The Socio-Technical Dynamics of Renewable Energy Policies in Germany

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Abstract

Growing environmental concerns and human-caused climate change increase the pressure on policymakers for rapid action to transform how societies convert energy, produce goods, or transport freight. Innovation and technological progress may contribute to such transitions. However, technological change is hard to predict, requires time, and may be laden with political conflicts. Although more sustainable technologies are available, incentivizing demand and deployment are crucial to accelerate transitions. As transformations develop over decades, understanding the temporal dynamics of policies is critical for governance.

In Germany, the renewable energy act incentivizes the deployment of renewable energy technologies by remunerating electricity fed into the common grid. This dissertation assesses how socio-technical developments of solar and wind energy conversion technologies and the renewable energy act interactively shaped each other. Drawing on frameworks such as technological innovation systems, legitimacy, framing, and policy feedback, the contents of 16,485 newspaper articles and additional empirical studies were scrutinized. Combining methods from natural language processing, machine learning, and statistics, this thesis develops text models to assess changes in content and sentiment in large corpora over time. Three studies focus on the shifts in media framing of the German renewable energy act, the underlying co-evolution of technological and policy processes, and the development of the legitimacy of wind power.

The results confirm that renewable energy deployment and policy are contested with varying intensity over time. Where change ought to occur, non-linear dynamics of innovation and technology uptake, growing policy costs, economic interests of incumbents, and technology side effects increasingly complicate policymaking over time. The early phases of the renewable energy act were shaped by positive expectations toward renewable energy technologies, which later shifted towards an emphasis on policy costs. The findings highlight the importance of the prosperity of underlying innovation systems as supporters of policy ambition and maintenance over time. However, policy costs and side effects must be managed effectively to withstand increasing contestation. These results may contribute to advancing the successful governance of sectoral transitions likely to unfold over several decades.

Contents

Part I

Overview

Chapter 1

Introduction

1.1 Motivation

Agreeing on the harmful effects of human-caused climate change, governments worldwide have made pledges to reduce the greenhouse gas emissions of national economies. At the COP26 in Glasgow (2021), 153 nations have stated emission targets and agreed to strengthen these targets in the future[1]. The European Union has committed itself to net-zero emissions by the middle of the century.

Energy conversion, industry, and transport sectors make up 70% of global greenhouse gas emissions[2]. To reach ambitious greenhouse gas emission reductions, technological change in these sectors is required. Such technological change takes time. Several decades may pass from the invention of a new technology to its widespread deployment. Often, significant cost reductions have to be achieved before a technology is competitive with alternatives.

Several policy options are readily applicable to foster technological change. Research and development support, deployment policies, or measures to increase the costs of incumbent technologies offer a broad set of options along the technology learning curve. However, with lowering costs and increasing competitiveness, political frictions around policy measures may also increase. The increasing deployment

[1]Nationally Determined Contributions (COP26, 2021).
[2](EPA, n.d.)

of a new technology may also be controversial in society, where the perception of adverse side effects can increase. Maintaining technology support policies over extended periods is a non-trivial task for policymakers, where several particular interests must be pondered. Therefore, it is critical to develop an understanding of the underlying policy processes.

Particularly the electricity sector has witnessed intense political activity. In 2020, 145 countries worldwide had implemented some form of renewable electricity policy[3]. Globally, the share of renewables in electricity production increased from 20% in 2010 to 29% in 2020. In Germany, the share of renewable electricity increased from 17% in 2010 to 40% in 2021[4]. German renewable energy support dates back to the 1970s when governments started to support research and development activities. First deployment policies were implemented in the early 1990s and are in force until today (2022). Thus, German renewable energy policy is a well-suited case to study the political struggles of technology deployment policies. The concepts and findings developed in this study may well be transferable to other renewable electricity policies or support schemes in other sectors.

1.2 Objective and Research Questions

This thesis aims to derive an improved understanding of the timing and co-evolution of political, technological, and societal processes when dedicated policy measures support the deployment of technologies. Such processes depend on various actors, such as policy makers, proponents of incumbent and new technologies, and mass publics. Therefore, for developing a deep understanding of the timing and development of technology support schemes, it is vital to consider the variety of stakeholders and public arenas that engage with such a policy measure.

A prominent example of a policy measure to support the market adoption of technologies is the German renewable energy act (Erneuerbare Energien Gesetz; EEG). Since 2000, the EEG has supported the adoption of photovoltaic, wind, and biomass electricity generation with a feed-in tariff scheme. Over time, the EEG

[3](REN21, 2021)
[4](Destatis, 2022)

has experienced various amendments. Understanding the course of development of these amendments is at the core of the objective of this thesis.

This thesis scrutinizes the policy process of the EEG and its relations to the socio-technical system in detail to provide insights into the dynamics of deployment policies. Mass audiences play an essential role in the policy process as voters and evaluators of technologies and policies. When policies or technologies lose public endorsement, the maintenance of support schemes becomes increasingly tricky. Hence, this thesis devotes attention to the public perception of the EEG and the technologies it targets. Specifically, this thesis addresses three empirical research questions:

(1) How did the framing of the German renewable energy act develop over time?

(2) How did the EEG and the German photovoltaic sector co-develop?

(3) How did the legitimacy of wind power in Germany develop over time?

This thesis undertook considerable statistical and conceptual developments to assess these three research questions and generalize the results. Conceptually, this thesis develops three proposals arising from the findings that contribute to our understanding of the relationships between policies, technology, and society. First, it proposes that framing a policy in public arenas follows a pattern similar to issue-attention life cycles. Extending upon the identified pattern, second, this dissertation proposes to perceive the co-development of policies and technologies through a life cycle model, whose stages are shaped by differing feedback loops between policy subsystems and innovation systems. Third, it proposes that technologies formerly considered legitimate can undergo a process of gradual delegitimation emerging from the local level and diffusing into the general perception of technology.

Addressing empirical research questions (1) and (3), this thesis assessed the EEG and wind power media coverage in national newspapers. Classically, the treatment of questions of framing or legitimacy is a case for content analysis methods. However, manual content analysis methods are limited in the amount of data they can process at a reasonable cost. Therefore, this thesis develops and combines methods from natural language processing, machine learning and statistics to enable in-depth analyses of large sets of documents. A particular focus of these developments is the adequate representation of time and sentiment in the models developed.

1.3 Structure of the Thesis

The cumulative dissertation is structured in two parts. Part I contains this introduction (Chapter 1). A typology of instruments to support technology development and deployment is provided in Chapter 2, along with an introduction to deployment policies for renewables, and the research case that this thesis explores: German renewable energy policy and the renewable energy act. Chapter 3 builds up the conceptual foundation for analyses carried out in this thesis. It first outlines what is known about the dynamics of socio-technical systems and their politics and blends over to the analytical constructs assessed in this dissertation: Technological innovation systems, technology legitimacy, and framing, which are assumed to link to policy via feedback processes and agenda-setting. In Chapter 4, empirical and statistical methods are discussed that provide the basis for automated content analysis of two large newspaper corpora concerning the EEG and wind power. Chapter 5 summarizes the findings of the three papers and sketches their contributions to the understanding of the socio-technical dynamics of deployment policies. Chapter 6 provides critical reflections upon the case-study-oriented approach to theory building of this thesis and the methods and data deployed. Chapter 7 summarizes the findings of this dissertation and concludes Part I with policy implications. Part II contains the following research papers:

Paper A. This paper is published in the journal *Patterns* (Dehler-Holland et al., 2021b) and assesses the framing of the German renewable energy act across the period from 2000 to 2017 in German prestige newspapers. The article develops a text mining pipeline using natural language processing and machine learning methods to model large samples of German texts. The representation of temporal dynamics in models of newspaper coverage receives extensive attention using natural spline models and changepoint analysis.

Paper B. This paper is currently under review with the journal *Research Policy* (Dehler-Holland, 2021). It develops an analytical framework by combining technological innovation system life cycles and policy feedback to reassess empirical results on the politics regarding the renewable energy act following a synthesis approach. Building upon the results of Paper A, the findings give rise to the proposal of an ideal-typical life cycle model of technology deployment policies.

Paper C. This paper is published in the journal *Technological Forecasting and Social Change* (Dehler-Holland et al., 2022). A preprint is published in the *Working Paper Series in Production and Energy* (Dehler-Holland et al., 2021a). Extending the method set of Paper A, this paper provides an operationalization of technology legitimacy with unsupervised text models. The method is applied to a large set of newspaper articles on wind power in Germany.

Chapter 2

The Research Case

This chapter introduces a typology for instruments applied in technology policy. Technology deployment policies are identified as a specific subset of instruments dedicated to providing incentives for technology deployment. For renewable energies, we discuss some measures in more detail. Subsequently, the research case of this thesis – the German renewable energy act – is described.

2.1 Innovation Policy Instruments

To foster the development of technologies in general, policymakers have a broad range of instruments at their disposal. Rogge and Reichardt (2016) propose to cluster policy instruments along the two dimensions of the type of instrument and its primary purpose (Table 2.1). The 'type' refers to whether an instrument predominantly provides economic incentives, addresses the regulatory framework within which technologies are produced or used, or attempts to address informational deficits in technology development. On the other hand side, the 'purpose' of an instrument describes whether the instrument focuses on fostering technology development on the supply side ('technology push'), supports the market uptake of new technology ('demand pull'), or whether it addresses systemic issues perceived in technology development and deployment. While such a typology might not be free of overlaps or cover all possible purposes (Rogge and Reichardt, 2016, 1624), it is undoubtedly helpful to identify common properties of subsets of policy instru-

Table 2.1: Type-purpose policy instrument typology with examples (Rogge and Reichardt, 2016).

	Primary purpose		
Primary type	**Technology push**	**Demand-pull**	**Systemic**
Economic instruments	R&D grants and loans, tax incentives, state equity assistance	Subsidies, feed-in tariffs, trading systems, taxes, levies, deposit-refund-systems, public procurement, export credit guarantees	Tax and subsidy reforms, infrastructure provision, cooperative RD&D grants
Regulation	Patent law, intellectual property rights	Technology/performance standards, prohibition of products/practices, application constraints	Market design, grid access guarantee, priority feed-in, environmental liability law
Information	Professional training and qualification, entrepreneurship training, scientific workshops	Training on new technologies, rating and labeling programs, public information campaigns	Education system, thematic meetings, public debates, cooperative R&D programs, clusters

ments. Within a broader policy mix, such instruments can be deployed alongside each other to use synergistic effects of various instruments.

When it comes to the timing of usage of specific instruments, Breetz et al. (2018) have noted that in certain stages along a technology's learning curve, specific instruments may be more likely to be applied than others. In the early development stages of a technology, programs that foster research and development (R&D) or the support of demonstration projects play an essential role in lowering technology costs by increasing learning effects ('technology-push'). When the focal technology has reached a state where significant cost reductions can only be reached by a rapid increase in the number of produced units, measures that stimulate demand and market development are deployed ('demand-pull') (Breetz et al., 2018). When the technology costs approach the costs of incumbent technologies, measures that 'level the playing field' become important.

This thesis focuses on policies that provide economic incentives to technology adopters that represent an economic demand-pull instrument in the typology introduced above. In consonance with the literature (Hoppmann et al., 2013; Schmidt et al., 2016), this thesis will use the term *technology deployment policy* (TDP) for such instruments, the German renewable energy act (EEG) being a prominent example. Compared to policies employed in the early phase of technology development, such as R&D support, TDPs can be challenged by considerable political headwinds as competition with established technologies increases while market prices become more competitive (Breetz et al., 2018). Therefore, TDPs call for a detailed understanding of the underlying technological and political dynamics. The following section discusses deployment policies implemented in the field of renewable energies.

2.2 Deployment Policies for Renewable Energies

This thesis focuses on policies that provide financial incentives for deploying technologies. Different instrument designs have been implemented with varying success for renewable energy deployment. Generally, the effects of implementing deployment policies have been found to successfully exceed the mere deployment of technologies and initial market creation. Deployment policies for renewable energy policies have also successfully incentivized innovation (Pitelis et al., 2020).

Deployment policies for renewables are implemented to overcome barriers to deployment. Most importantly, alternative technologies might also be supported by existing subsidies, and the failure to fully internalize costs confronts the new technology's liabilities and initially higher costs (Sawin, 2006, 72f). Technical and financial risks increase the uncertainty of deployment (Sawin, 2006, 73). Particularly wind and solar power generation are characterized by their cost structure, where high upfront investment meets vanishingly low operational costs. Consequently, renewable energy generation lowers electricity market prices (Sensfuß et al. 2008), and the coincidence of generation from renewables undermines its own value in electricity markets, which has been termed the "cannibalization effect" (López Prol et al., 2020). Such dynamics complicate the integration of renewables in existing market designs (Fraunholz, 2021).

For characterizing deployment policies, scholars divided policies into quantity-based instruments that seek to control the number of adopted units and price-based mechanisms, where policymakers determine prices. In economic terms, under perfect market and information conditions, such measures should arrive at the same prices and quantities; however, under uncertainty, both models yield considerably different results (e.g., Kitzing et al., 2020).

For renewable energies, both kinds of policies have been applied internationally. Particularly feed-in tariffs that remunerate electricity fed into the common grid have been a popular measure to support the adoption of renewable energy technologies (Fouquet, 2013). Similarly, feed-in premiums ensure a certain income level when electricity from renewables is sold directly on wholesale markets. By guaranteeing the remuneration for a period in the future, such schemes reduce uncertainty on future incomes. Interestingly, in feed-in tariffs, it has been observed that competition mainly concerns the best construction sites, as project developers must not compete for prices (Butler and Neuhoff, 2008).

Also quantity-based measures found applications for renewable energies. For example, governments may fix quotas for renewable energies in utilities' portfolios and emit tradable green certificates to electricity generators that can be traded to fulfill a quota (Haas et al., 2004; Ragwitz and Steinhilber, 2014). However, in terms of effectiveness and efficiency, such quotas have shown mixed results (Ragwitz and Steinhilber, 2014). Additionally, auctions or tenders for renewable capacities have become increasingly popular (Haufe and Ehrhart, 2018). In such a scheme, governments as auctioneers fix a quantity (e.g., the installed capacity of a specific renewable energy technology) and let bidders compete for the lowest offers, for example, in terms of the expected feed-in premium of projects. In principle, such schemes can help correct information asymmetries between project developers and auctioneers prevalent in other schemes such as feed-in premiums (Haufe and Ehrhart, 2018). However, auctions come with a trade-off between high realization rates and efficient pricing (Kreiss et al., 2017; Matthäus, 2020).

Often, remuneration schemes are financed by surcharges to the electricity bills of final electricity customers. However, Germany abolished its surcharge by the time of finalizing this thesis (July 2022) and finances prospective remuneration by the national budget. The following section provides an overview of the history of renewable energy policy in Germany and the renewable energy act in particular.

2.3 German Renewable Energy Policy

This thesis aims to develop our understanding of the co-development of technological, political, and societal processes when applied policy measures support the adoption of new technologies. This section introduces the research case of this thesis – German renewable energy policy, or, more specifically, the antecedence and development of the German renewable energy act (Erneuerbare-Energien-Gesetz; EEG).

In Germany, the political support for renewable energy technologies such as wind and solar dates back to the 1970s. In the light of the energy crisis of the 1970s and changing public opinion, governments increased their expenditure on research and development (R&D) for renewables (Jacobsson and Lauber, 2006). Until the early 1990s, renewables met unfavorable market conditions in a market that was dominated by coal and nuclear energy generation (Jacobsson and Lauber, 2006). However, after the nuclear incidents in Chornobyl, public support for nuclear power decreased, and the first proposals for a feed-in scheme for renewable energy generation were circulated (Jacobsson and Lauber, 2006). In 1989, a market formation program to install 100 MW of wind power was initiated. At the same time, the 1,000 roofs program aimed at demonstrating the potential of solar power production (Lauber and Mez, 2004). In 1990, the feed-in law (*Stromeinspeisungsgesetz*) was introduced, requiring utilities to connect renewable energy plants to the grid and securing electricity prices for renewable generation at a fixed proportion of the average tariff for final customers (Lauber and Mez, 2004). While the feed-in law aimed to increase hydro power generation, the new law also stimulated wind power development but was too low to increase solar power installations significantly (Figure 2.1). Between 1990 and 2000, installed wind capacities increased from 55 MW to 6097 MW (Bundesministerium für Wirtschaft und Klimaschutz, 2022a) and led to the fast development of the wind power industry in Germany (Bergek and Jacobsson, 2003).

During the 1990s, climate protection became more and more important on the political agenda, and with it, the consensus that renewable energies should develop faster. In the forerun of the elections in 1998, all parties stated that the share of renewable energies should increase (Hake et al., 2015, 538). After the elections, the new government composed of social democrats and greens agreed on a plan to phase out nuclear power and to support the expansion of renewable energies further. The simultaneous progress of the liberalization of the European electricity markets and its power price-lowering effects made investments under the old feed-in

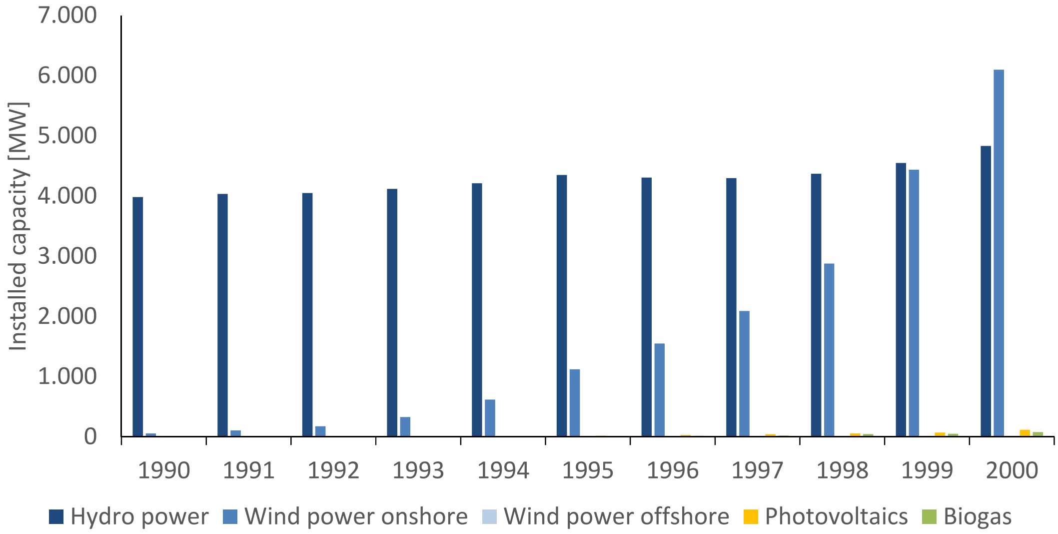

Figure 2.1: Development of the installed renewable energy capacity in Germany 1990-2000 (own illustration based on data from Bundesministerium für Wirtschaft und Klimaschutz, 2022a).

law increasingly unattractive. Its successor sought to decouple price developments and remuneration and guaranteed priority feed-in to renewables (Hake et al., 2015, 540). The German renewable energy act (Erneuerbare-Energien-Gesetz; EEG) entered into force in March 2000 and guaranteed fixed feed-in tariffs for 20 years, collected from end customers via a surcharge to the yearly electricity bill. In the years to come, wind power installations grew further, and, together with the 100,000-roofs program, the EEG fostered an increase in solar power installations (Figure 2.2).

