW-Strompreisanalyse_no_halbjaehrlich_Ba_online_28012021.pdf.

Bergek, A., Jacobsson, S., 2003. The emergence of a growth industry: A comparative analysis of the German, Dutch and Swedish wind turbine industries. In: Metcalfe, J. S., Cantner, U. (Eds.), Change, Transformation and Development. Physica-Verlag HD, Heidelberg, pp. 197–227.

Bergek, A., Hekkert, M.P., Jacobsson, S., 2008. Functions in innovation systems: A framework for analysing energy system dynamics and identifying goals for system building activities by entrepreneurs and policy makers. In: Foxon, T., Köhler, J., Oughton, C. (Eds.), Innovation for a low carbon economy: economic, institutional and management approaches. Edward Elgar Publishing.

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., Truffer, B., 2015. Technological innovation systems in contexts: conceptualizing contextual structures and interaction dynamics. Environ. Innov. Soc. Trans. 16, 51–64. https://doi.org/10.1016/j.eist.2015.07.003.

Bertoldi, P., 2022. Policies for energy conservation and sufficiency: review of existing policies and recommendations for new and effective policies in OECD countries. Energ. Buildings 264 (3), 112075. https://doi.org/10.1016/j.enbuild.2022.112075.

Bhattacharya, U., Hsu, P.H., Tian, X., Xu, Y., 2017. What affects innovation more: policy or policy uncertainty? J. Financ. Quant. Anal. 52 (5), 1869–1901. https://doi.org/10.1017/S0022109017000540.

Binz, C., Truffer, B., 2017. Global innovation systems—a conceptual framework for innovation dynamics in transnational contexts. Res. Policy 46 (7), 1284–1298. https://doi.org/10.1016/j.respol.2017.05.012.

Borshchevska, Y., 2016. Putting a competitive advantage at stake? Energiewende in the discursive practices of German industrial actors. J. Int. Stud. 9 (3), 99–113. https://doi.org/10.14254/2071-8330.2016/9-3/8.

Breetz, H., Mildenberger, M., Stokes, L., 2018. The political logics of clean energy transitions. Bus. Politics 20 (04), 492–522. https://doi.org/10.1017/bap.2018.14.

Breschi, S., Malerba, F., 1997. Sectoral innovation systems: Technological regimes, Schumpeterian dynamics, and spatial boundaries. In: Edquist, C. (Ed.), Systems of innovation. Technologies, institutions and organizations. Pinter - A Cassell imprint.

BSW-Solar, 2019. Statistische Zahlen der deutschen Solarstrombranche (Photovoltaik). https://www.solarwirtschaft.de/fileadmin/user_upload/bsw_faktenblatt_pv_2019_3.pdf.

Burroughs, R., 2017. Positive and negative feedback in policy formulation. In: Handbook of policy formulation, pp. 63–79. https://doi.org/10.4337/9781784719326.00009.