Besides the growing wind industry, the solar module industry started to proliferate in Germany, particularly between 2004 and 2008 (Quitzow, 2015). However, after that period, module prices fell rapidly due to the end of silicon shortages in the world market, and the market shares of German producers declined (Quitzow, 2015). Therefore, feed-in tariffs in the EEG were lowered several times between 2009 and 2012, and the political atmosphere turned towards a restriction of renewable energy expansion (Lauber and Jacobsson, 2016). The EEG amendments of 2012 brought along a monthly degression of the feed-in tariff when the yearly targets ("Ausbaukorridor") were overachieved and set an overall goal of 52 GW

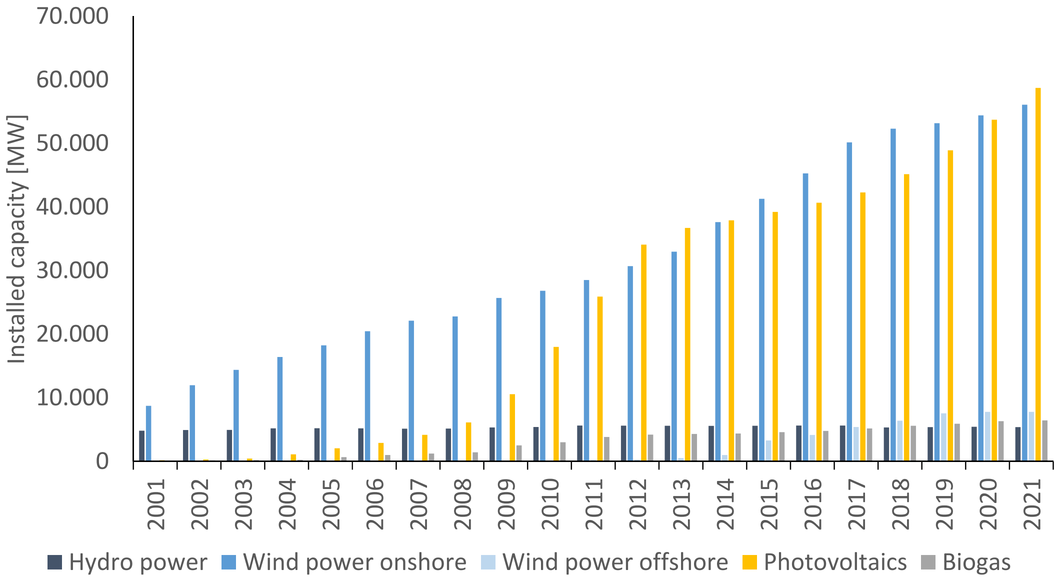

Figure 2.2: Development of the installed renewable energy capacity in Germany 2001-2021 (own illustration based on data from Bundesministerium für Wirtschaft und Klimaschutz, 2022a).

of installed capacity for solar photovoltaics. Additionally, the amendments incentivized market integration by introducing a voluntary feed-in premium.

After an intense debate on the height of the EEG surcharge and its distribution among customers and the intervention of the European Commission to increase market integration, the EEG 2014 introduced a pilot phase for tenders for solar energy with the prospects of adopting tenders for other technologies as well (Leiren and Reimer, 2018). After introducing tenders in 2017, wind power witnessed a slowdown in annual installations (Figure 2), blamed on long approval processes and conflicts with residents and environmental protection (Fuchs, 2020).

This introduction of the research case should suffice to provide an intuition for the developments this thesis seeks to understand in more detail from political, technological, and social perspectives. The above introduction illustrates a case with an unusual high policy intensity driven by technology-specific policies (Schmidt and Sewerin, 2018). The unusual fast development of renewable energy technologies and industries led to the perception of Germany as a "world leader in renewables" (Kemfert, 2017). These developments make the German EEG an extreme case, interesting for longitudinal studies (Schmidt et al., 2019). Following the literature on case study research, such extreme cases are well suited for exploratory studies and theory building (Seawright and Gerring, 2008). The following chapter will outline the frameworks used to gain insights into the dynamics of the interplay of society, technology and industry development, and policies.

Chapter 3

Theoretical Background

This dissertation aims to explore the socio-technical dynamics of renewable energy policies. For that purpose, this chapter discusses concepts that have been developed to assess change in socio-technical systems and identifies technological change and legitimacy as variables interrelated to the development and change of policies. It then sets out to sketch frameworks helpful to conceptualize the relationship between policy subsystems, technological change, and legitimacy.

More precisely, from the literature on socio-technical transitions (Section 3.1), Technological Innovation Systems (TIS) and their life cycles are identified as promising concepts to describe technological change (Section 3.2). A function necessary for the success of a TIS is technology legitimacy governing technology's relations with the broader public and policymakers (Section 3.3). As technology legitimacy and political discourse is often manifested (and measured) on public stages such as the media, Section 3.4 introduces agenda-setting as a framework to explain the relationships between mass publics and policymakers. The concept of policy feedback is introduced to link the development of policies to TIS developments (Section 3.5).

3.1 Dynamics of Socio-Technical Systems and Policy

In order to develop a comprehensive understanding of the interrelations of technologies, policies, and the broader society, this thesis adopts a systemic view. This section provides an overview of the notion of socio-technical systems and their change dynamics. Under the umbrella of *socio-technical* or *sustainability transitions*, frameworks have been developed and employed to conceptualize change processes. After a brief overview of these frameworks, this section focuses on what we know about the temporal development of transitions and their politics. This section closes with an overview of life cycle models of technological, societal, and political development as a promising avenue to further our understanding of the co-evolution of political and technical processes.

Socio-technical systems describe sectors such as energy supply or transportation as consisting of the actors and their networks and relevant institutions necessary to fulfill a specific service or function (e.g., energy provision, transport, communication) and include actors engaged in the diffusion and use of technologies (Markard et al., 2012; Geels, 2004). Actors such as firms, research institutes, public authorities, users, civic groups, or the media provide resources such as knowledge, capital, regulations, or cultural meaning necessary to fulfill a societal function (Geels, 2004). Actors and resources are strongly interrelated. For example, firms rely on universities to educate a skilled workforce, distribution networks, and consumers. These tight linkages between the system's elements indicate that system change depends on multiple factors (Köhler et al., 2019, p. 3), may 'lock in' to sub-optimal paths (Unruh, 2000), and poses challenges to conscious governance of change processes.

Shifts from one socio-technical system to another have been termed *socio-technical transitions* (Geels and Schot, 2010; Geels, 2004). Transitions involve technological innovation, changes in user behavior, and the 'societal embedding' of technologies by regulations, markets, or cultural features (Geels and Schot, 2010, 11). Transitions towards more sustainable system states have been termed sustainability transitions (Markard et al., 2012). (Markard et al., 2012) identified four main theoretical frameworks that are employed regularly to understand sustainability transitions: (1) transition management; (2) strategic niche management; (3) the multi-level perspective; and (4) technological innovation systems (TIS). The first two frameworks mainly aim at deriving propositions on steering sustainability transitions by fostering technological development. The multi-level perspective assumes three analytical levels to describe transitions: (1) the niche within which new technologies emerge; (2) the socio-technical regime that represents the "institutional structuring of existing systems" (Köhler et al., 2019, 4); (3) the landscape, comprising exogeneous developments (Geels, 2002). Innovations occur on the niche level that subsequently interacts with the regime and gradually become part of it. Landscape pressures on the regime eventually help an innovation break through the existing regime. Technological innovation systems (TIS) focus on actors, networks, and institutions relevant to the production of a focal technology. A technology further develops when the TIS can fulfill certain functions, such as knowledge creation or legitimation (for a detailed discussion of TIS and its notions of development and change, see Section 3.2).

Recent scholarship develops an interest in the timing and temporal dynamics of transitions, particularly concerning the energy field. The question of timing is crucial, as abatement of greenhouse gas emissions needs to be quick to avoid adverse effects of human-caused climate change. A recent review of historical case studies revealed that most transitions within the energy sector from a system majorly determined by the usage of one energy carrier to another had taken decades or even centuries (Sovacool, 2016). However, there are examples where significant shifts in supply and demand technologies were achieved in less than ten years (Sovacool, 2016, 207ff). These findings caused skepticism about whether a transition to a renewable energy system will be achievable within a reasonable timeframe, at least on a global level (Smil, 2016; Grubler et al., 2016), but also with optimism that governed transitions can achieve a higher pace (Kern and Rogge, 2016; Bromley, 2016). However, Grubler et al. (2016, 24) note that "faster transitions, while possible in theory, require a deep understanding of the determinants of the rates of change of complex social, economic, and technological systems that need to be translated into carefully designed policies, incentives, and communication strategies in order to achieve accelerated transitions". Therefore, a deeper understanding of the timing of societal and policy processes is of pivotal importance in understanding the dynamics of transitions.

Consequentially, transition scholars have called for engaging with the politics of transitions more intimately (e.g., Meadowcroft, 2009). Following these calls, the last fifteen years witnessed intensified attention to the politics of transitions (Edmondson, 2020, 13). Empirical work in the field mainly focused on the relations between innovative new entrants and incumbents, strategies of new entrants, and how party politics in government reflects and aggravates tensions between incumbent and new actors (Edmondson, 2020, 13f). When it comes to specific policies (or policy mixes), research on sustainability transitions has started to adopt viewpoints from policy process theory to gain insights into the making of innovation policies (Kern and Rogge, 2018; Köhler et al., 2019). Key findings include that policies shape the development and diffusion of technologies, but, equally important, technological change also impacts the policy process (Hoppmann et al., 2014; Markard et al., 2016). These interdependencies have led to the description of policy and technology processes as co-evolving (Edmondson et al., 2019; Hoppmann et al., 2014). However, while providing deep insights into the relations between policy process and technological development, these frameworks have not yet attempted to propose hypotheses about how these relations (ideal-typically) might unfold over time. Therefore, the following paragraphs briefly showcase notions of *life cycle models* of industries and societal attention to issues and technologies that may give clues about regularities in technology and policy development.

The literature on industry or product life cycles suggests that regular patterns exist in the evolution of industries (Klepper, 1997). Industry life cycles seek "to explain changes in technological development and industry structure over the period that the industry ages" (Peltoniemi, 2011, 349). Industry life cycles assume that industries pass through emergence stages with high entry and exit rates and diverse research and development activities, where companies learn from each other and develop shared performance criteria for the product (Peltoniemi, 2011). Together, companies strive for the legitimation of their products (Aldrich and Fiol, 1994). Industry maturity is reached when research and development shift their focus from products to production processes, a dominant design emerges, and the number of producers reduces (shake-out) (Peltoniemi, 2011). The literature on industry life cycles found ample empirical evidence on regularities in industry development; however, it is less focused on industry decline and institutional contexts such as politics (Markard, 2020, 4). Lately, (Markard, 2020) build upon these findings to introduce a life cycle model of technological innovation systems and address the shortcomings of neglecting industry's context relations (due to its importance for this thesis, Section 3.2 elaborates on the conceptualization of dynamics of TIS in more detail). As this thesis is interested in the change of relationships between the public, technologies, and policies, the following briefly addresses central concepts of the dynamics of public attention and expectations towards technology and political issues in the following.

Technologies often encounter phases of high expectations, followed by disappointment (van Lente et al., 2013). Such hype cycles can also affect the development of industries by increasing the activity of firms in phases of high expectations. For example, in the case of fuel cells, hyped expectations increased the innovation activities (Konrad et al., 2012; Ruef and Markard, 2010). The early literature on hype cycles proposed a model[5] that related increased technology expectations to technology maturity. Increased expectations occur when technology is relatively immature and are followed by a 'trough of disillusionment' when high expectations are not met (Fenn and Raskino, 2008). Following this phase, the technology increases in maturity, and eventually, increased diffusion occurs. However, empirical evidence suggested that the predictive value of this model was poor, as empirical cases show that phases of high expectations and disappointment can repeatedly occur over a technology's life cycle (Dedehayir and Steinert, 2016). Due to the value of hype and disappointment phases to understanding innovation activities, the concept was not dismissed altogether. Recent research conceptualizes the emergence of such patterns as a performative process where opponents and supporters of technology exchange on public stages and struggle for discursive influence (Kriechbaum et al., 2021). Hype and disillusionment are the outcomes of who dominates the public discourse at a particular time. Interesting to the thesis is the observation that support policies can trigger events of hypes but can also be a consequence (Kriechbaum et al., 2017, 77).

[5] The hype cycle model was originally proposed by Gartner Inc. (Fenn and Raskino, 2008).

When it comes to political action, public attention is an important social phenomenon (Newig, 2004). Decades of research have shown the tight interactions between policy, media, and public agendas (instead of many, see Soroka, 2002). Regarding attention toward political or societal issues[6], Downs (1972) described the patterns of public attention towards a focal issue in a cyclic fashion that received much attention in political science (Gupta and Jenkins-Smith, 2015). Along with long-term cycles of public attention to issues, political change can occur as a reaction to public pressures (Downs, 1972, 39–42): In the *pre-problem stage*, an issue already prevails, but public attention did not yet take note of it. When the issue gets noticed after triggering events, a stage of *alarmed discovery and euphoric enthusiasm* follows, in which the public expects that the focal issue can be solved in a relatively short time. In a third stage, the public *realizes that the costs* of any progress in the focal issue are high, as in solving the issue, benefits might have to be redistributed among large portions of the population. After the public has realized the costs, the attention to a focal issue *gradually declines* in the fourth phase of the issue attention cycle. Boredom, frustration with the perceived costs of a solution, and the threat of losing benefits lead to a decrease in attention, while on the public agenda, other issues compete for sparse attention resources. In the *post-problem stage*, an issue faces lower attention, but institutions and policies that have already been created in earlier stages might persist. Problems that have passed the cycle can sporadically rekindle attention.

This section discussed the key terms of socio-technical dynamics and introduced models that have contributed to describing the dynamics of technology and its relations to the broader public over time. The following sections will delve into technological innovation systems (TIS), give insights into technology legitimacy as an essential concept governing the relations between technology and society, and introduce policy feedback.

[6] "whatever is in contention among a relevant public" (Soroka, 2002, 6).

3.2 Technological Innovation Systems and the TIS Life Cycle

When it comes to technology policy, it might be a blatancy to mention that the state of development of the focal technology plays a vital role in shaping dedicated policies. However, Schmidt and Sewerin (2017) recently argued that technology development opportunities and its potential for creating local industries and jobs might soon outweigh cost-minimizing strategies in international climate and energy politics. Also, on a national level, technology development influences the deployment of specific policy instruments and political discourse (Breetz et al., 2018). Particularly in Germany, the well-being of the energy industry was a reoccurring argument in political debates (Schmidt et al., 2019).

Against this background, this section introduces the framework of Technological Innovation Systems (TIS) to understand the success factors of innovations and deployment. After briefly embedding TIS into the broader innovation literature, I discuss recent developments in the TIS literature that extend the basic concept. Particular weight will be given to developments that enable the TIS framework to account for structural change and relations to its environment, such as policy or sectoral systems.

The idea of innovation systems emerged in the 1980s and 1990s from the discontent with the treatment of innovation and technology by neo-classical economics (Sharif, 2006). Inspired by Schumpeter, innovation system scholars argued that rational choices by actors and assumptions of stable equilibria are insufficient to assess innovation, as “[a]ny true innovation involves uncertainty since the outcome per definition is unknown” (Sharif, 2006, 754). Therefore, knowledge, learning, and networks of actors are essential constituents of innovation systems (Carlsson and Stankiewicz, 1991). The innovation system literature includes an interactive understanding of innovation as an interaction between demand and supply, departing from classical ‘linear’ assumptions that view technology as emerging from applied science. (Weber and Truffer, 2017, 103).

Innovation system frameworks can be broken down into core components: actors, institutions, networks, system resources, and system boundaries (Weber and Truffer, 2017). Scholars considered national (Lundvall, 1992, 1988; Freeman, 1987; Nelson, 1993), regional (e.g., Asheim and Gertler, 2005), even global innovation systems (Binz and Truffer, 2017), sectoral systems (Malerba, 2002; Breschi and Malerba, 1997) or focussed on technology to delineate system boundaries (Carlsson and Stankiewicz, 1991). Within the different traditions, the core components are more or less pronounced. For example, Nelson (1993) and Freeman (1987) emphasize the role of institutions such as social norms, policies, regulations, and the general role of the state in national innovation systems. In contrast, Lundvall (1988, 1992) focuses on learning in companies as an essential driver of innovation (Weber and Truffer, 2017). Technological innovation systems define their system boundaries along with components necessary for the production and adoption of specific technologies such as wind power or solar photovoltaics; therefore, system boundaries may encompass regional or national borders (Carlsson and Stankiewicz, 1991).

Carlsson and Stankiewicz (1991, 111) perceive technological (innovation) systems as "a network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology". The following paragraphs will elaborate on the different components of this definition and their interrelations.

Within innovation systems, *agents* or *actors* differ in their economic competencies (Carlsson and Stankiewicz, 1991, 100f). Firms might be focused on producing combustion engines or photovoltaic panels. Therefore, each actor brings along a specific set of skills and knowledge and different ways to use them. However, innovative activity brings a high degree of uncertainty, wherefore learning processes and information search are vital constituents of innovation (Carlsson and Stankiewicz, 1991, 103). As information needs may well surpass the abilities of individual actors, *networks* become essential for exchanging information among actors. The second function of networks is strategic: networks are important to create system resources of interest to all network participants, such as political support by R&D programs (Musiolik et al., 2012).

Innovative activity does not occur in a void – *institutions* such as social norms, policies, regulations, or informal rules shape interactions between actors and innovative activity. Such institutions do not only depend on actors within a TIS but relate the TIS to its broader context, within which other systems such as political, financial, or sectoral systems contribute to shaping technology development (Bergek et al., 2015). Carlsson and Stankiewicz (1991, 110) emphasize the state's role in mitigating risks of innovative actors, where the functioning of capital markets, fiscal policies, subsidy schemes, public procurement or rules to regulate markets and competition are critical institutional arrangements.

Having introduced the structural components of technological innovation systems that enable researchers to describe a TIS, the question arises of how the change and development of TIS can be understood. A prominent approach to TIS dynamics has been the proposal of several system processes or functions (Table 3.1) whose fulfillment is vital for the prosperity of a TIS (Hekkert et al., 2007; Bergek et al., 2008a,b). By identifying the core functions, areas of potential policy intervention can be identified that go beyond structural weaknesses when the target of policymaking is to foster the development of a specific technology and TIS (Bergek et al., 2008b). While in the literature, different sets or lists of functions have been proposed, it may be helpful to summarize them into four key processes to provide an intuition: knowledge creation, market formation, investment mobilization, and technology legitimation (Binz et al., 2016b). An extension of the functions approach was termed 'motors of innovation', which details the interplay of the different functions (Suurs, 2009).

While the functional approach helps to understand the dynamics and key drivers of development, the TIS framework was also criticized for paying little attention to developments in the environment of a TIS (e.g., Markard and Truffer, 2008). However, such relations to entities or structures outside of the focal TIS are essential considering the goal of this thesis to shed light on the relations of technological and political developments. In that regard, Bergek et al. (2015) proposed formalizing context relations on a scale between *external links* and *structural couplings* that ranges from the one-sided influence of the context on the TIS to mutual interdependency due to the involvement of TIS elements in other contexts. Such relations affect the functions of a focal TIS in various ways. For example, context structures may be other TIS, political systems, or sectoral embeddings (Bergek et al., 2015). At first sight, one might be inclined to think that defining the context of a TIS does not contribute much to understanding TIS dynamics as it introduces addi-

Table 3.1: Functions of technological innovation systems (Hekkert et al., 2007).

Function	Description
Entrepreneurial Activities	Entrepreneurs take risks and experiment with the recombination of technological knowledge. This function is strongly dependent on the fulfillment of the other functions.
Knowledge Development	Learning and knowledge are crucial for innovation.
Knowledge Diffusion	For the development of a TIS, knowledge must be exchanged within networks. Knowledge can diffuse in networks between producers, users, and developers.
Guidance of the Search	As resources are limited, the TIS must focus on specific options for further investment. The choice of options also depends on the TIS' societal embedding, preferences, and expectations.
Market Formation	New technology competes with already established ones. The creation of protected niches where learning can occur is crucial for TIS development.
Resources Mobilization	Financial and human resources must be mobilized for TIS development. This includes governmental and industry support for R&D.
Creation of Legitimacy	Vested interests may oppose the introduction of a new technology, its introduction must be legitimated appealing to societal expectations, and advocacy coalitions can lobby for resources or favorable tax regimes.

tional structure. However, the definition of context relations seems to be fruitful in understanding the change of innovation systems when context structures vary (e.g., van der Loos et al., 2021) and plays a vital role in the concept of TIS life cycles (Markard, 2020).

Much of the literature has considered TIS in a more or less static state. Markard (2020) instead argues that actors, networks, and context relations must be considered in flux when thinking of a TIS life cycle. He outlines how a TIS can be characterized as being in a *formative*, *growth*, *mature*, or *decline* phase. The formative phase is characterized by a small number of actors, low sales, and little growth (Markard, 2020, 7). The TIS relies on resources from R&D funding, the applications of technology may be unclear, and market developments are highly uncertain.

The TIS relies on context structures and adapts to these. Actors from the TIS start to form closer relations to its context, mainly to generate resource flows. In the growth phase, high entries and sales increases shape the TIS. Structurization by common institutions such as performance parameters and technical standards accelerates, application cases of the technology have emerged, and a dominant design may establish (Markard, 2020, 7). Links to the context increase fast, and ties to, e.g., customers or other TIS establish and grow stronger (Markard, 2020, 8). Within the mature phase, sales are high, but growth is low. TIS structures and networks are stable, and entries and exits are low (Markard, 2020, 8). The TIS is structurally coupled to its context, and context and TIS are co-dependent (Markard, 2020, 10). Technological progress tends to be incremental. The decline phase is characterized by lowering sales numbers and actors leaving the TIS. The technology may be criticized, and actors may engage in defensive actions like political lobbying (Markard, 2020, 8). Often, a decline phase might be triggered by external shocks from the context (Markard, 2020, 10), such as a loss of legitimacy of the focal technology. The misalignment with its context may lead to reduced regulatory support and decreasing resources, and the relations between TIS and its context loosen (Markard, 2020, 10). It should be made clear that such simplified models should be understood as *ideal-typical* (Penna and Geels, 2012) in that realizations may differ from the proposed model, for example, when phases of decline and growth alternate (Hekkert and Negro, 2009). Nonetheless, such models have been fruitful in contrasting empirical cases and explain deviations from the model (Penna and Geels, 2012; Geels and Penna, 2015; Penna and Geels, 2015).

This section gave an overview of the history of the TIS framework emphasizing the emergence of concepts to describe the dynamics and changes of an innovation system. This thesis aims to provide insights into the relations of technological development on the one hand and the development of politics and policies on the other. A function pivotal to understanding the TIS context relations concerning politics and policies is the legitimation of TIS and the focal technology (Markard et al., 2015). The following section is devoted to laying out the foundations of technology legitimacy.

3.3 Technology Legitimacy

From the perspective of TIS actors, the maintenance of technology legitimacy is of high importance, as a technology considered illegitimate may face troubles in the maintenance of resource flows or be deployed altogether (Markard et al., 2016). On the other hand, technology legitimacy also becomes a political variable, as the support of illegitimate technology may also fire back to policy makers' public endorsement (Wallner, 2008). Particularly when alternatives to a specific technology are rare to reach political goals, maintaining technology legitimacy becomes a political issue. With that said, this section turns to provide an overview of the literature on legitimacy.

The legitimacy of social objects is a core concept of social science, and its development is often attributed to Max Weber's explorations of the legitimacy of political power (Deephouse and Suchman, 2008; Johnson et al., 2006; Suchman, 1995). In management studies, the legitimacy of organizations such as firms and companies developed as a part of organizational institutionalism (Suchman, 1995; Aldrich and Fiol, 1994; Greenwood et al., 2008; Scott, 1995). From here, legitimation and legitimacy found their way into the TIS functions literature (Bergek et al., 2008c) and, scholars developed frameworks to assess the legitimacy of specific technologies (Geels and Verhees, 2011; Harris-Lovett et al., 2015; Markard et al., 2016; Jansma et al., 2020; Binz et al., 2016a; Weiss and Nemeczek, 2021). This section outlines the technology legitimacy framework.

This thesis follows Markard et al.'s (2016) definition of "technology legitimacy as a commonly perceived alignment (or misalignment) of a focal technology with institutional structures in its context". Clarifying the concept of legitimacy, recent analysis brought three important perspectives to light: the literature understands legitimacy as (1) a property of a particular object; (2) perception; or (3) a process (Suddaby et al., 2017). Each perspective emphasizes different aspects of legitimacy. The next paragraphs discuss how the three perspectives are prevalent in the technology legitimacy literature and how each perspective relates to technology and transition policy.

The property perspective sees legitimacy as an "asset or resource – a thing - possessed in measurable quantity by some legitimacy object in relation to others"

(Suddaby et al., 2017, 7). Management research has focussed on questions of how legitimacy can be measured. Legitimacy is created by aligning the focal technology with institutions within its context (Markard et al., 2016). The property perspective has brought multiple attempts to delineate different dimensions of legitimacy (Suchman, 1995; Scott, 1995; Aldrich and Fiol, 1994), such as pragmatic, normative, and cognitive legitimacy (Suchman, 1995). The technology legitimacy literature has adopted different versions of these dimensions (Geels and Verhees, 2011; Harris-Lovett et al., 2015; Markard et al., 2016; Jansma et al., 2020; Binz et al., 2016a). In this view, technology can 'gain' legitimacy by aligning with institutional context structures. Therefore, in this perspective, exploring context structures that the focal technology might be related to is an integral part of studies (Markard et al., 2016).

The treatment of legitimacy primarily as a process builds upon a constructionist understanding of social reality, where social processes in which legitimacy is created are brought into focus (Suddaby et al., 2017, 24). According to this position, legitimacy is not considered static but a product of constant interactions between social entities (Suddaby et al., 2017, 24). This perspective is also represented in the technology legitimacy literature. In their study of Dutch nuclear energy, Geels and Verhees (2011, 913) suggest that "cultural legitimacy of technologies derives from the content and meaning of discourses, which depend on the way that deep-structural elements, concepts, ideas, metaphors, arguments, and images are ordered and related. For innovation journeys, actors aim to produce legitimacy by articulating positive discourses around new technologies". The role of different actor groups or alliances in creating legitimacy has been an important topic in the technology legitimacy literature (Kishna et al., 2017; Patala et al., 2019; Genus and Iskandarova, 2020; Jain and Ahlstrom, 2021). A pivotal concept referred to by the technology legitimacy literature (Geels and Verhees, 2011; Markard et al., 2016; Binz et al., 2016a) appears to be Johnson et al.'s (2006) description of legitimation as a social process passing the stages of (1) innovation (2) local validation (3) diffusion and (4) general validation. Following Binz et al. (2016a), the first two phases are characterized by an innovation that locally addresses specific needs, and TIS actors create "normative networks, change normative associations and induce theorizing about the innovation, yet without directly attacking deeply institutionalized dimensions of the dominant regime" (Binz et al., 2016a, 252). In the diffusion phase, the innovation diffuses in multiple contexts and comes into contact with the general public and broad societal norms or rules (Binz et al., 2016a, 252). Actors organize in interest groups or intermediaries to perform 'institutional work'. Gradually, while the innovation diffuses into multiple contexts, it becomes more and more 'taken-for-granted'. (Binz et al., 2016a; Suchman, 1995).

Legitimacy as perception refers to the subjective element of legitimacy as a matter of taste or judgment on an object (Suddaby et al., 2017). It focuses on individual evaluations and collective actors while maintaining the process perspective of legitimacy as an outcome of discursive processes. Legitimacy, from this perspective, is a multilevel phenomenon, existing at a collective level when a majority of actors recognize an object as legitimate (Suddaby et al., 2017, 41). Consequently, scholars that assume this perspective often focus on the level of individuals and their sociocognitive processes on the one hand and collective processes that lead to a judgment on an aggregated level (Suddaby et al., 2017, 51). This perspective is rarely assumed in technology legitimacy studies. However, particularly regarding energy technologies, there is a link to the research on technology acceptance (e.g., Wüstenhagen et al., 2007), exploring individual perceptions of technologies and technological properties related to acceptance. Particularly wind power has witnessed a long history of research on factors contributing to its local acceptance, such as sound or visual impacts and environmental factors (e.g., Rand and Hoen, 2017).

Delineating legitimacy as a property, process, or perception also entails different policy implications. Understood as a property, policymakers aiming at increasing the adoption of a particular technology must ensure that the technology, in general, is well-aligned with existing institutions. For example, wind power development must align with environmental protection, grid regulations, or other infrastructural interdependencies. The process perspective increasingly sheds light on the different actors and their particular interests in adopting (or failure of) a technology. It highlights that legitimacy must be maintained over long periods. Regime resistance must possibly be undermined to achieve long-term transitions (Kivimaa and Kern, 2016). Focusing on legitimacy as a matter of perception, or, similarily, of acceptance, induces the need to factor in local issues such as project planning procedures or participation in projects.

From an empirical perspective, the question arises of how to measure legitimacy appropriately. Due to its importance in political discourse, this thesis focuses on media accounts of political processes and technologies. Therefore, the following section introduces framing and agenda-setting as hypotheses linking societal and political processes.

3.4 Agenda-Setting, Framing, and the Media

For both technology legitimacy and policy, mass publics play an essential role as evaluators of policies and technologies (Larsen, 2018; Markard et al., 2016). Media plays a vital role in shaping public and policy agendas (Newig, 2004), particularly by picking and emphasizing certain aspects of societal issues (Shoemaker and Vos, 2009). A pivotal framework to understanding how media outcomes influence the perception of societal issues is framing.

In this thesis, we follow Entman's (1993, 52) definition of framing as "to select some aspects of a perceived reality and make them more salient in a communicating text, in such a way as to promote a particular problem definition, causal interpretation, moral evaluation and/or treatment recommendation for the item described". Hence, for policies and technologies, it is crucial which particular aspects are emphasized in media discourse. Certainly, a technology majorly depicted as avoiding greenhouse gas emissions meets more favorable political conditions than a technology that is said to have adverse environmental effects. However, the determination of relationships between politics, the public, and framing largely relies on arguments that, at its core, rely on the frequency of exposure to media outlets. Research on agenda-setting has drawn a complex picture of these interrelations.

Under the umbrella of agenda-setting research, scholars have been interested in those relationships for decades. An agenda can be understood as "a ranking of the relative importance of various public issues" (Dearing 1989, p. 310, as cited in Soroka, 2002, 6). Agenda-setting researchers investigated the causal relationships

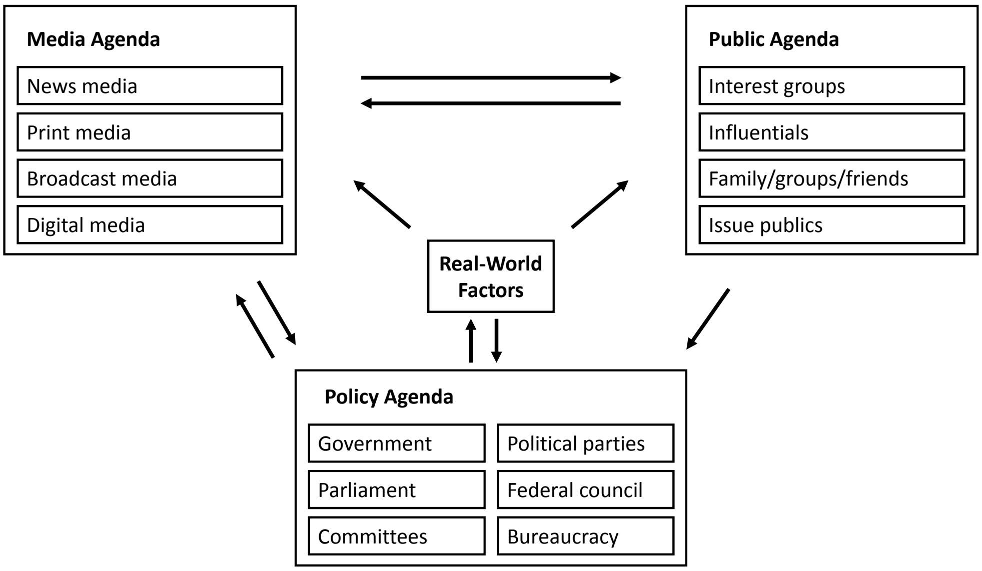

Figure 3.1: An expanded model of the agenda-setting process (adapted from Soroka, 2002, 11).

between public, media, and policy agendas. One of the most influential studies was arguably the one of McCombs and Shaw (1972) on the effect of media attention on public agendas on different issues in presidential campaigns in the US. However, scholars have also investigated the influence of media on parliamentary debates (Vliegenthart et al., 2016) or proposed that, in general, media attention follows political elites (Bennett, 1990). From the abundance of evidence for the different causal relations, Soroka (2002, 10) concluded that "[a]ccumulated evidence, then, suggests that there is no single direction of influence between the media and policy agendas" and "there is considerable evidence that the direction of causality in the media-public relationship cannot be assumed". Consequentially, he proposed that an extended model of agenda-setting must consider all such causal relationships (Figure 3.1). However, media effects research also went beyond this 'first level' of agenda-setting. In the agenda-setting tradition, researchers extended their focus from the salience of issues or objects to the 'second-level' effects of attributes of a given issue in the media on public perceptions (McCombs et al., 1997; Kiousis et al., 1999), a research strand that closely ties framing to agenda-setting[7] (McCombs, 2005).

[7] There is intense debate on whether these two concepts can be equated (e.g., Scheufele, 2009).

Certainly, interactions between journalists and different news sources within the media system must be considered necessary in what issues and attributes become salient in the media agenda (McCombs, 2005, 548). However, researchers also repeatedly stressed that framing is also a matter of power and that the influence of societal and governmental elites or societal movements should not be neglected (Vliegenthart and van Zoonen, 2011; Entman, 2007; Carragee and Roefs, 2004). Also, within the legitimacy literature, it is acknowledged that media is a public stage on which actors compete for attention according to economic and political interests (Geels and Verhees, 2011). These considerations contribute to understanding the media framing of techno-political issues when assessing the co-development of policies and technologies in society. However, the above considerations also show that for exploring the relationships between the public and politics, one must go beyond exploring the media portrayal. Therefore, in the following section, we explore theories of the policy process in more detail.

3.5 Policy Processes and Policy Feedback

After introducing technological innovation systems to analyze technological dynamics and linking media to the political sphere, this section provides an overview of policy feedback processes as a framework to analyze the influence of technological progress and change on the political processes of technology policies. First, an overview of theories of the policy process is provided. Second, the focus shifts on policy feedback and why it resonates well with describing the temporal evolution of technology policy.