Campbell, A.L., 2012. Policy makes mass politics. Annu. Rev. Polit. Sci. 15 (1), 333–351. https://doi.org/10.1146/annurev-polisci-012610-135202.
Capano, G., Woo, J.J., 2017. Resilience and robustness in policy design: a critical appraisal. Policy Sci. 50 (3), 399–426. https://doi.org/10.1007/s11077-016-9273-x.
Carlsson, B., Stankiewicz, R., 1991. On the nature, function and composition of technological systems. J. Evol. Econ. 1 (2), 93–118. https://doi.org/10.1007/BF01224915.
Costantini, V., Crespi, F., Martini, C., Pennacchio, L., 2015. Demand-pull and technology-push public support for eco-innovation: the case of the biofuels sector. Res. Policy 44 (3), 577–595. https://doi.org/10.1016/j.respol.2014.12.011.
Dehler, J., Keles, D., Telsnig, T., Fleischer, B., Baumann, M., Fraboulet, D., Faure-Schuyer, A., Fichtner, W., 2017. Self-Consumption of Electricity from Renewable Sources. In: Europe's Energy Transition - Insights for Policy Making. Elsevier, pp. 225–236.
Dehler-Holland, J., Schumacher, K., Fichtner, W., 2021. Topic modeling uncovers shifts in media framing of the German renewable energy act. Patterns 2 (1), 100169. https://doi.org/10.1016/j.patter.2020.100169.
Dehler-Holland, J., Okoh, M., Keles, D., 2022. Assessing technology legitimacy with topic models and sentiment analysis – the case of wind power in Germany. Technol. Forecast. Soc. Change 175, 121354. https://doi.org/10.1016/j.techfore.2021.121354.
Dewald, U., Fromhold-Eisebith, M., 2015. Trajectories of sustainability transitions in scale-transcending innovation systems: the case of photovoltaics. Environ. Innov. Soc. Trans. 17, 110–125. https://doi.org/10.1016/j.eist.2014.12.004.
Dewald, U., Truffer, B., 2011. Market formation in technological innovation systems—diffusion of photovoltaic applications in Germany. Ind. Innov. 18 (3), 285–300. https://doi.org/10.1080/13662716.2011.561028.
Dewald, U., Truffer, B., 2012. The local sources of market formation: explaining regional growth differentials in German photovoltaic markets. Eur. Plan. Stud. 20 (3), 397–420. https://doi.org/10.1080/09654313.2012.651803.
Di Stefano, G., Gambardella, A., Verona, G., 2012. Technology push and demand pull perspectives in innovation studies: current findings and future research directions. Res. Policy 41 (8), 1283–1295. https://doi.org/10.1016/j.respol.2012.03.021.
Downs, A., 1972. Up and down with ecology - the issue-attention-cycle. Public Inter. 28, 38–50.
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. https://doi.org/10.1016/j.respol.2018.03.010.
Edmondson, D.L., Rogge, K.S., Kern, F., 2020. Zero carbon homes in the UK? Analysing the co-evolution of policy mix and socio-technical system. Environ. Innov. Soc. Trans. 35, 135–161. https://doi.org/10.1016/j.eist.2020.02.005.
Eicke, L., Weko, S., 2022. Does green growth foster green policies? Value chain upgrading and feedback mechanisms on renewable energy policies. Energy Policy 165 (1), 112948. https://doi.org/10.1016/j.enpol.2022.112948.
Fankhaeser, S., Sehlleier, F., Stern, N., 2008. Climate change, innovation and jobs. Clim. Pol. 8 (4), 421–429. https://doi.org/10.3763/cpol.2008.0513.
Freeman, C., 1995. The 'national system of innovation' in historical perspective. Camb. J. Econ. https://doi.org/10.1093/oxfordjournals.cje.a035309.
Fuenfschilling, L., Truffer, B., 2014. The structuration of socio-technical regimes—conceptual foundations from institutional theory. Res. Policy 43 (4), 772–791. https://doi.org/10.1016/j.respol.2013.10.010.
Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. Res. Policy 33 (6–7), 897–920. https://doi.org/10.1016/j.respol.2004.01.015.
Geels, F.W., Tyfield, D., Urry, J., 2014. Regime resistance against low-carbon transitions: introducing politics and power into the multi-level perspective. Theory Cult. Soc. 31 (5), 21–40. https://doi.org/10.1177/0263276414531627.
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. https://doi.org/10.1016/j.respol.2016.01.015.
Gupta, K., Jenkins-Smith, H., 2015. Anthony Downs, "up and down with ecology: The 'issue-attention' cycle". In: Lodge, M., Page, E.C., Balla, S.J. (Eds.), The oxford handbook of classics in public policy and administration. Oxford University Press.
Gürtler, K., Postpischil, R., Quitzow, R., 2019. The dismantling of renewable energy policies: the cases of Spain and the Czech Republic. Energy Policy 133, 110881. https://doi.org/10.1016/j.enpol.2019.110881.
Hake, J.-F., Fischer, W., Venghaus, S., Weckenbrock, C., 2015. The German Energiewende – history and status quo. Energy 92, 532–546. https://doi.org/10.1016/j.energy.2015.04.027.
Hekkert, M.P., Negro, S.O., 2009. Functions of innovation systems as a framework to understand sustainable technological change: empirical evidence for earlier claims. Technol. Forecast. Soc. Change 76 (4), 584–594. https://doi.org/10.1016/j.techfore.2008.04.013.
Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: a new approach for analysing technological change. Technol. Forecast. Soc. Change 74 (4), 413–432. https://doi.org/10.1016/j.techfore.2006.03.002.
Helveston, J.P., He, G., Davidson, M.R., 2022. Quantifying the cost savings of global solar photovoltaic supply chains. Nature 612 (7938), 83–87. https://doi.org/10.1038/s41586-022-05316-6.
Hess, D.J., 2014. Sustainability transitions: a political coalition perspective. Res. Policy 43 (2), 278–283. https://doi.org/10.1016/j.respol.2013.10.008.
Hipp, A., 2021. R&D collaborations along the industry life cycle: the case of German photovoltaics manufacturer. Ind. Corp. Chang. 30 (3), 564–586. https://doi.org/10.1093/icc/dtaa054.
Hirschl, B., 2008. Erneuerbare Energien-Politik. VS Verlag für Sozialwissenschaften, Wiesbaden.
Hoon, C., 2013. Meta-synthesis of qualitative case studies: an approach to theory building. Organ. Res. Methods 16 (4), 522–556. https://doi.org/10.1177/1094428113484969.
Hoppmann, J., Peters, M., Schneider, M., Hoffmann, V.H., 2013. The two faces of market support—how deployment policies affect technological exploration and exploitation in the solar photovoltaic industry. Res. Policy 42 (4), 989–1003. https://doi.org/10.1016/j.respol.2013.01.002.
Hoppmann, J., Huenteler, J., Girod, B., 2014. Compulsive policy-making—the evolution of the German feed-in tariff system for solar photovoltaic power. Res. Policy 43 (8), 1422–1441. https://doi.org/10.1016/j.respol.2014.01.014.
Howlett, M., 2019. Procedural policy tools and the temporal dimensions of policy design. Int. Rev. Public Policy 1 (1), 27–45. https://doi.org/10.4000/irpp.310.
Huenteler, J., Schmidt, T.S., Ossenbrink, J., Hoffmann, V.H., 2016. Technology life-cycles in the energy sector — technological characteristics and the role of deployment for innovation. Technol. Forecast. Soc. Change 104, 102–121. https://doi.org/10.1016/j.techfore.2015.09.022.
IRENA, 2021. Inspire renewable energy technology patent reports. http://inspire.irena.org/Pages/patents/Patents-Search.aspx.
IRENA, IEA, REN21, 2018. Renewable energy policies in a time of transition. IRENA, OECD/IEA and REN21.
Jacobs, A.M., Weaver, R.K., 2015. When policies undo themselves: self-undermining feedback as a source of policy change. Governance 28 (4), 441–457. https://doi.org/10.1111/gove.12101.
Jacobsson, S., Lauber, V., 2006. The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology. Energy Policy 34 (3), 256–276. https://doi.org/10.1016/j.enpol.2004.08.029.
Jacobsson, S., Sandén, B., Bångens, L., 2004. Transforming the energy system — the evolution of the German technological system for solar cells. Technol. Anal. Strateg. Manag. 16 (1), 3–30. https://doi.org/10.1080/0953732032000199061.
Jänicke, M., 2012. Dynamic governance of clean-energy markets: how technical innovation could accelerate climate policies. J. Clean. Prod. 22 (1), 50–59. https://doi.org/10.1016/j.jclepro.2011.09.006.
Jann, W., Wegrich, K., 2017. Theories of the policy cycle. In: Fischer, F., Miller, G.J. (Eds.), Handbook of public policy analysis. Routledge.
Jordan, A., Matt, E., 2014. Designing policies that intentionally stick: policy feedback in a changing climate. Policy. Sci. 47 (3), 227–247. https://doi.org/10.1007/s11077-014-9201-x.
Kern, F., 2015. Engaging with the politics, agency and structures in the technological innovation systems approach. Environ. Innov. Soc. Trans. 16, 67–69. https://doi.org/10.1016/j.eist.2015.07.001.
Kern, F., Rogge, K.S., 2018. Harnessing theories of the policy process for analysing the politics of sustainability transitions: a critical survey. Environ. Innov. Soc. Trans. 27, 102–117. https://doi.org/10.1016/j.eist.2017.11.001.
Klein Woolthuis, R., Lankhuizen, M., Gilsing, V., 2005. A system failure framework for innovation policy design. Technovation 25 (6), 609–619. https://doi.org/10.1016/j.technovation.2003.11.002.
Köhler, J., Raven, R., Walrave, B., 2020. Advancing the analysis of technological innovation systems dynamics: introduction to the special issue. Technol. Forecast. Soc. Chang. 158 (4), 120040. https://doi.org/10.1016/j.techfore.2020.120040.
Kriechbaum, M., López Prol, J., Posch, A., 2018. Looking back at the future: dynamics of collective expectations about photovoltaic technology in Germany & Spain. Technol. Forecast. Soc. Change. 129, 76–87. https://doi.org/10.1016/j.techfore.2017.12.003.
Kungl, G., 2015. Stewards or sticklers for change? Incumbent energy providers and the politics of the German energy transition. Energy Res. Soc. Sci. 8, 13–23. https://doi.org/10.1016/j.erss.2015.04.009.
Kungl, G., 2018. Die großen Stromkonzerne und die Energiewende. Dissertation. Campus Verlag.
Kungl, G., Geels, F.W., 2018. Sequence and alignment of external pressures in industry destabilisation: understanding the downfall of incumbent utilities in the German energy transition (1998–2015). Environ. Innov. Soc. Trans. 26, 78–100. https://doi.org/10.1016/j.eist.2017.05.003.
Langbroek, J.H.M., Franklin, J.P., Susilo, Y.O., 2016. The effect of policy incentives on electric vehicle adoption. Energy Policy 94, 94–103. https://doi.org/10.1016/j.enpol.2016.03.050.
Larsen, E.G., 2018. Policy feedback effects on mass publics: a quantitative review. Policy Stud. J. 97 (4), 1507. https://doi.org/10.1111/psj.12280.
Lauber, V., Jacobsson, S., 2016. The politics and economics of constructing, contesting and restricting socio-political space for renewables – the German renewable energy act. Environ. Innov. Soc. Trans. 18, 147–163. https://doi.org/10.1016/j.eist.2015.06.005.
Lauber, V., Mez, L., 2004. Three decades of renewable electricity policies in Germany. Energy Environ. 15 (4), 599–623. https://doi.org/10.1260/0958305042259792.
Lee, D., Hess, D.J., 2019. Incumbent resistance and the solar transition: changing opportunity structures and framing strategies. Environ. Innov. Soc. Trans. 33 (6), 183–195. https://doi.org/10.1016/j.eist.2019.05.005.
Leipprand, A., Flachsland, C., 2018. Regime destabilization in energy transitions: the German debate on the future of coal. Energy Res. Soc. Sci. 40 (6253), 190–204. https://doi.org/10.1016/j.erss.2018.02.004.
Leipprand, A., Flachsland, C., Pahle, M., 2017. Energy transition on the rise: discourses on energy future in the German parliament. Innov.: Eur. J. Soc. Sci. Res. 30 (3), 283–305. https://doi.org/10.1080/13511610.2016.1215241.