Policy scholars have proposed different models of the policy process (Sabatier, 2007). Each comes with a different focus on the role of actors, their networks, institutions, core beliefs, or the policy context (Cairney and Heikkila, 2014). Prominent examples are the multiple streams framework (Kingdon, 2001), punctuated equilibrium (Baumgartner and Jones, 2004), advocacy coalitions (Sabatier, 1988), and policy feedback (Pierson, 1993). Each framework comes with its understanding of policy change. For example, the multiple streams framework assumes that three largely independent streams co-exist, and policy change becomes most likely ("window of opportunity") when policy entrepreneurs temporarily draw connections between these streams. Within the *policy* or *solution stream*, possible policy designs are developed that "search for problems"; within the *problems stream*, societal issues are discussed and become more or less salient over time; the *politics stream* is determined by the political power structures between political actors such as governments or interest groups. The multiple streams framework emphasizes the element of chance and agency in policy change; one of its main contributions can be seen in showcasing that the introduction of a new policy often is not a linear process from problem to solution but a coexistence of solutions and problems that must be linked (Kern and Rogge, 2018). In contrast, the advocacy coalition framework assumes that the policy subsystem is shaped by coalitions sharing specific belief systems (Sabatier, 1988). Policy change comes about through gradual learning processes. Advocacy coalitions, therefore, emphasize the collective component of policy change. These examples should clarify that the choice of the theoretical lens also entails which aspects of the policy process can be analyzed in detail.

Concerning the market uptake of new technologies, an essential aspect of policies is the policy outcome[8] and its influence on future policymaking (Kern and Rogge, 2018). Particularly, enacting a support regime for the adoption of a particular technology usually comprises a redistribution of resources to actors relevant to the focal technology, possibly followed by a reconfiguration of actor structures and increasing interests in maintaining or terminating the policy. On the other hand, such reconfigurations are likely to influence future policymaking. This relationship between policy outcomes and subsequent policymaking lies at the heart of *policy feedback* (Pierson, 1993), which "at the broadest level, [...] simply refers to how policies affect politics over time" (Béland, 2010, 569). Therefore, policy feedback has been identified as a promising theory to be linked to transition research (Kern and Rogge, 2018; Edmondson et al., 2019). In the following, I provide a broad understanding of the framework.

Although the idea of policy feedback dates back several decades, (Pierson, 1993)'s (Pierson, 1993) seminal article structures much of the later research on policy feedback. Pierson identified resource and interpretive effects as two main causes of emerging feedback. Such effects can occur when a policy measure provides re-

[8]Policy outcomes are defined as the actual effects of a policy in society as opposed to policy output, which refers to laws and bills generated in the political process.

sources to specific individuals. Such individuals can be subsets of the population, increasing the likelihood of forming and mobilizing interest groups (Pierson, 1993) or mass publics (Campbell, 2012). Examples of the latter are social security policies that potentially influence the population's life choices on jobs, retirement, or child care (Pierson, 1993, 606). For this thesis, the German feed-in tariff scheme is an important example, providing resources to a significant fraction of the population to install rooftop photovoltaic systems while distributing costs to (almost) the entire population by the surcharge added to electricity bills.

On the other hand, the recent scholarship also differentiated different feedback mechanisms arising from policy effects. Oberlander and Weaver (2015) proposed differentiating socio-political, administrative, and fiscal feedback. Socio-political feedback can be summarized as the formation of interest groups due to increased benefits or losses to such groups. Negative fiscal feedback occurs when the funding demand of the focal policy increases or funding streams become inadequate (Oberlander and Weaver, 2015, 42). Administrative feedback is determined by whether the administration can translate the policy into successful action and avoid visible failures (Oberlander and Weaver, 2015, 42). For example, the division of responsibilities among various organizations with different objectives can undermine the administrative ability to apply a policy successfully. Edmondson et al. (2019) translated these insights into a framework to analyze the co-evolution of policy (mixes) and the socio-technical system (Table 3.2). However, their works did not provide a conceptualization of the interacting development of technology and policies over time.

Table 3.2: Description of policy effects and feedback (Dehler-Holland (2021) based on 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., CO2 taxes, surcharges; Reallocation of resources can affect the behavior of target groups towards more sustainable modes, but can also have unintended consequences.
Interpretive Effects (IE)	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, and regulations, 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
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

Chapter 4

Methods

So far, we have introduced the research case and sketched the theoretical underpinnings of this thesis that include the goal of assessing media framing of the German renewable energy act and the legitimacy of wind power in Germany. This chapter discusses the methodological choices undertaken in detail. The first section discusses what quantitative content analysis should measure when assessing framing and conclude that automated content analysis offers suitable tools for the task (Section 4.1). Section 4.2 identifies topic models as a promising instrument, a field that has brought forward several model classes. Section 4.3 provides an overview of notable developments and weighs the pros and cons of different approaches. Data preparation is discussed (Section 4.4) before this chapter turns to issues of model evaluation and validation (Section 4.5).

4.1 Quantitative Content Analysis and Framing

Part of the objectives of this thesis is to assess the media framing of the German renewable energy act (EEG) and, relatedly, the development of the legitimacy of wind power in Germany. Methods deployed to assess the framing of a particular object in media can be subsumed under the umbrella of content analysis.

Indeed, the relationship between frame analysis and content analysis is almost a tautological one: How can we assess the framing of an object in a text without referring to its contents? However, media effects research suggests that the political significance of framing largely stems from the continuous and repeated exposure of politicians and the public to specific ways an object is presented (see Section 3.4). Therefore, a main interest of this thesis is a quantitative one: To identify how wind power or the renewable energy act are depicted in large bodies of newspaper coverage dependent on time. Content analysis researchers have developed sets of criteria to conduct such studies.

Riff et al. (2014, 19) propose a tangible definition of quantitative content analysis as "the systematic and replicable examination of symbols of communication, which have been assigned numeric values according to valid measurement rules, and the analysis of relationships involving those values using statistical methods, to describe the communication, draw inferences about its meaning, or infer from the communication to its context, both of production and consumption". Therefore, to develop a research design that satisfies scientific criteria, researchers must define measurement rules that are valid and relevant to the research question that is pursued. Furthermore, quantifying the contents of "symbols of communication" (newspaper articles, in our case) opens up possibilities for statistical assessment of relationships between measured entities.

The concept of framing, as conceived by Entman (1993), readily indicates what should be measured in a body of text in order to understand how an object is being framed: it is the salience of aspects that promote a "particular problem definition, causal interpretation, moral evaluation and/or treatment recommendation for the item described" (p.52). For this study, two questions arise: First, relevant aspects must be identified. Second, their salience must be measured.

For the first question, content analysis scholars usually develop a coding scheme of categories of the underlying texts based on prior knowledge of the subject of study (Krippendorff, 2004, 150ff)[9]. This is often complemented by an iterative process of assessing a subset of texts to refine the coding scheme. When applied consistently throughout the entire sample, the coding results enable the application of analytical tools such as statistics to analyze the contents of a set of documents. However, human coding entails high demands on the capabilities of

[9] Krippendorff (2004) calls it data language.

coders (Krippendorff, 2004, 127ff), and when large amounts of texts need to be coded, it becomes labor-intensive and costly.

Classically, the second question is answered by applying the coding scheme to the entire set of documents of interest by one or more human coders. Texts, or parts of them, are assigned to predefined categories, and the salience of specific categories can then be measured as the frequency of their occurrence across the entire corpus. However, the reliability of the outcomes strongly depends on the quality of the coding scheme or measurements and the coder's capabilities (Riff et al., 2014, 95).

To address parts of these difficulties of classical human-coded quantitative content analysis, researchers increasingly seize the opportunities of computational methods to assess textual data. An interest of this thesis lies in understanding the development of framing (and the development of legitimacy) over extended periods. Therefore, the amount of texts to be processed is considerable. Consequentially, this thesis proposes to rely mainly on computational approaches to content analysis, which we will discuss in the following sections.

4.2 Automated Content Analysis and Text-as-Data

The main interest of this section is to select a method to identify categories to structure the contents of a large set of documents that provide information on how the renewable energy act was framed or what happened to the legitimacy of wind power. In the field of Natural Language Processing (NLP), this task is commonly referred to as text classification[10], and analysts can select from a broad range of methods (see Figure 4.1) that augment, not replace, human interpretation of texts (Grimmer and Stewart, 2013). One of the first questions to answer in the decision process is whether categories are known a-priori or not.

When categories are known or already defined, methods to choose from range from simple dictionary approaches to supervised learning techniques (Grimmer and Stewart, 2013). Dictionary methods often form the basis of more complex assessments, for example, sentiment analysis (Feldman, 2013). Researchers con-

[10]Unsupervised learning strategies are also often referred to as clustering.

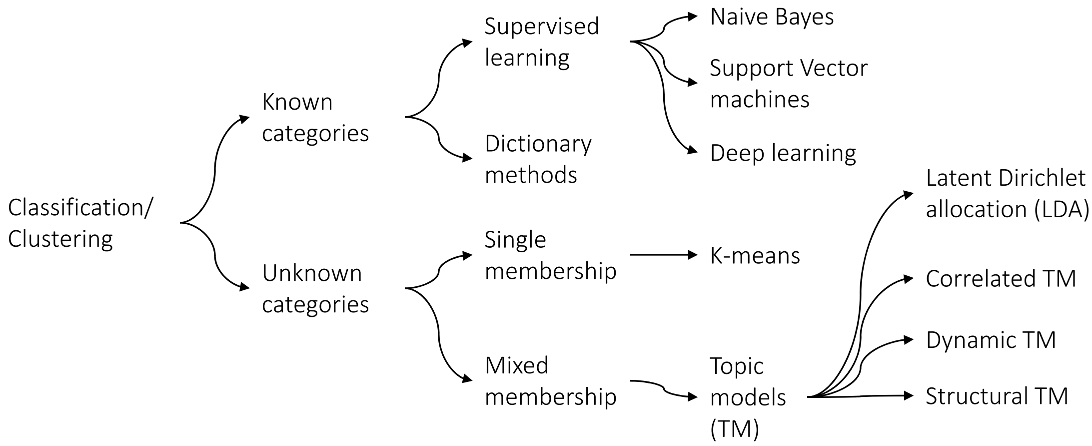

Figure 4.1: Overview of methods available for automated content analysis with examples (adapted from Grimmer and Stewart, 2013).

struct a dictionary of words to be counted within the corpus from prior knowledge. The frequency of occurrence of particular words can then be used and interpreted by statistical means. While dictionary methods have been said to be the simplest way for quantitative content analysis Grimmer and Stewart (2013), recently, such methods have been augmented by word embeddings to assess the words' context in large corpora (e.g., word2vec: Mikolov et al., 2013a,b) that have been successfully applied, for example, to understand the emergence of different technology foci in the development of autonomous vehicles (Woo et al., 2021).

The second class of supervised methods offers a broad set of models to generalize classifications from human-coded training sets to larger corpora and experience rapid development due to the importance of NLP methods to search engines and the ever-growing availability of unstructured (text) data in social networks and general commercial applications. They range from popular methods such as naïve Bayes or support vector machines to deep learning techniques for extensive reviews, see (Kowsari et al., 2019; Minaee et al., 2021). The field of deep learning neural networks for NLP is evolving fast from the application of recurrent or convolutional neural networks to the development of the transformer (Vaswani et al., 2017) and pretrained models on massive corpora such as Wikipedia (Devlin et al., 11.10.2018). All these developments can be used to inform text classification tasks. However, when it comes to particular applications, researchers face similar issues as when coding text collections manually: for supervised methods to perform well, a sizable coded training set is critical for supervised models to identify categories in unknown texts correctly. Coding schemes must be developed, and coders must be educated as if a manual content analysis is conducted (Grimmer and Stewart, 2013, 276). Therefore, for scientific applications, the class of unsupervised learning models becomes attractive.

Also, unsupervised methods offer a broad set of possible models that can be differentiated by whether they allow a document to belong to multiple categories (mixed membership model) or not (single membership model) (Grimmer and Stewart, 2013, 282). Single membership models comprise various general-purpose clustering algorithms such as k-means (Grimmer and King, 2011) that can be applied to texts once the texts are translated to numerical data (e.g., to the document-term matrix). The vast possibilities of choices of distance metrics or objective functions of cluster algorithms complicate choosing an appropriate model (Grimmer and King, 2011).

On the other hand, mixed membership models presuppose that texts may belong to different categories or comprise different topics. Within the last decades, topic models have been proposed most prominently by Blei et al. (2003). Topic models build upon a hierarchical structure, where documents comprise a predefined number of topics, and topics are essentially a probability mass function over words (Grimmer and Stewart, 2013, 283f). Topic models have been found to be well aligned with media framing, where texts typically contain multiple frames and "the sets of terms that constitute topics index discursive environments, or frames, that define patterns of association between a focal issue and other constructs" (DiMaggio et al., 2013, 593). Therefore, this thesis proposes to rely on this set of methods for its empirical endeavors.

4.3 Topic Modeling

The term topic model is used for a wide array of text analysis techniques dating back to the 1980s. Early approaches include the analysis of tf-idf (term frequency-inverse document frequency) matrices and latent semantic indexing (LSI) that uses singular value decompositions of the tf-idf matrix to describe the variation in a corpus. Furthermore, probabilistic LSI (pLSI) introduced the notion of a document consisting of terms drawn from multinomial variables representing the topics (Vayansky and Kumar, 2020, 2f). However, topic modeling became increasingly popular with the development of Latent Dirichlet Allocation (LDA; Blei et al., 2003), upon which many subsequent model developments were built (Chauhan and Shah, 2022). The following paragraphs provide an overview of LDA and developments directly addressing weaknesses of the basic model (Blei and Lafferty, 2006). Topic modeling, in general, has undergone various evolutions and refinements for specific applications, for example, short texts as often encountered in social media, and the reader is referred to Vayansky and Kumar (2020) for a well-structured overview.

LDA is a generative probabilistic model of a set of texts (Blei et al., 2003) that assumes that a text is generated by a probabilistic process within which words are drawn from multinomial distributions, whose parameters θ (the topics) are themselves drawn from a probability distribution. This process makes the model a hierarchical one, consisting of corpus, document, and word-level variables. More formally, the basic generative process assumed by Blei et al. (2003) assumes that each document d in a corpus D is generated as follows:

1. Choose $N \sim Poisson(\zeta)$, the number of words of document d.
2. Choose $\theta \sim Dir(\alpha)$.[11]
3. For each of the N words w_n:
    (a) Choose a topic $z_n \sim Multinomial(\theta)$.
    (b) Choose a word w_n from $p(w_n|z_n,\ \beta)$, a multinomial probability conditioned on the topic.

Where the number of topics k is fixed as well as the number of words in the vocabulary V and β is a parameter matrix of dimension $k \times\ V$ and $\beta_{ij} = p(w^j = 1|z^i = 1)$, the probability of a word when a particular topic is given. To estimate LDA models, different techniques such as Gibbs sampling or variational inference methods have been applied (Chauhan and Shah, 2022).

[11]The Dirichlet distribution is replaced by a logistic normal distribution in the cases of CTM, DTM and STM.

LDA has been successfully applied in a broad range of applications (Jelodar et al., 2019). However, its weaknesses also inspired further model developments. First, as LDA assumes that topics are distributed following a Dirichlet distribution (step 2. in the generative process above), LDA cannot account for the possibility that the occurrence of topics within a document might be correlated (Vayansky and Kumar, 2020, 6). Therefore, Blei and Lafferty (2007) proposed the correlated topic model (CTM), replacing the Dirichlet distribution with a logistic normal distribution. While this distribution assumes a covariance structure for the topics, this comes at the price of more difficult inference or model estimation (Blei and Lafferty, 2007). However, leveraging possible correlations between the occurrences of different topics also improves model fit.

An additional feature of LDA is that LDA treats all documents as drawn from the same topic distribution. Particularly when a set of documents ranges over an extended period, this assumption may not correctly account for changes in content over time (Vayansky and Kumar, 2020, 10). Therefore, the dynamic topic model (DTM; Blei and Lafferty, 2006) extends basic LDA by assuming that the parameters of topic distributions may depend on time. Assuming discrete time slices, a DTM consists of a sequence of models for each time slice, where topics at time t depend on the topics in $t-1$ again building upon a logistic normal distribution of the topics (Blei and Lafferty, 2006, 114). However, to keep the model tractable, topic correlations are not estimated (Vayansky and Kumar, 2020; Blei and Lafferty, 2006, 12), and problems may arise when the number of documents is not equal in all time slices (Vayansky and Kumar, 2020).

Another promising model has been proposed to explicitly account for experimentation in the social sciences (Roberts et al., 2016a). The structural topic model (STM) assumes that topic proportions and topic content may vary with external covariates such as time or the publisher of a document. Here, it is assumed that the parameters of the logistic normal distribution of the topics (step 2. above) may depend linearly on a set of covariates X (see Figure 4.2 for an illustration[12]). Furthermore, correlations between the topics are considered to influence the topic distribution. Given the interest of this thesis in analyzing frames influential for

[12] For simplicity reasons, a discussion of how content-covariate relations are modelled is not included. The reader is referred to Roberts et al. (2016a).

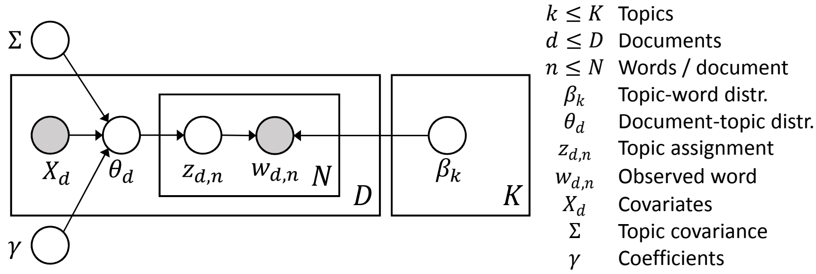

Figure 4.2: Graphical illustration of the structural topic model (adapted from Blei and Lafferty, 2007; Roberts et al., 2016a).

the perception of social objects (wind power, renewable energy act) and their development over time, specifying an STM with time as covariates appears to be the canonic choice. Compared to DTM, STM allows assessing how the topic distribution changes over time while holding topics themselves fixed. The salience of different aspects of the object of interest can be measured and analyzed over time, even if the number of documents per time step varies substancially. Furthermore, correlations give rise to the possibility of analyzing topical meta structures. Additionally, manual validation procedures (see Section 4.5) can be applied, as a detailed assessment of DTM may imply reading texts from each time slice, increasing the workload prohibitively.