Leiren, M.D., Reimer, I., 2018. Historical institutionalist perspective on the shift from feed-in tariffs towards auctioning in German renewable energy policy. Energy Res. Soc. Sci. 43, 33–40. https://doi.org/10.1016/j.erss.2018.05.022.

Lockwood, M., 2013. The political sustainability of climate policy: the case of the UK climate change act. Glob. Environ. Chang. 23 (5), 1339–1348. https://doi.org/10.1016/j.gloenvcha.2013.07.001.

Mäkitie, T., Andersen, A.D., Hanson, J., Normann, H.E., Thune, T.M., 2018. Established sectors expediting clean technology industries? The Norwegian oil and gas sector's influence on offshore wind power. J. Clean. Prod. 177 (1), 813–823. https://doi.org/10.1016/j.jclepro.2017.12.209.

Malerba, F., 2002. Sectoral systems of innovation and production. Res. Policy 31 (2), 247–264. https://doi.org/10.1016/S0048-7333(01)00139-1.

Marcus, A., 1981. Policy uncertainty and technological innovation. Acad. Manage. Rev. 6 (3), 443–448. https://doi.org/10.5465/amr.1981.4285783.

Markard, J., 2020. The life cycle of technological innovation systems. Technol. Forecast. Soc. Change 153, 119407. https://doi.org/10.1016/j.techfore.2018.07.045.

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: an emerging field of research and its prospects. Res. Policy 41 (6), 955–967. https://doi.org/10.1016/j.respol.2012.02.013.