In order to apply topic models effectively, several techniques are available to reduce computational burdens while maintaining their informational contents. As in German language texts, words are often inflected, additional challenges arise to map words with the same semantic meaning. The following section introduces methods addressing such challenges.

4.4 Preprocessing

Applying methods for automated content analysis effectively demands a high degree of normalization of the underlying texts that maintain their fundamental features in the best possible way. This section aims to introduce some of the most common procedures on the way from the text source to their representation as a vector (document-term matrix).

Text data may be available in many different formats, from handwriting to interviews that must be transcribed. From such data sources, text must be translated into machine-readable formats. However, texts are often already digitized, which makes the analysis of texts a lot easier. Nevertheless, even in this case, text data retrieved from databases available to the researcher must be prepared and cleansed to apply text models. Texts may have different data formats or be structured in ways peculiar to a particular source. Therefore, texts must be brought into a format that can be processed with software tools and relieved of structural elements such as preambles or appendices not informative on the text's contents (such as authorship, date, and source). Such formatting issues are critical when texts from different data sources are analyzed jointly. To facilitate further processing, texts are often split up into lists of words (tokens; tokenization) that are easily assessed or compared with other lists or dictionaries.

After these first basic preprocessing steps, the analyst can proceed to leverage language structures to reduce data sets and map words to each other. First, common language contains many words that, while grammatically necessary to produce proper sentences, do not add to contents in a meaningful way. Therefore, ubiquitous words such as articles or prepositions are often filtered out by lists of so-called stop words (Lucas et al., 2015). This thesis proposes a more sophisticated way of reducing the corpus vocabulary. Advances in NLP methods allow users to identify the roles words play within sentences: Part-of-Speech taggers label words in a given sentence according to their function as verbs, nouns, adjectives, or particles with increasing precision (Voutilainen, 2003). Labeling each word accordingly allows for a convenient reduction of the corpus by excluding particles or prepositions (Dehler-Holland et al., 2021b, 2022). In this way, estimation procedures of text models can be accelerated.

Additionally, the automatic processing of language is complicated by inflections familiar in many languages. Inflections make it more challenging to identify words with the same meaning but in a different case, tense, or genus. Therefore, most preprocessing procedures for text modeling apply methods to identify root forms.

Most common is the usage of stemmers that reduce words to a common stem[13]. Often, such procedures are based on a simple removal of word suffixes which may produce errors where words with similar meanings are not associated with each other (Hull, 1996). The German language in particular comes with a richer morphology than English (Burchert et al., 2003). In such cases, lemmatization, a technique that leverages syntactical information such as part-of-speech labels in conjunction with dictionaries to identify the correct canonical form of a word can improve text analysis (May et al., 2016).

After preprocessing the documents, they are translated into a document-term matrix indicating the frequency of each term within a document. Based on the preparation of data and choosing a suitable model class, models can now be fitted. However, additional choices are required that comprise the number of topics and validation procedures.

4.5 Evaluation and Validation

Inference procedures for the model classes described above lead to nonconvex optimization problems that emit multiple local solutions (Roberts et al., 2016b). Therefore, solutions must be picked from the various possible models that fulfill specific quality criteria. This includes the choice of the number of topics as well as, given a fixed number of topics, the choice of an initialization procedure. Furthermore, careful validation is vital to obtain a valid interpretation of topics once a promising model is chosen. Labels are assigned to each topic that facilitate further research and should be descriptive of topical content. When additional systematic information is available, promising algorithms for automatically labeling topics have been proposed (Savin et al., 2022). Generally, such methods are scarce, and researchers rely on expert assessments.

For evaluating topic models and machine learning procedures in general, evaluating model fit by measuring held-out likelihood or perplexity, which measures how well a model can predict unseen documents, is common (Rüdiger et al., 2022,

[13] Even for English, stemming might not increase model quality (Schofield and Mimno, 2016). However, May et al. (2016) show that lemmatization has positive effects for morphologically rich languages.

7). However, choosing models that maximize those measures may produce topics that are less semantically meaningful because human evaluators have more difficulties in their interpretation (Chang et al., 2009). For the goals of this study, the interpretability of topics related to frames is fundamental. Therefore, Chang et al. (2009, 1) propose that perplexity or held-out likelihood "are useful for evaluating the predictive model, but do not address the more expl[or]atory goals of topic modeling"[14]. Therefore, Roberts et al. (2014, 1069) propose to evaluate topic models quantitatively by balancing measures for (1) *semantic coherence* and (2) *exclusivity* of words in order to select suitable models.

Mimno et al. (2011) compared expert annotations of texts with the results of an LDA topic model and identified four common interpretation issues of experts given a set of topics. Based on these issues, they found that measuring the co-occurrence of words with high probability weights in a given topic across all documents provides a quantitative measure that is well suited to address these issues. Denoting the frequency of documents that contain two words v and $v\prime$ at least once as $D(v, v\prime)$, and assuming a list of the M most probable words of topic k *semantic coherence* is defined as:

$$C_k = \sum_{i=2}^{M} \sum_{j=1}^{i-1} \log \left(\frac{D\left(v_i, v_j\right) + 1}{D(v_j)} \right).$$

However, Roberts et al. (2014) remark that while semantic coherence helps to identify topics that are internally consistent, it cannot account for the fact that topics might be very similar to each other. Therefore, they propose to weigh semantic coherence against the *exclusivity* of words to the topic. For that purpose, the exclusivity of words can be balanced against their frequency by their harmonic mean (Airoldi and Bischof, 2016; Bischof and Airoldi, 2012). For each topic k and word v and the empirical distribution function $ECDF$ and a weight $\omega \in [0, 1]$:

$$FE_{k,v} = \left(\frac{\omega}{ECDF\left(\beta_{k,v} / \sum_{j=1}^{K} \beta_{j,v}\right)} + \frac{1-\omega}{ECDF\left(\beta_{k,v}\right)} \right)^{-1}.$$

[14]Spelling corrected by the author.

Based on these measures, models with different numbers of topics can be compared quantitatively, and the choice of a well-interpretable model can be supported. However, it must be noted that additional detailed manual assessment of the model results is still critical, and careful validation is key to obtaining credible results.

In manual and automated content analysis, validation of the results is an integral part of each research design (Grimmer and Stewart, 2013; Krippendorff, 2004, 313ff). Krippendorff (2004, 319) typology of validation distinguishes between face validity, social validity, and empirical validity. While face validity refers to the observation that research results are perceived as plausible or obviously true by observers, social validity comprises the value of the research to public debates and its contributions to the understanding or solving of critical social issues. The following paragraphs are devoted to presenting criteria for empirical validity of an automated content analysis endeavor.

For automated content analysis tasks, Quinn et al. (2010) propose to focus on five concepts of validity. First and foremost, *semantic validity* refers to whether the developed category system is coherent, in the sense that they correspond to "the meanings these texts have for particular readers or the roles they play within a chosen context" (Krippendorff, 2004, 323). When using unsupervised learning techniques such as topic modeling, several methods come into question to validate given results. Researchers often use lists of the most probable words associated with a topic to find a common label for a topic and validate its coherence (Chang et al., 2009). Leveraging frequency against the exclusivity of words to a topic as described above can facilitate validation and interpretation (Airoldi and Bischof, 2016). Furthermore, manual close-reading of sub-samples is advised to ensure that human understanding of texts corresponds to the automatically generated categories or labels (Quinn et al., 2010; Grimmer and Stewart, 2013).

Furthermore, the degree of correlation with other variables that measure similar context characteristics as the construct in question can bestow validity to the model (*convergent construct validity*) (Quinn et al., 2010). Similarly, *discriminant construct* validity assesses deviations of the constructs from the behavior of already known variables and whether they occur where they ought to occur (Quinn et al., 2010). For example, media reports on a specific policy could be compared to the contents and frequency of parliamentary debates or repeated public opinion surveys.

Predictive validity of a model can be assessed by comparing model measures to external events and the degree to which the model results can anticipate results (Quinn et al., 2010; Krippendorff, 2004). Particularly in the case of this thesis, where time series of topic salience play a vital role, model results can be compared against political events. Finally, and most basically, *hypothesis validity* describes whether the derived modeling results can be used to assess the research questions posed.

Chapter 5

Summary of the Research Papers

The preceding chapters of this thesis introduced the research case of the German renewable energy act and renewable energy technologies (Chapter 2), presented the theoretical background that the three papers both build upon and contribute to (Chapter 3), and justified methodological choices made in paper A and C (Chapter 4). This chapter summarizes the three papers that comprise this thesis. For each paper, this chapter outlines the context of the study, summarizes the chosen methodology, and displays major results.

5.1 Paper A: Topic Modeling Uncovers Shifts in Media Framing of the German Renewable Energy Act

Media framing plays a vital role in political processes, mediating between the public and the political sphere (see Section 3.4). This particular role in political processes makes media accounts an important piece of the puzzle when aiming at deriving an intimate understanding of policy processes. Media accounts of political processes can give hints about how the public might perceive a policy and provide policymakers with clues on how the public sphere evaluates its actions and policies (Fawzi, 2018). Particularly newspaper articles are a promising source of information, as they have a wide circulation within political and public spheres,

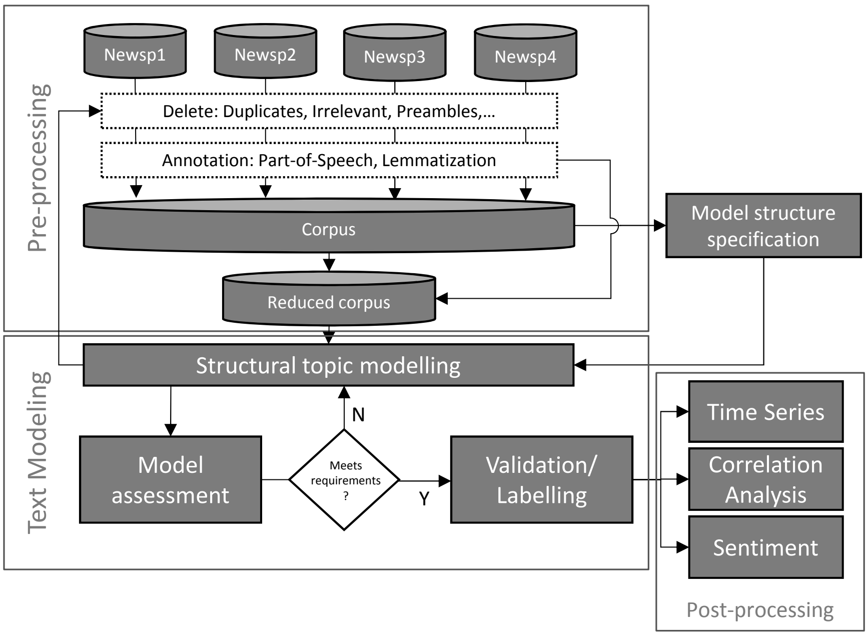

Figure 5.1: Graphical illustration of the developed topic modeling pipeline (adapted from Paper C: Dehler-Holland et al., 2022).

are produced with a high frequency, and have relatively low hurdles to access. Additionally, and opposed to other high-frequency data available to assess political processes, such as transcripts of parliamentary debates, newspaper articles draw on a broader set of sources besides politicians, such as interest groups, business leaders, or scientists who are considered an essential part of policy subsystems. They are suited to assess changes in public political debates over time for these reasons.

The German EEG came into force in 2000. Since then, several amendments have adapted the law to an evolving context of technological and political developments (see Section 2.3). A host of studies has observed political processes that led to policy change (compare Paper B); however, media framing of the EEG has not been studied. Therefore, *Paper A* (Dehler-Holland et al., 2021b) assessed articles from five national newspapers[15] from 2000 to 2017 and how the framing of the EEG developed over time.

[15] Newspapers included are *Frankfurter Allgemeine Zeitung*, *Süddeutsche Zeitung*, *die tageszeitung*, *Die Welt*, *Handelsblatt*.

In order to provide insights into the contents of 6,645 articles, Paper A developed a text modeling pipeline consisting of preprocessing procedures, structural topic modeling (STM), and validation processes (see Figure 5.1). To analyze changes in framing over time, Paper A included time as a covariate for topic proportions (compare Section 4.3) as a natural spline model. The mean prevalence $\mu_{k,t}$ of a topic k can then be modeled as

$$\mu_{k,t} = \sum_{i=1}^{N} b_{k,i} \cdot bs_i\,(t),$$

with a set of base splines bs_i for a number of knots N that Paper A proposes to specify using a changepoint analysis on the time series of document frequencies that provide prior knowledge on the progression of discourse intensity.

Additionally, in the analysis of media framing, the sentiment of topics is informative as an indicator for the general positioning of media accounts towards a particular topic. Paper A proposes the weighted average of words from a given sentiment lexicon as a canonic measure for topic sentiment. Given sentiment scores $s_w \in [-1, 1]$ of words w from the vocabulary V and word occurrence probabilities $\beta_{w,k}$ per topic k from a topic model, topic sentiment can be defined as

$$ts_k = \sum_{w \in V} \beta_{w,k} \cdot s_w.$$

To ensure semantic validity (Section 4.5), two authors of Paper A read a subset of articles for each topic highly associated with the topic. After evaluating a range of possible models regarding their semantic coherence and exclusivity, they defined labels and a short content description in an interactive exchange process. Additionally, predictive validity was established by comparing time series models for topics with the succession of political and external events. To give a sense of convergent validity, the findings were discussed alongside existing studies of parliamentary discourse.

The results of Paper A show that the appreciation of the renewable energy industry was the dominant frame associated with the EEG until 2011. From 2011 onwards, the costs associated with the EEG and specifically the EEG surcharge that dis-

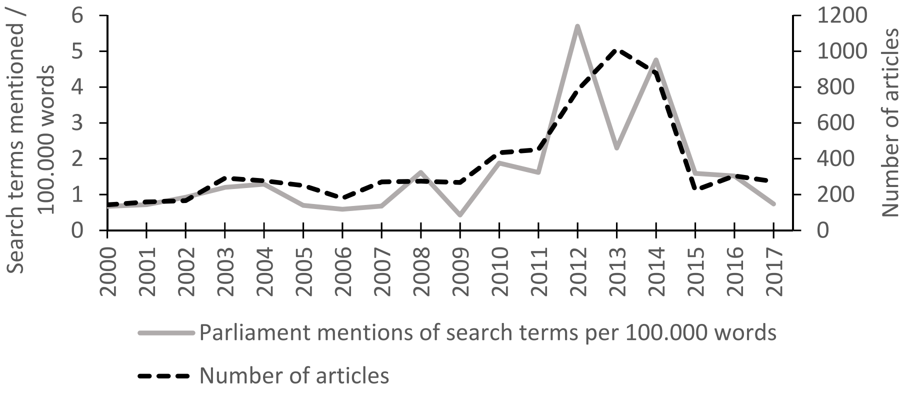

Figure 5.2: Comparison of the number of articles published in five national newspapers and usage of the search terms in parliamentary debates. Both time series correlate strongly $(0.798, p < 0.0001)$. (own elicitation and: Die Zeit, 2019).

tributed the costs to final customers dominated the media representation of the EEG. While topics addressing the renewable energy industry were predominantly associated with positive sentiment for reasons such as job creation in the industry or international technology leadership, topics associated with costs are associated with negative sentiment. Until 2011, reports on the solar photovoltaics industry contributed the major share of prevalence of the renewable energy industry, while attention devoted to the solar industry suddenly dropped afterward.

These results revealed that media reporting followed a previously described pattern in the literature on the attention toward specific societal issues (Section 3.1). A partial explanation for these specific patterns may be found in the fact that the EEG is dedicated to supporting specific technologies, which have often been perceived in cycles of high expectations and disappointment.

Regarding their effects on politics and the public and considering the contingency of effects, these results are difficult to interpret. However, the results allow for the hypothesis that the underlying political processes may also follow a pattern similar to issue attention cycles, including a phase of optimistic perception and support of the technologies in question, followed by an increase in the perception of costs (see Section 3.1). Some initial support for the similarity of media and political discourse is provided by analyzing the frequency of parliamentary mentions of the search terms used to generate the data set underlying this study (Figure 5.2). However, deriving a deeper understanding of the underlying processes in the interaction of political and technological systems is the core aim of Paper B.

5.2 Paper B: From Virtuous to Vicious Cycles – Towards a Life Cycle Model of Technology Deployment Policies

Given the need to understand the political and technological processes underlying the evolution of technology policies (Section 3.1), *Paper B* (Dehler-Holland 2021) delves into the EEG developments over time. Paper A has established that public attention towards the EEG followed a well-known cyclic pattern. However, it could not establish a theory of the critical drivers of such a pattern. The broader research on issue attention cycles, in general, is faced with this issue, mainly because it remains difficult to establish firm causal relationships between policymaking, the public, and the media (Gupta and Jenkins-Smith, 2015). This general weakness in theoretical development has prompted Gupta and Jenkins-Smith (2015, 324) to propose to link issue attention more closely to theories of the policy process.

In this context, Paper B reassesses the literature available on the political developments underlying the progression of the German EEG following a synthesis approach. To systematically reassess the plethora of existing studies on German renewable energy policy and the EEG, it leverages policy feedback (Section 3.5) as an evaluation framework for the dynamics of policy processes. As the instance of policies that support the deployment of technologies is unique in that technological developments may interact with policy processes, the development of technological innovation systems along its life cycle is included as an additional variable (Section 3.2). Using both frameworks, empirical studies of the EEG and particularly the development of the solar photovoltaics industry were screened for significant events related to the initial hypothesis that policy processes underlying the attention cycle established in Paper A follow a similar pattern.

The results show that the basic patterns of an attention cycle can also be identified in the progression of political and technological developments. The period between 2004 and 2009 was shaped by political enthusiasm toward renewable energies. This enthusiasm was primarily caused by the rapid development of the German solar photovoltaics industry that could generate jobs and establish the frame of international leadership of an important future technology. However, with increasing deployment and dropping technology costs, political awareness of rapidly increasing policy costs developed and caused a series of policy changes ranging from cutbacks of the feed-in remuneration over the broader exemption of industry companies from the EEG surcharge to the gradual introduction of a tendering scheme for renewables since 2014. These developments can be related to the declining German solar TIS that faced considerable competition from abroad and increasing policy feedback from interest groups such as the German industry and utilities.