Markard, J., Hekkert, M., Jacobsson, S., 2015. The technological innovation systems framework: response to six criticisms. Environ. Innov. Soc. Trans. 16, 76–86. https://doi.org/10.1016/j.eist.2015.07.006.

Markard, J., Suter, M., Ingold, K., 2016a. Socio-technical transitions and policy change – advocacy coalitions in Swiss energy policy. Environ. Innov. Soc. Trans. 18, 215–237. https://doi.org/10.1016/j.eist.2015.05.003.

Markard, J., Wirth, S., Truffer, B., 2016b. Institutional dynamics and technology legitimacy – a framework and a case study on biogas technology. Res. Policy 45 (1), 330–344. https://doi.org/10.1016/j.respol.2015.10.009.

Mautz, R., Byzio, A., Rosenbaum, W., 2008. Auf dem Weg zur Energiewende: Die Entwicklung der Stromproduktion aus erneuerbaren Energien in Deutschland: eine Studie aus dem Soziologischen Forschungsinstitut Göttingen (SOFI). Universitätsverlag Göttingen, Göttingen.

Meadowcroft, J., 2011. Engaging with the politics of sustainability transitions. Environ. Innov. Soc. Trans. 1 (1), 70–75. https://doi.org/10.1016/j.eist.2011.02.003.

Meckling, J., Hughes, L., 2018. Protecting solar: global supply chains and business power. New Political Econ. 23 (1), 88–104. https://doi.org/10.1080/13563467.2017.1330878.

Messing, S., 2020. Wie kam das Ausschreibungsmodell in das Erneuerbare-Energien-Gesetz? Nomos Verlagsgesellschaft mbH & Co. KG.

Mori, A., 2018. Socio-technical and political economy perspectives in the Chinese energy transition. Energy Res. Soc. Sci. 35, 28–36. https://doi.org/10.1016/j.erss.2017.10.043.

Mowery, D.C., Nelson, R.R., Martin, B.R., 2010. Technology policy and global warming: why new policy models are needed (or why putting new wine in old bottles won't work). Res. Policy 39 (8), 1011–1023. https://doi.org/10.1016/j.respol.2010.05.008.

Negro, S.O., Hekkert, M.P., 2008. Explaining the success of emerging technologies by innovation system functioning: the case of biomass digestion in Germany. Tech. Anal. Strat. Manag. 20 (4), 465–482. https://doi.org/10.1080/09537320802141437.

Noblit, G.W., Hare, R.D., 1988. Meta-ethnography: synthesizing qualitative studies. SAGE.

Normann, H.E., 2015. The role of politics in sustainable transitions: the rise and decline of offshore wind in Norway. Environ. Innov. Soc. Trans. 15 (4), 180–193. https://doi.org/10.1016/j.eist.2014.11.002.

Nuñez-Jimenez, A., Knoeri, C., Hoppmann, J., Hoffmann, V.H., 2022. Beyond innovation and deployment: modeling the impact of technology-push and demand-pull policies in Germany's solar policy mix. Res. Policy 51 (10), 104585. https://doi.org/10.1016/j.respol.2022.104585.

Oberlander, J., Weaver, R.K., 2015. Unraveling from within? The affordable care act and self-undermining policy feedbacks. Forum 13 (1). https://doi.org/10.1515/for-2015-0010.

O'Neill, K., Gibbs, D., 2020. Sustainability transitions and policy dismantling: zero carbon housing in the UK. Geoforum 108 (5), 119–129. https://doi.org/10.1016/j.geoforum.2019.11.011.

Patashnik, E.M., Zelizer, J.E., 2009. When policy does not remake politics: the limits of policy feedback. APSA 2009 Toronto meeting paper. https://ssrn.com/abstract=1449996.

Patashnik, E.M., Zelizer, J.E., 2013. The struggle to remake politics: Liberal reform and the limits of policy feedback in the contemporary American state. Perspect. Polit. 11 (4), 1071–1087. https://doi.org/10.1017/S1537592713002831.

Peters, M., Schneider, M., Griesshaber, T., Hoffmann, V.H., 2012. The impact of technology-push and demand-pull policies on technical change – does the locus of policies matter? Res. Policy 41 (8), 1296–1308. https://doi.org/10.1016/j.respol.2012.02.004.