Based on this reinterpretation of established findings, Paper B takes the first step and proposes a life-cycle model of technology deployment policies (TDP) as an ideal-typical order of events that may occur when a TDP is implemented in general. The concept is inspired by the notion of issue attention cycles and its hypotheses on political activities accompanying the ups and downs of attention towards a societal issue (see Section 3.1 and Paper A) and is supported by references to other cases. One of the core assumptions of the model is that TDP, successful in increasing the adoption of the focal technology, over time also increases policy costs and the competition of the focal technology with incumbent technologies. Such an increase in costs and competition, on the other hand, increases the engagement of opponents of the policy and technology and affects the probability of subsequent policy change. Additionally, the perception of technology side effects such as increasing challenges of grid integration of PV or legitimacy issues grow. Formally, increasing actors' engagement is described by changes in policy feedback and the TIS life cycle (Section 3.2, Section 3.5). When earlier phases are shaped by increasing positive feedback of the growing focal TIS to political and societal actors and the perception of positive spillovers of technology adoption and TIS development (e.g., job creation, technology leadership), increasing negative feedback opens up windows of opportunities for policy change. In such a changing environment, TIS prosperity becomes important for policy maintenance or succession.

5.3 Paper C: Assessing Technology Legitimacy with Topic Models and Sentiment Analysis – The Case of Wind Power in Germany

For technology policies to be effective in fostering deployment, the legitimacy of the focal technology is a vital concern. In the extreme, a technology considered illegitimate by a fraction of influential stakeholders may face severe difficulties reaching deployment goals. Legitimacy is a core prerequisite for dedicated policies: As policymakers also must be considered a source of legitimacy, at least a certain degree of legitimacy is necessary for its support.

Wind power has long been known to conflict with residents' interests, and, as possibly with any technology, its deployment must be pondered carefully against environmental concerns. Research on the acceptance of wind power found that individual wind power projects often raise concerns related to perceptions of landscapes, alleged adverse health effects due to noise or shadow flicker, and, as a result of such concerns, negative effects on property values (Ellis and Ferraro, 2016; Rand and Hoen, 2017). While such acceptance issues are related to the perceptional view on legitimacy (see Section 3.3), such local issues only become a political issue when conflicts diffuse into the wider public and affect the broader perception of technology. Therefore, applying a processual lens (Section 3.3) to wind power's legitimacy helps identify whether wind power's legitimacy is at stake on a politically relevant level.

To do so, *Paper C* (Dehler-Holland et al., 2022) assesses 9,840 articles from four German newspapers[16] published over the period from 2009 to 2018. The assessment largely followed Markard et al.'s (2016) framework for technology legitimacy and applied a topic modeling pipeline similar to Paper A (Section 5.1, Figure 6) to the corpus of articles concerning wind power. However, methodological challenges arose when applying topic modeling to operationalize a rich, fine-grained concept such as technology legitimacy.

[16]Newspapers included are *Frankfurter Allgemeine Zeitung*, *Süddeutsche Zeitung*, *die tageszeitung*, *Die Welt*.

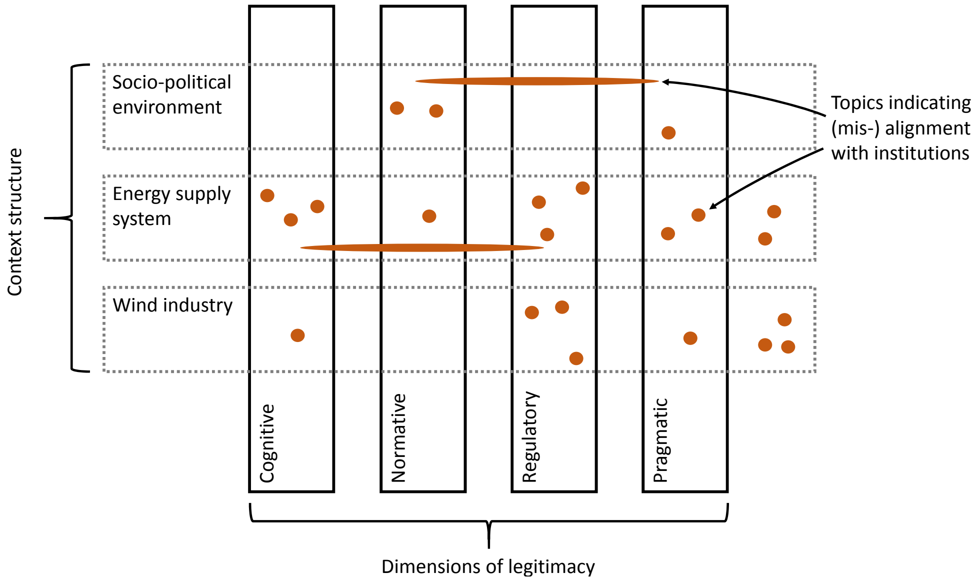

Figure 5.3: : Illustration of the identification and matching of legitimacy dimensions and topics (Paper C: Dehler-Holland et al., 2022).

Similar to Paper A, Paper C develops an STM with time as a topic covariate and builds upon the notion of topic sentiment. However, as defined above, topic sentiment cannot shed light on the temporal development of sentiment across the entire corpus. Therefore, Paper C defines *weighted sentiment* $ts_k \cdot \mu_{t,k}$ of topic k as the product of mean prevalence at time t and topic sentiment to account for temporality. Additionally, an essential concept of technology legitimacy is the contexts in which the focal technology is embedded. Paper C proposes to assess the technology's context structures by leveraging the model's covariance matrix as a graph structure. We divide the graph into sub-graphs by optimizing modularity by interpreting correlations as edges and vertices corresponding to topics. This procedure delivers three well-interpretable context structures (or sub-graphs): the *socio-political environment*, the *energy supply system*, and the *wind industry*. From a methodological point of view, a major challenge arises from identifying topics that relate to the legitimacy of wind power and the evaluation of its directionality (i.e., whether it contributes to or undermines legitimacy).

In order to identify topics possibly relevant to wind power's legitimacy, Paper C proposes to intersect the context structures topics contribute to with cognitive, normative, regulatory, and pragmatic dimensions of legitimacy proposed by the legitimacy literature (Figure 5.3). The procedure sheds light on relevant actors, infrastructure, and interests, while at the same time enabling to evaluate reasons for the relationship between topic content and legitimacy. Furthermore, the directionality was assessed based on the topic's qualitative descriptions, prevalence, sentiment, and an assessment of the topics' graph neighborhoods on whether it closely relates to conflict topics.

Despite its generally high legitimacy due to its ability to produce electricity without local greenhouse gas emissions, the results of Paper C suggest that the legitimacy of wind power in Germany is increasingly threatened. Particularly in wind power's socio-political environment that comprises local policy issues and wind power's relationship to its societal and natural environment several problems gain in prominence. Over time, topics that address wind power's effects on humans and animals and its relations to its environment become highly prevalent and point to an increased perception of the inherent normative conflicts of wind power. Additionally, topics that indicate legal and regional political conflicts increase in prevalence where these regulatory issues are often closely related to such normative conflicts. On a pragmatic level, increasing electricity bills due to the EEG surcharge and the insolvency of Prokon in 2014 that led to the introduction of a small investors protection law (*Kleinanlegerschutzgesetz*) in Gernany, criticized for preventing civic participation, can be seen as detrimental to legitimacy.

The time following the observational period provides ample evidence for the importance of legitimacy in the policy process, where the issues identified in this study continue to linger. When participation in wind power auctions declined, the government proposed to increase the compulsory distance of wind turbines to settlements to a minimum of 1,000 meters. Although the proposal did not become law, political discourse on the EEG pivoted around options to increase community participation in wind power and adapt the legal framework to the increasing number of lawsuits against local projects. Proposals for the EEG amendments in 2022/2023 "Osterpaket": (Bundesministerium für Wirtschaft und Klimaschutz, 2022b) contain the suggestion to declare wind power as being in superior public interest ("*überragendes öffentliches Interesse*") to improve wind power's legal position compared to environmental, landscape or infrastructural considerations.

While the literature has described a process of legitimation (Section 3.3), a similar process of delegitimation has not yet been described. Based on previous empirical studies of technology legitimacy and its results, Paper C proposes that such a process of delegitimation may pass phases similar to those of legitimation: Within local contexts or local projects, challenges to the acceptance of the focal technology arise. Transmitted, for example, by the media, such local issues may diffuse to the general perception of the focal technology and may lead to a delegitimation of the technology in public. The case of wind power in Germany confirms this process, where acceptance issues are repeatedly articulated on a local level and increasingly perceived on the national level (by newspapers and policymakers). Today, wind power opposition initiatives have bundled their local engagement (e.g., Vernunftkraft). However, in this context, it is essential to note that wind power in Germany is far from being generally delegitimated, as its contributions to a power system with low emissions make it an important source of electricity.

Chapter 6

Critical Reflection

Despite the attention of this thesis to a sound research design for assessing socio-technical dynamics of renewable energy policies, the analyses and theoretical propositions have some limitations that should be considered when interpreting them. The following chapter discusses these limitations, provides an outlook toward future research, and points to promising methodological extensions.

This thesis provides a case study of renewable energy policy and the development of two technologies (wind and solar power) that co-evolved with the focal policy measure. Explorative case studies are well suited to derive rich theory; however, such theory should be further elaborated and tested within different settings such as national contexts or other technologies. Additional studies could help to strengthen the proposals of this thesis further or provide evidence for departure from the ideal-typical models proposed by the papers. One outcome of such a broader research scope could be the definition of different pathways of the chains of events and identifying key drivers (e.g., Geels et al., 2016).

The geographical scope of the case study was primarily confined to a single country, namely Germany. As this thesis largely focuses on the developments of an energy policy measure, this confinement is well justified, as national environments are still the most important jurisdiction within which policies are applied. However, technological development usually transcends national borders. Therefore, policy processes are increasingly impacted by developments beyond their direct control. Therefore, the political consequences of global innovation processes (Binz and Truffer, 2017) could be further explored and yield additional insights for policymakers.

Another limitation may arise from this thesis' focus on a single set of policy instruments, namely the EEG. Recent research expands its focus to include more comprehensive policy mixes that jointly improve the conditions for sustainable technology development (Rogge and Reichardt, 2016). In that context, the question of how the proposals for the temporal dynamics of policy processes of this thesis interact with other policy measures arises. An interesting observation by Breetz et al. (2018) was that the focus on policy measures with different purposes (Section 2.1) changes along the technology's learning curve. The proposed life-cycle model of deployment policies could be a first step for systematically theorizing the processes when such changes along the learning curve occur, and policymakers must extend their instrument repertoire towards, e.g., destabilizing incumbent regime structures (Kivimaa and Kern, 2016).

As a primary data source, this thesis draws upon newspaper articles. Media accounts as an indicator for political processes, in general, appear to be notoriously difficult to interpret, as causal relations between media, politics and the public are manifold. This thesis was able to offset such issues by extending content analysis findings by a synthesis of existing studies. In general, this might not be possible, and other data sources should complement the analysis. For example, parliamentary debates are another data source with relatively high frequency and therefore well suited to uncover political dynamics. Also social media may contribute to understand political discourse.

Indeed, media landscapes and perceptions are changing. Traditional prestige media is complemented by blogs, social media entries, or online forums of varying quality. Therefore, focusing on newspaper articles may increasingly limit the view on phenomena such as agenda setting, framing, or legitimacy. However, recent research on the issue has found that while the mechanisms might have changed, traditional news media still plays a key role, and coverage may even precede coverage in other channels or seriously amplify the salience of an issue (Langer and Gruber, 2021; Harder et al., 2017). Having said that, studying the representation of the EEG or renewable energy technologies within the social media sphere certainly would be an interesting future line of work that could profit from parts of the methods developed in this thesis.

In terms of data analysis, this thesis focuses on the temporal developments of newspaper contents. Future research may extend the scope of the analysis toward a more differentiated view of different regions within the country. In fact, deployment of renewable energies often varies with the availability of potential to reap, and wind power in Germany is often located in the northern and eastern parts of the country, while solar power concentrates in the south. Also, the solar module industry was clustered in a specific region within Germany. One may hold that the profits and losses of renewable energy deployment and the EEG are not distributed uniformly across the country. Such uneven distribution may entail different perceptions of technology and policy, leading to regional legitimacy and policy framing variations. Answering these questions certainly requires extensions of the data base to include a reasonably chosen sample of regional newspapers and the development of rigorous hypothesis testing strategies over time and regions. The results would enable more fine-grained policy suggestions, pointing to regions needing higher policy and technology legitimation.

From a discourse analysis perspective, it would be highly informative to identify actors and link them to specific framings of technologies and policies. Ideally, this would provide insights into actors' positions in discourse over time to identify advocacy or opponent coalitions and how they influence the framing in newspaper reporting. In principle, the NLP literature offers methods for recognition of 'named entities' in written texts, building upon domain-specific dictionaries or leveraging the syntactic structures of sentences. Furthermore, direct or indirect speech can be identified. Notably, deep learning techniques contribute to a quick evolution of the field. However, establishing a link between identified actors and topics within a text would be challenging to address methodologically, given that texts often comprise more than one topic. A first simple step towards that goal could be identifying interviews or comments within the existing corpus and linking them to interviewees and affiliated organizations. Such a procedure would effectively limit the number of actors cited within a document and could therefore more directly associate actors and topics.

To measure the sentiment associated with topics, we defined topic sentiment by a posterior assessment of topic distributions of a structural topic model. While this procedure yielded meaningful results, the topic model cannot leverage sentiment analysis within the estimation procedure. Other topic model approaches can include sentiment in topic estimates; however, their representation of time is limited. It was beyond the scope of this thesis to refine STM in terms of sentiment assessment. However, such an advance could contribute to a better dynamic assessment of sentiment associated with topics.

Chapter 7

Conclusions

This thesis explored the socio-technical dynamics of renewable energy policies, where the term *dynamics* inherently refers to the temporal dimension and policy change. As crucial variables interrelated with the change in policies and politics, this thesis identified technological and industrial development and the perceptions of policy and technology within society. The dissertation draws on the framework of technological innovation systems to conceptualize these variables. For technology development, literature on innovation systems proposes to conceive system dynamics as a life cycle through phases of formation, growth, maturity, and decline, whose relationships to its context, such as policy subsystems, vary by phase. The relationships between technology and society can be described as the technology's legitimacy, where a processual perspective helps assess the dynamics of this relationship. This thesis identified policy feedback, framing, and agenda-setting as valuable to link policy processes, technological development, and societies' perceptions of technology.

In order to explore the public perception of policy and technology, this thesis draws on two large sets of newspaper articles concerning the German EEG and wind power. Manual quantitative content analysis of such large corpora remains costly. Therefore, this thesis deployed a set of methods from natural language processing, machine learning, and statistics to develop models of the newspaper corpora. However, methodological challenges arose from specifying models for temporal dynamics, sentiment, and complex social science concepts such as technology legitimacy. For that purpose, this thesis contributed procedures (1) to enhance structural topic models with spline regression and changepoint analysis; (2) to derive topic sentiment from the posterior topic distribution; and (3) to operationalize technology legitimacy with topic models. The resulting topic models provide insights into the temporal dynamics of the framing and legitimacy of the EEG and wind power. To further link these findings to political discourse, this thesis performed a synthesis of existing case studies on the German EEG, for the first time linking technological innovation system life cycles with policy feedback. The following paragraphs summarize the findings and highlight theoretical and policy implications.

Framing of the EEG. Media framing of societal objects has important implications for the perceptions of public and political audiences. In democratic systems, media plays an essential role as transmitters and gatekeepers of what information is deemed important. Therefore, the outcomes of framing processes can indicate whether an object is perceived as legitimate. Additionally, they can indicate the arguments applied in the underlying political struggles among stakeholders. Against this background, a topic model for 6,645 articles was developed to assess how the framing of the German renewable energy act changed over time. The results show that around 2011, dominant frames changed from focusing on renewable energy technologies and their economic spillovers to emphasizing the costs related to the policy and the EEG surcharge. Analysis of the sentiment associated with the topics revealed that while topics related to renewable technologies predominantly were connoted positively, topics related to costs were more pessimistic. Such a shift in framing, along with surveys indicating that costs are also increasingly dominating the perception of the EEG, affects the leverage of policymakers towards maintaining support for renewables. Consequently, the EEG surcharge was lowered and finally abolished in July 2022. In general, the fate of the EEG surcharge shows the political difficulties of incentivizing behavior change via increasing costs of energy carriers, which is also relevant to the imposition of CO2 taxes or prices. Additionally, the results showed that media reporting followed a cyclic pattern that gives rise to further explorations of this dissertation.

Life cycle of deployment policies. In the light of necessary greenhouse gas reductions in the coming years to avoid excessive global warming and the considerable gap between necessities and actual developments, accelerating the speed of transitions to more sustainable states of society is critical. Transition scholars, therefore, turned their attention to the timing of sustainability transitions in general and energy transitions specifically. As speeding up such transitions is a political issue of balancing various interests, understanding the timing of political processes supporting transitions is of immense importance. Against this background, this dissertation assessed existing studies on the German renewable energy act identifying feedback mechanisms between policy subsystems, the solar PV innovation system, and developments in the electricity sector using a synthesis approach. The results show how the increasing solar PV deployment and rapid industry development spurred by policy caused a virtuous cycle of mutual reinforcement. However, when policy costs increased and the competitiveness of German module producers dwindled, opportunities for policy change opened up. These findings are generalized in a life-cycle model of deployment policies, drawing upon the policy feedback and innovation systems literature. A key takeaway of the model is that even if initial enthusiasm for policy and technology is considerable, tipping points may be reached that increase the likelihood of policy change. Such tipping points can indicate that the time has come for policymakers to extend the focus of transitional policies toward mechanisms that also destabilize the existing incumbent regime. From a policy design perspective, the challenge in setting up appropriate support mechanisms is to bestow enough flexibility while maintaining a credible long-term perspective.