Pierson, P., 1993. When effect becomes cause: policy feedback and political change. World Polit. 45 (04), 595–628. https://doi.org/10.2307/2950710.

Pilgrim, S., Harvey, M., 2010. Battles over biofuels in Europe: NGOs and the politics of markets. Sociol. Res. Online 15 (3), 45–60. https://doi.org/10.5153/sro.2192.

Prontera, A., 2021. The dismantling of renewable energy policy in Italy. Environ. Politics 30 (7), 1196–1216. https://doi.org/10.1080/09644016.2020.1868837.

Purkus, A., Gawel, E., Thrän, D., 2019. The role of a renewable energy target for the transport sector beyond 2020: Lessons Learned from EU biofuel policy. In: Gawel, E., Strunz, S., Lehmann, P., Purkus, A. (Eds.), The european dimension of germany's energy transition, 34. Springer International Publishing, Cham, pp. 527–542.

Quitzow, R., 2013. The co-evolution of policy, (market and industry in the solar energy sector).

Quitzow, R., 2015. Dynamics of a policy-driven market: the co-evolution of technological innovation systems for solar photovoltaics in China and Germany. Environ. Innov. Soc. Trans. 17, 126–148. https://doi.org/10.1016/j.eist.2014.12.002.

Quitzow, R., Huenteler, J., Asmussen, H., 2017. Development trajectories in China's wind and solar energy industries: how technology-related differences shape the dynamics of industry localization and catching up. J. Clean. Prod. 158, 122–133. https://doi.org/10.1016/j.jclepro.2017.04.130.

Renn, O., Marshall, J.P., 2016. Coal, nuclear and renewable energy policies in Germany: from the 1950s to the "Energiewende". Energy Policy 99, 224–232. https://doi.org/10.1016/j.enpol.2016.05.004.

Reusswig, F., Komendantova, N., Battaglini, A., 2018. New governance challenges and conflicts of the energy transition: renewable electricity generation and transmission as contested socio-technical options. In: The Geopolitics of Renewables. Lecture Notes in Energy, 61. Springer, Cham. https://doi.org/10.1007/978-3-319-67855-9_9.

Rogge, K.S., Reichardt, K., 2016. Policy mixes for sustainability transitions: an extended concept and framework for analysis. Res. Policy 45 (8), 1620–1635. https://doi.org/10.1016/j.respol.2016.04.004.

Rosenbloom, D., Berton, H., Meadowcroft, J., 2016. Framing the sun: a discursive approach to understanding multi-dimensional interactions within socio-technical transitions through the case of solar electricity in Ontario, Canada. Res. Policy 45 (6), 1275–1290. https://doi.org/10.1016/j.respol.2016.03.012.

Rosenbloom, D., Meadowcroft, J., Cashore, B., 2019. Stability and climate policy? Harnessing insights on path dependence, policy feedback, and transition pathways. Energy Res. Soc. Sci. 50, 168–178. https://doi.org/10.1016/j.erss.2018.12.009.

Rosenow, J., Gibb, D., Nowak, T., Lowes, R., 2022. Heating up the global heat pump market. Nat. Energy 7 (10), 901–904. https://doi.org/10.1038/s41560-022-01104-8.

Schmid, N., Sewerin, S., Schmidt, T.S., 2019. Explaining advocacy coalition change with policy feedback. Policy Stud. J. 109 (1), 183. https://doi.org/10.1111/psj.12365.

Schmidt, T.S., Huenteler, J., 2016. Anticipating industry localization effects of clean technology deployment policies in developing countries. Glob. Environ. Chang. 38 (4), 8–20. https://doi.org/10.1016/j.gloenvcha.2016.02.005.

Schmidt, T.S., Schmid, N., Sewerin, S., 2019. Policy goals, partisanship and paradigmatic change in energy policy – analyzing parliamentary discourse in Germany over 30 years. Clim. Policy 355 (6321), 1–16. https://doi.org/10.1080/14693062.2019.1594667.

Seawright, J., Gerring, J., 2008. Case selection techniques in case study research. Polit. Res. Q. 61 (2), 294–308. https://doi.org/10.1177/1065912907313077.