Legitimacy of wind power. For the deployment of policies that support the adoption of technologies, the technology's legitimacy is crucial to secure ongoing public support. Wind power's local acceptance has long been challenged by residents' perceptions of landscapes, health considerations, and environmental concerns such as wildlife protection. However, local concerns gain political significance when they leave local contexts and diffuse more widely. Against this background, this dissertation developed a topic model of 9,840 articles from German prestige newspapers to assess wind power's legitimacy. Results show that the salience of landscape issues and health and environmental concerns increased across time. The coverage of such issues is tightly related to legal and political conflicts on regional levels. Periodically, costs related to wind power and the EEG surcharge contribute to wind power's media perception, as well as the insolvency of a project developer that led to the reduction of participatory options in wind power projects. The results give rise to a conceptualization of delegitimation as a process starting in a local and confined context that diffuses to the broader public. For policy makers, this process points to the importance of engaging already on the local level, for example, by increasing local participation in the profits of wind power projects. Additionally, the legal framework must effectively balance public and stakeholder interests.

Overall, the results provide insights into the political challenges that arise in the course of maturing long-term sustainability transitions, where with increasing deployment, legitimacy issues of technology come to the fore, and rising policy costs and competition increase political pressure. These results apply to the case of the German energy transition but may transcend to other cases of renewable energy policies and technology development in general.

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Part II

Research Papers

Paper A

Topic modeling uncovers shifts in media framing of the German renewable energy act

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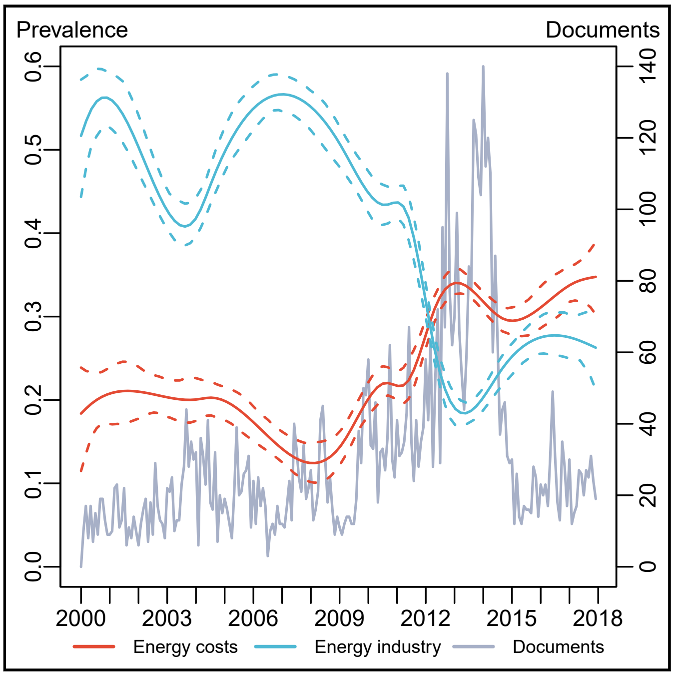
Article

Patterns

Topic Modeling Uncovers Shifts in Media Framing of the German Renewable Energy Act

Graphical Abstract



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In Brief

A structural topic model is developed to assess the temporal dynamics of topic prevalence and sentiment in newspaper coverage of the German Renewable Energy Act. The results show that coverage followed a pattern similar to issue-attention cycles. Newspapers predominantly reported on the renewable energy industry until, in 2012, framing changed, and from then on, costs dominated the agenda. The shift in framing can affect political leverage in reaching more ambitious renewable energy targets.

Highlights

- We assess coverage of the German Renewable Energy Act in newspapers over 18 years
- Change-point analysis enables structural topic modeling to capture temporal dynamics
- We introduce the notion of topic sentiment to assess the emotional content of topics
- Positive accounts of the renewable industry shift to costs imposed on society

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Article

Topic Modeling Uncovers Shifts in Media Framing of the German Renewable Energy Act

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THE BIGGER PICTURE Worldwide, policymakers push for a faster adoption of renewable energy technologies to mitigate climate change. Although policies that support the adoption of new technologies often have positive effects on innovation and job creation in an industry, they also involve costs borne by society. Media representations often have effects on public opinion on a policy. To understand how media reports on the German Renewable Energy Act developed over time, we developed advanced text mining models. We find that media coverage has shifted from positive accounts of the renewable energy industry toward the costs that the Renewable Energy Act imposes on society. If such patterns generalize, then public support and long-term renewable goals might be endangered. We propose that policies could be designed so that new innovative technologies, such as batteries or power-to-gas, and the optimism created by new technologies rub off onto "old" renewables to maintain broad public support.

1 2 3 4 5 **Development/Pre-production:** Data science output has been rolled out/validated across multiple domains/problems

SUMMARY

Renewable energy policies have been recognized as a cornerstone in the transition toward low-emission energy systems. Media reports are an important variable in the policy-making process, interrelating politicians and the public. To understand the changes in media framing of a pioneering renewable energy support act, we collected 6,645 articles from five Germany-wide newspapers between 2000 and 2017 on the German Renewable Energy Act. We developed a structural topic model based on a change-point analysis to assess the temporal patterns of newspaper coverage. We introduced the notion of topic sentiment to elucidate the emotional content of topics. The results show that after its enactment, optimism about renewable energies dominated the media agenda. After 2012, however, the Renewable Energy Act was more associated with its costs. Such shifts in renewable energy policy framing may limit political leverage to reach ambitious climate and energy targets.

INTRODUCTION

In light of climate change, the need to curb greenhouse gas emissions has been widely recognized, and political consensus has been reached that strong measures have to be taken.[1] However, there is also consent that the achievement of the ambitioned emission targets requires fundamental shifts in existing industries, user preferences, and markets.[2–4] The change processes required and the connected challenges in the energy sector have been commonly termed as energy transitions.[2,5]

Within energy transitions, renewable energy technologies play a pivotal role in creating an energy system with low emissions.[6] By 2016, 126 countries worldwide had implemented some form of renewable electricity policy.[7] Renewable energy technologies have achieved substantial cost reductions, yet financial risks still curb a faster development in many countries, and support policies are needed to lessen such risks.[7,8] Fast technology development, on the other hand, calls for policymakers to adapt to changing situations.[9]

The German Renewable Energy Act (Erneuerbare-Energien-Gesetz, or EEG) is one of the first policies supporting the market uptake of renewable energy technologies, and the German energy transition has attracted wide interest internationally.[10] The German EEG was enacted in 2000 and relies on a feed-in tariff

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or feed-in premium scheme that distributes the support for renewable electricity to many consumers through a surcharge on the electricity bill (EEG surcharge). The first significant amendments in 2004 prolonged and raised support for solar energy. A series of amendments between 2009 and 2012, among other changes, adjusted the legislation to rapidly falling solar module prices and rapid innovation in the solar sector. Amendments in 2014 and 2016 gradually introduced renewable energy tenders. In 2011, the nuclear incidents in Fukushima, Japan, caused a paradigm shift in German energy policy to phase out nuclear power by 2022. Along with the rapid expansion of wind, solar, and biomass energy, the EEG surcharge on electricity prices rose to 6.88 c€/kWh. However, various energy-intensive industries are eligible for exemptions from the EEG surcharge.

The intense dynamics of the EEG have attracted considerable scientific interest. From the scientific literature on the German energy transition policy,[11–23] we emphasize some conclusions important for our findings: researchers agree that the German energy regime has shifted from a fossil-dominated system toward a renewable system.[11,20,21] This shift has mostly been incremental, based on small policy steps rather than a radical shift in policy,[22,23] but the nuclear phase-out in 2011 represents a landmark.[11] Over time, the political discourse has de-radicalized and shifted to mainstream economical thinking,[16] and different cost narratives have accompanied the implementation of the EEG.[12] The importance of the "energy trilemma" policy goals of low environmental impacts, low energy costs, and energy security are rather stable in the parliamentary discourse. However, a decisive role in the discourse is played by a fourth goal, namely the performance of the energy industry.[21] Furthermore, policymakers' opinions[24] and public attitudes[25] toward the energy transition are strongly guided by the importance that individuals attribute to particular policy goals.

Within the political process, the media plays an important but ambiguous role. The indexing hypothesis states that media outlets closely follow governmental debates.[26] However, research also indicates that critical coverage of debates must not be based on corresponding critical elite political discourse.[27,28] On the other hand, issues perpetuated by the media may or may not enter the political agenda, depending on various circumstances.[29] McCombs and Shaw[30] have shown that the media agenda also sets public agendas by making specific issues more salient than others. On a more detailed level, attribute agenda setting posits that the media also sets the agenda regarding certain aspects of an issue.[31] Similarly, Entman argues that by selecting aspects of reality and making them more salient, framing contributes to how the media promotes certain problems, interpretations, or solutions.[32,33] On the other hand, public opinion is assumed to affect political decisions as well.[34,35] However, the multitude of existing studies has shown that all such effects are contingent.[27–29] Thus, media agenda and framing must not be congruent with elite political debates or public opinion and constitute a significant research gap, contributing to research on policy and political communication.

Some studies have analyzed newspaper coverage to understand aspects of German energy policy. Antal and Karhunmaa analyze how the German energy transition is reflected in international (non-German) newspapers and show that it is perceived differently depending on national contexts.[10] Schmid et al. showcase how advocacy coalitions in energy policy change over time and use newspaper articles to assess actors' positions and networks in the discourse.[36] Newspaper coverage that addresses specific renewable technologies has been scrutinized as well.[15,37] Rochyadi-Reetz and colleagues[38] provide an overview of international framing studies on renewable energy technologies and a comparative analysis in 11 countries. A content analysis of German newspaper coverage focusing on the evolution of coverage and the media framing of policy goals over time regarding the German EEG has not been conducted.

Due to the various amendments that the EEG has undergone, we expect that media coverage will experience shifts in the salience of policy goals and, therefore, shifts in the media framing of the EEG. In addition, technologies regularly face high expectations that often are disappointed afterward.[39,40] As the EEG supports different technologies, we are interested in how those technologies individually contribute to the media perception of renewable energies in the political context. Furthermore, as the indexing hypothesis suggests, media coverage often follows elite political discourse. We are thus interested in the representation of the political discourse and its salience in the media. Summarizing, three guiding questions structure this paper:

(1) How does the salience of the EEG and of policy goals in media representation change over time?
(2) Which topics contribute to the salience of the different policy goals?
(3) How are political debates and political activity linked to media coverage?

We show that the German EEG's media discourse follows a pattern similar to an issue-attention cycle:[41,42] the media discourse of the German EEG shifts from technology and industry optimism to emphasizing costs of the policy. This finding is surprising, as the policy discourse literature identified a regime shift from a fossil-dominated energy system to a renewable system in parallel to our findings.[11] To avoid potential bias from single sources,[43,44] we included the five largest national German newspapers in our sample, spanning the period from 2000 to 2017. The sample of 6,645 articles makes manual content analysis costly.[45]

For the analysis of large corpora, unsupervised topic models such as latent Dirichlet allocation have successfully provided insights into the contents of texts.[46,47] More recent developments of topic models have proposed to include metadata in topic models as covariates. The structural topic model[48–50] (STM) extends topic modeling by assuming a relationship between covariates and corpus content. Those structural features make STM a suitable candidate for our endeavor. We exploit the assumption that textual contents also depend on external factors in that we develop a detailed model of the temporal dynamics of newspaper coverage of the German EEG. STM has been successfully applied to test hypotheses on covariate-content relationships,[48,51–53] but rarely used as a device for detailed time-series analysis. We apply a topic modeling pipeline,[54] including preprocessing, lemmatization, corpus reduction, structural topic modeling, and, finally, careful validation. We make two

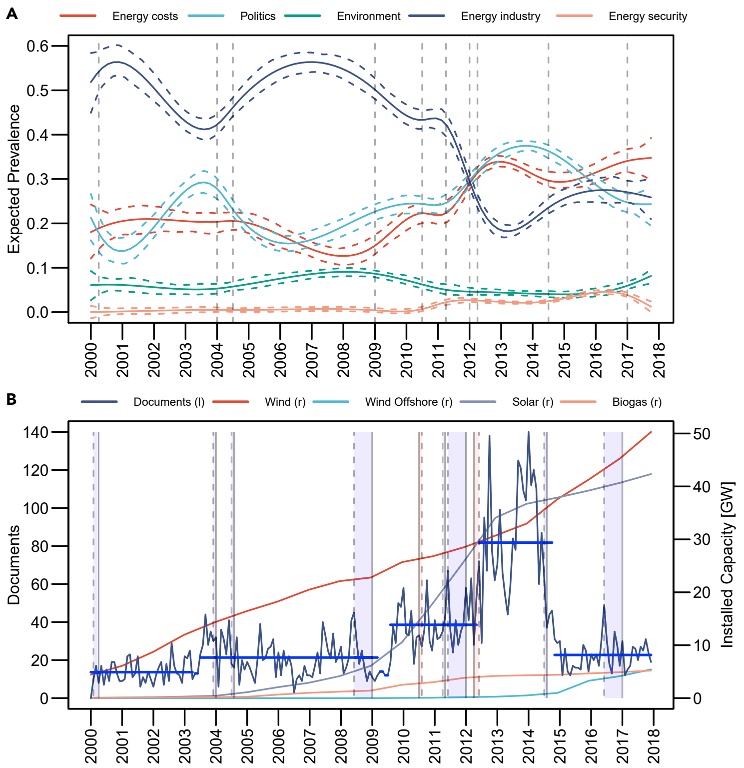

Figure 1. Prevalence of Policy Goals and Politics and Salience of the EEG over Time

(A) Evolution of policy goal coverage. The graph shows how the renewable energy industry loses prevalence over time, in contrast to the increasing prevalence of costs associated with the EEG. Curves are natural spline models as described under Experimental Procedures. Dashed curves indicate the 95% quantile. Model estimates can be found in Table S3.

(B) Left axis (l): change-point analysis of the number of documents per month covering the German Renewable Energy Act (EEG) from 2000 until 2017. Breaks in the horizontal line indicate change points, i.e., a change in mean and variance. Vertical lines indicate a change in legislation. Dotted lines are the point in time when that legislation passed Parliament. Surfaces mark the span between decision and entry to force of the legislation. Red surfaces indicate that the policy change was made retroactively (notably in 2010 and 2012). Right axis (r): installed renewable energy capacity is plotted.[60]

methodological contributions that integrate the needs of temporal content analysis into topic models and are of interest to data scientists pursuing similar objectives.

First, choices on the temporal model must be made. We choose a natural spline model to assess the temporal dynamics of newspaper coverage. Inspired by interrupted time-series analysis,[55] we propose to set spline knots based on a change-point analysis[56,57] of overall article counts to sufficiently introduce external information into the content analysis. In our case, a detailed analysis reveals that such decisions can also be made based on domain expertise: the identified change points coincide with amendments of the underlying policy.

Second, the emotional content of texts is essential to understanding media coverage and its potential effects. A classical tool to assess emotional content is sentiment analysis.[58,59] Most sentiment analysis techniques are based on assessing single words, sentences, or documents and describe sentiment as a polarity score between positive and negative.[58] However, our interest lies particularly in assessing sentiment associated with the topics that we identified with our STM. To that end, we introduce the notion of *topic sentiment*, which neatly builds upon STM's description of topics as a distribution of words. Using sentiment lexicons, one can calculate the expected sentiment of a topic, conditional to, of course, a certain lexicon. The concept of topic sentiment captures the overall qualitative impression of the emotional content of topics well.

RESULTS

The presentation of the results is structured along with the three guiding questions: we first analyze how the media representation of the EEG changes over time concerning the four policy goals of limiting the environmental burden of energy supply, energy security, limiting energy costs, and energy industry prosperity. In addition, we separate political activity as an individual category and link it to the changes in attention to policy goals. We assess newspaper article counts across the entire period from 2000 to 2017 to understand the EEG's overall media attention. The remainder of the Results section analyzes the four policy goals with attention to politics in detail, e.g., by resolving them by the different renewable energy technologies or cost drivers.

Some preliminary remarks on our methodological approach might help in understanding the results (further details under Experimental Procedures). Structural topic modeling assumes that a pre-specified number of semantically interpretable themes or topics defines each text's content and the whole collection. Each document comprises different topics to varying shares. We identify 49 topics that we assigned content-wise to the four policy goals and political activity. We assess the share of specific topics in the whole dataset (*prevalence*) in dependence on time. The time-series results of our STM are used to analyze the change in prevalence of factors that contribute to the media representation of the four main policy goals and politics. By conducting a sentiment analysis, we assign a sentiment score $-1 \ll ts_t \ll 1$ to each topic t to understand its emotional content. Furthermore, we assess a choice of articles by close reading to understand the contents of each topic and to define labels for each topic.

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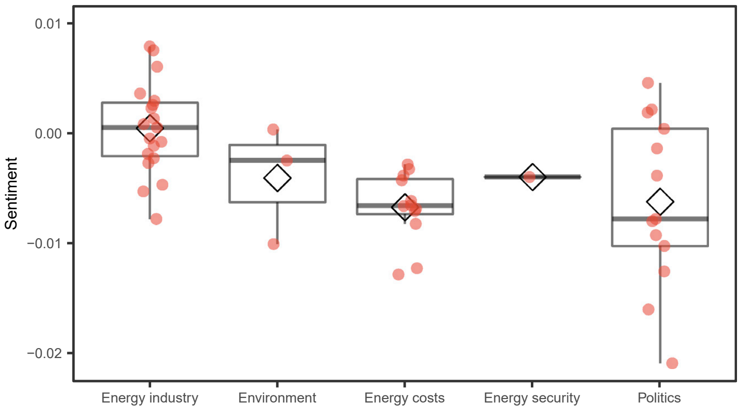

Figure 2. Topic Sentiment per Policy Goal
We find that the industry goal is covered most positively, while costs are discussed in negative contexts. Pink dots represent the topic sentiment. Whiskers display 1.5× the interquartile range. The lower and upper hinges correspond to the first and third quartiles, respectively. Transparent diamonds display the mean sentiment per category; the centerline is the median.