Seibt, A., 2015. Lobbying für erneuerbare Energien. Springer Fachmedien Wiesbaden, Wiesbaden.

Sensfuß, F., Ragwitz, M., Genoese, M., 2008. The merit-order effect: a detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. Energy Policy 36 (8), 3086–3094. https://doi.org/10.1016/j.enpol.2008.03.035.

Sewerin, S., Béland, D., Cashore, B., 2020. Designing policy for the long term: agency, policy feedback and policy change. Policy Sci. 53 (2), 243–252. https://doi.org/10.1007/s11077-020-09391-2.

Smith, A., Kern, F., 2009. The transitions storyline in Dutch environmental policy. Environ. Politics 18 (1), 78–98. https://doi.org/10.1080/09644010802624835.

Stefes, C.H., 2010. Bypassing Germany's Reformstau: the remarkable rise of renewable energy. Ger. Politics 19 (2), 148–163. https://doi.org/10.1080/09644001003793222.

Stokes, L.C., Breetz, H.L., 2018. Politics in the U.S. energy transition: case studies of solar, wind, biofuels and electric vehicles policy. Energy Policy 113 (3), 76–86. https://doi.org/10.1016/j.enpol.2017.10.057.

Stokes, L.C., Warshaw, C., 2017. Renewable energy policy design and framing influence public support in the United States. Nat. Energy 2 (8), 981. https://doi.org/10.1038/nenergy.2017.107.

Strunz, S., 2014. The German energy transition as a regime shift. Ecol. Econ. 100, 150–158. https://doi.org/10.1016/j.ecolecon.2014.01.019.

Strunz, S., Gawel, E., Lehmann, P., 2016. The political economy of renewable energy policies in Germany and the EU. Util. Policy 42, 33–41. https://doi.org/10.1016/j.jup.2016.04.005.

Sühlsen, K., Hisschemöller, M., 2014. Lobbying the 'Energiewende'. Assessing the effectiveness of strategies to promote the renewable energy business in Germany. Energy Policy 69, 316–325. https://doi.org/10.1016/j.enpol.2014.02.018.

O'Sullivan, M., Edler, D., Lehr, U., 2018. Ökonomische Indikatoren des Energiesystems: Methode, Abgrenzung und Ergebnisse für den Zeitraum, pp. 2000–2016. https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/oekonomische-indikatoren-und-energiewirtschaftliche-gesamtrechnung.pdf?_blob=publicationFile&v=18.

Suurs, R.A.A., 2009. Motors of Sustainable Innovation: Towards a Theory on the Dynamics of Technological Innovation Systems. Utrecht University.

Suurs, R.A.A., Hekkert, M.P., 2009. Cumulative causation in the formation of a technological innovation system: the case of biofuels in the Netherlands. Technol. Forecast. Soc. Change 76 (8), 1003–1020. https://doi.org/10.1016/j.techfore.2009.03.002.

Suurs, R.A.A., Hekkert, M.P., 2012. Motors of sustainable innovation: understanding transitions from a technological innovation system's perspective. In: Verbong, G., Loorbach, D. (Eds.), Governing the Energy Transition. Routledge, pp. 152–179.

Suurs, R.A.A., Hekkert, M.P., Kieboom, S., Smits, R.E.H.M., 2010. Understanding the formative stage of technological innovation system development: the case of natural gas as an automotive fuel. Energy Policy 38 (1), 419–431. https://doi.org/10.1016/j.enpol.2009.09.032.

Ulmanen, J., Bergek, A., 2021. Influences of technological and sectoral contexts on technological innovation systems. Environ. Innov. Soc. Trans. 40, 20–39. https://doi.org/10.1016/j.eist.2021.04.007.

Walrave, B., Raven, R., 2016. Modelling the dynamics of technological innovation systems. Res. Policy 45 (9), 1833–1844. https://doi.org/10.1016/j.respol.2016.05.011.

Weaver, R.K., 2010. Paths and forks or chutes and ladders?: negative feedbacks and policy regime change. J. Publ. Policy 30 (2), 137–162. https://doi.org/10.1017/S0143814X10000061.

Weber, K.M., Truffer, B., 2017. Moving innovation systems research to the next level: towards an integrative agenda. Oxf. Rev. Econ. Policy 33 (1), 101–121. https://doi.org/10.1093/oxrep/grx002.