Coverage Shifts from Technology Optimism to a Cost Discourse

From 2000 to 2011, the EEG is debated most frequently in the context of the energy industry. In 2004, we notice a dent in industry attention, just before the 2004 amendments of the EEG (Figure 1A). Political activity gains a larger share of coverage during that time. Whereas interest in the EEG's industry effect peaks in 2007, coverage of topics related to energy costs is lowest. Renewable energy technologies are increasingly installed. From 2007 onward, costs gain prevalence, while the renewable industry loses attention until, in 2011, costs and political debates exceed industrial optimism and subsequently dominate the media agenda. Notably, the switch in attention to policy goals entails an increased coverage of political activities in 2013 and 2014 (Figure 1A). In addition, the number of articles that mention the EEG almost doubles from 2011 to 2012, just when cost issues become the most important policy goal on the media agenda (Figure 1B).

Figure 1A shows that the prevalence of the four policy goals varies greatly. Figure 1B demonstrates that the intensity of attention awarded to the EEG differs substantially, peaking between 2012 and 2014, directly after the change in framing. In addition to the intensity of coverage, the positive or negative connotation of newspaper coverage yields important information. We thus conducted a sentiment analysis to assess the emotional connotations of the topic's vocabulary distributions.

The sentiment analysis shows that, in general, the EEG tends to be presented in a negative tone, with the majority of topics having negative topic sentiment. This result is not particularly surprising, given the general negativity trend in news coverage attributable to negativity biases in human cognition.[61] Notably, energy industry topics are covered in a relatively positive tone (Figure 2): topics that relate to industry goals have a more positive sentiment than sustainability or cost topics. The lowest topic sentiment is attributed to topics that cover conventional energy production (Table 1). The qualitative assessment affirms that renewable energy technologies are particularly associated with positive accounts of job creation, industry leadership, and innovativeness. All energy cost topics are discussed in a negative tone. They discuss the EEG surcharge that must be borne by consumers, its effects on power prices or its distribution, and the overall costs of the energy transition (Table 1). Moreover, the analysis reveals that topics relating to the political process are rather diverse. They range from the overall minimum in the debate on cutbacks of solar feed-in remuneration (topic 42, Table 1) to topics that show a positive connotation.

The shift in attention to policy goals and topic sentiment shows how the media framing of the EEG switched from emphasizing economic gains that renewable technologies bring to an emphasis on costs that have to be borne by society, particularly households, while parts of the industry can avoid them. To further understand this shift in the framing of the EEG, it is interesting how the different attributes of the policy goals changed. In the next sections, we will analyze the different policy goals and the apparent change in media representation in more detail.

Energy Industry Coverage Dominated by Solar

Until 2012, the energy industry and technology coverage dominated the media perception of the EEG. The EEG supports different technologies, such as solar, wind, and biomass electricity production. It is thus a natural question, which technology received the most attention over time? A closer look into the energy industry category reveals that the topic model was able to differentiate between the different renewable energy sources, but also between conventional energy carriers (Table 1). We will discuss the energy industries in some detail (Figure 3) regarding topics that mainly drove attention during specific periods. We reduce the presentation of results to the technologies that contributed most to the shift in framing in 2011.

Splitting up the energy industry coverage by technologies, we find that solar power contributes the largest share of coverage (Figure 3A). While the run-up of the EEG amendments in 2004 co-occurs with a drop in solar energy coverage in 2003, the amendments reinforced political support for solar energy, and coverage grows fast afterward. The solar industry was depicted as a crucial future industry in Germany, and job creation in the sector contributed to its positive image (topic 34). Similarly, stocks of German solar companies were booming. However, reports also reflect the uncertainties that EEG amendments triggered for the companies. Most notably, reports show that solar stocks plummeted before the amendments in 2004, reflecting significant uncertainties whether the support would be maintained (topic 39).

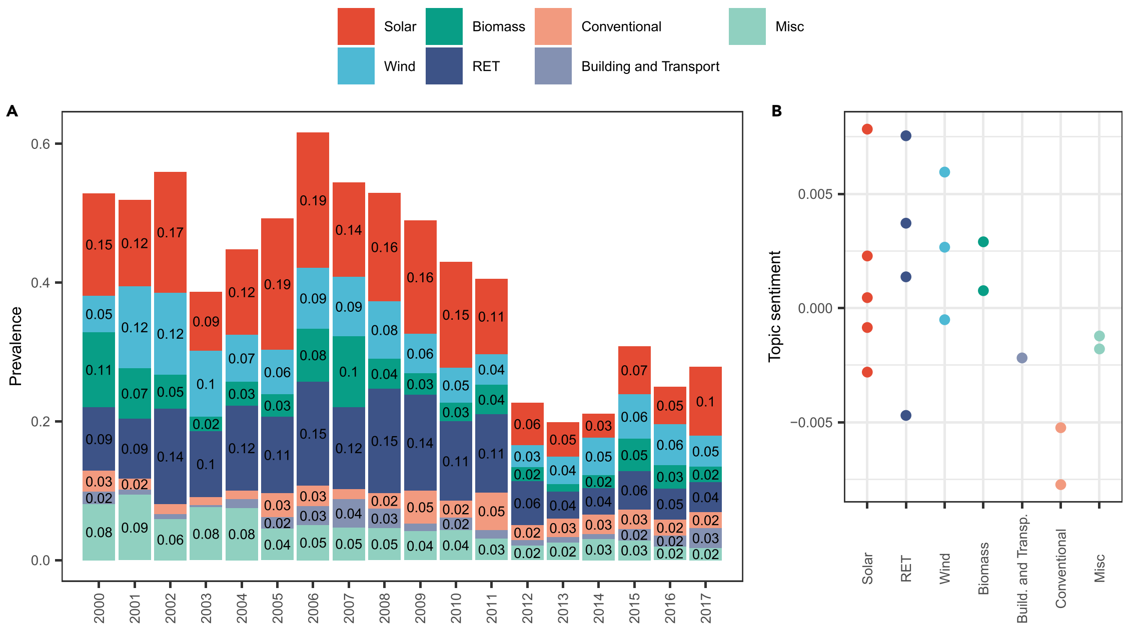

Figure 3. Prevalence and Topic Sentiment of Energy Industry Topics

(A) Split of energy industry category. Solar energy and renewable energy technologies (RET) contribute most to the coverage of the energy industry.

(B) Topic sentiment of the different technologies.

From 2004 onward, newspapers increasingly point to the growing international competition in the solar panel market, particularly from Asia (topic 33). Fears rise that German companies are losing their competitive advantages. Finally, the solar industry coverage sharply declines after 2011 (Figure 3A), when the German solar industry drastically loses market shares, and panel producers go bankrupt.[62] After 2012, solar energy production regains attention (Figure 3A), when it becomes clear that solar rooftop self-consumption, possibly in combination with batteries, becomes a profitable use case[63] (topic 48). The topic sentiment shows enthusiasm for solar energy, but also negative values when solar stocks are discussed (Figure 3B and Table 1).

Another sector, which attracts attention in the early years of the EEG, is the wind energy sector. Wind installations grow steadily (Figure 1A), and the industry is euphoric on its rapid development. Pilot plants are constructed as test cases for large new turbines (topic 8). Topic sentiment analysis shows that the language used concerning wind energy topics is predominantly positive (Figure 3B). The coverage of biomass energy generation exhibits several peaks (Figure 3A). Biomass energy production aroused criticism due to land-use conflicts that are also apparent in the coverage of transport due to the deployment of biofuels.

Other than these rather prominent technologies, renewable energy technologies are often discussed jointly, without reference to a specific technology (Figure 3A). Articles emphasize the positive economic effects of renewable energy production, such as job creation or international technology leadership in the sector (topic 32). Positive aspects of renewable technologies are also reflected in the vocabulary used to discuss renewable technologies. Compared with conventional power sources, topic sentiment is higher and predominantly positive (Figure 3B). Reports on innovative development of different technologies or energy storage are discussed with reference to the EEG, contributing to the media perception of innovativeness (topic 29).

All renewable technologies exhibit a drop in attention from 2011 to 2012. Reports on the solar industry in particular contribute to the change in framing of the EEG. The decrease in attention co-occurs with the rapid increase in attention to the costs of the EEG (Figure 1). We will now turn to a more detailed discussion of energy cost coverage to understand those changes better.

Changes in Energy Cost Coverage

The introduction of the EEG in 2000 falls in a phase of the rapid restructuring of the German energy sector. In 1998, the German government liberalized the electricity market. The liberalization still plays a significant role in the EEG discourse (Figure 4A, topic 12), in which the German energy industry association argues that the state skimmed off the profits of market liberalization by increasing the EEG surcharge.[64] Over time, the influence of the liberalization of the German electricity market and the related power price development on newspaper coverage ceases. Closely related to the liberalization, the abuse of market power of the vertically integrated utilities in the new electricity market becomes a steady topic (Figure 4B, topic 26). Utilities were accused of exerting their market power by the

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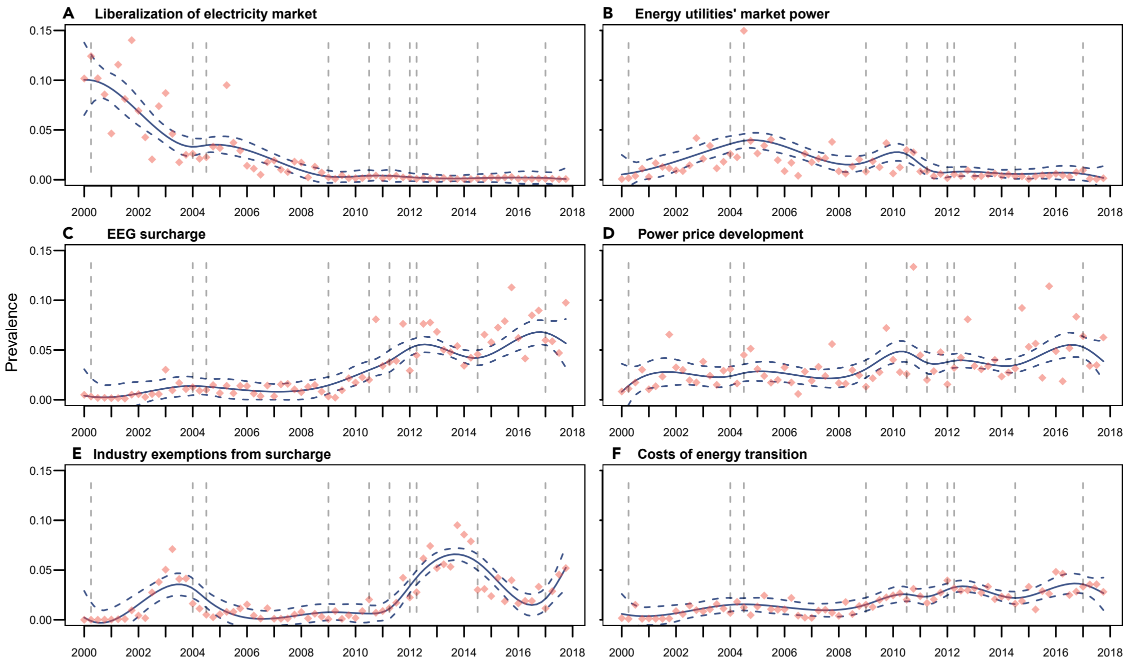

Figure 4. Prevalence of Topics Associated with Energy Costs

Prevalence is measured as the mean share of the focal topic with regard to all topics in the model. Whereas, in the early years, costs were associated with utilities' market power (B) and the EEG surcharge (C) was said to level out gains from market liberalization (A), with the increase in the EEG surcharge, it becomes a separate topic, and the power price (D) is reported increasingly. (E) Industry exemptions from surcharge; (F) costs of energy transition. Pink diamonds depict the average prevalence of the topic per quarter. The blue curve is a linear model based on natural splines to depict the trend, as described in the Experimental Procedures. Dashed blue curves indicate the 95% confidence interval, calculated by drawing Monte Carlo simulations from the topic distribution and fitting models to the simulations.[49] Dotted gray vertical lines indicate policy amendments of the EEG, as in Figure 1. Model estimates can be found in Table S4.

imposition of grid fees and pass-through tariffs. The topic disappears from the agenda with the completion of the unbundling process.

Whereas these topics disappear over time, the EEG surcharge and the general power price development enter the media agenda with force (Figures 4C and 4D, topics 4 and 19). The reports on the EEG surcharge contribute to the shift from industry contexts, in which the EEG was discussed previously, to the context of consumer prices and costs. This increase in coverage aligns with an increase in the household surcharge from 1.3 c€/kWh in 2009 to 5.28 c€/kWh in 2013. The exemption of energy-intense industries and the distribution of the EEG surcharge are discussed relative to amendments of the EEG (Figure 4E, topic 23). The discourse on the surcharge distribution to the industry also displays a strongly negative sentiment score (−0.013); in addition, overall costs of the energy transition increase in prevalence: expenditure for renewables within the EEG, but also their grid integration (Figure 4F, topic 40), is criticized. These topical changes contribute to the shift in framing of the EEG. From 2011 onward, the costs of the EEG, with particular emphasis on end consumer costs and their distribution, dominate the media agenda, replacing more positive accounts of the renewable energy industry.

Environmental Goals and Energy Security Face Lowest Coverage

Despite the demonstrated attention on cost considerations, industry matters, and political action, we turn the focus of this last section to environmental goals and energy security.

The policy goal of limiting the environmental burden of electricity supply is reflected in three topics. The EEG is discussed in the framework of climate change mitigation (topic 45). More systematic issues of transitions to sustainability in energy, transport, and building sectors are discussed, wherein the fragmented German policy is also criticized (topic 47). From the introduction of the European Emissions Trading Scheme (ETS) in 2005, the interaction of EEG and ETS is prevalent, and the EEG is said to counteract international agreements (topic 21).

Energy security is mainly reflected in the debate of missing transmission lines from northern Germany, where much of the wind energy capacities are installed, to the south, where consumption is higher due to industrial centers (topic 9). As a side topic, generation adequacy also enters the general debate on the market design (topic 13), albeit the focus here is on integrating renewables into markets and their cost efficiency.

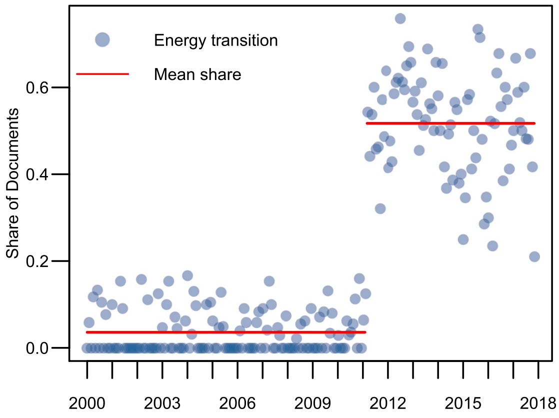

Figure 5. Usage of the Term "Energiewende" (Energy Transition)
In red, the mean share of documents per month that use the term before and after March 2011 is depicted.

Representation of Political Activity in Coverage

While the energy industry and energy costs receive a high level of attention, politics takes action to mitigate pressures that arise with regard to those policy goals. We therefore briefly investigate how political action is reflected in newspaper coverage. The analysis of topics devoted to the political process reveals that four major amendment debates can be distinguished and that the policy goals of energy cost control and industry prosperity are reflected in the coverage of political action. After the introduction of the EEG, Energy Concept 2004 (topic 18) was the first significant amendment to it. It prolonged and raised solar power support, introduced exemptions for energy-intense industries, and introduced renewable energy industry development as an explicit policy goal. The amendments between 2009 and 2012 (topic 42) struggled with the rapid deployment of solar power and reduced remuneration of new installations while raising renewable energy targets. In 2012 and 2013, an intense debate broke out on how to cap the electricity price development (topic 17) that was perceived to be driven by the EEG surcharge. Measures to cap solar installations were introduced. The amendments in 2014 and 2016 (topic 11) introduced a capacity auctioning scheme to increase competition for lower feed-in remuneration. Figure 1 shows how the four debates contribute to the coverage of political action of the EEG in the respective years. The high salience of the EEG between 2012 and 2014 is strongly related to the latter two debates (Figure 1B; topics 17 and 11) directly after the change in framing.

Along with the shift in policy goal attention we described above, the nuclear accidents in Fukushima, Japan, introduced changes to German energy policy and the decision for a rapid nuclear phase-out in 2011.[65] Directly after the nuclear accidents, the term "Energiewende" (energy transition) suddenly gained prominence (Figure 5). On March 29, 2011, 3 weeks after the nuclear accidents, Chancellor Angela Merkel demanded a faster shift to renewable energies and introduced the term Energiewende.[66] In June 2011, the government proposed the nuclear phase-out and framed the Energiewende as a Herculean task that would also bring tremendous opportunities for the future.[67] Since then, the term is commonly used in relation to the EEG. Although the term suggests a more substantial commitment to renewable energies, in fact, the renewable energy targets that already were made in the energy concept of 2010 have not been changed. In addition, the introduction of market measures was already decided in the energy concept of 2010. Our results show that newspapers quickly adopted and reproduced the new framing of German energy policy.

DISCUSSION

Structural Topic Modeling for Temporal Content Analysis

Our study found that advanced text modeling can yield valuable insights into news coverage of political instruments. In particular, our approach is able to assess temporal patterns of coverage in detail. The ability to analyze larger corpora has the advantage that multiple sources can be included in the sample, avoiding possible bias by a limitation of scope, and makes content available for rigorous statistical analysis. Comparing our findings with manual assessments of the political evolution of the German EEG show that those patterns can also be found in the policy literature.[11,12,23]

Our research is valuable for researchers and data scientists who pursue quantitative methods in content analysis. Our findings highlight that by combining change-point analysis and STM, we can define topic models sensitive to topic changes in highly dynamic settings. Furthermore, the notion of topic sentiment integrates well with topic modeling, as it uses the representation of topics as distributions of words. In manual content analysis, it is often highly labor intensive to assess the emotional content of topics by close reading.

However, an advanced data science approach cannot wholly avoid manual assessment.[68] Domain knowledge helps one to aggregate results to categories compatible with policy analysis and interpret the findings. An avenue for future research on topic sentiment may include n-grams into the analysis, as topic modeling does not harvest information encoded by the word order in a text but relies on the bag-of-words assumption. The field of natural language processing progresses quickly, and promising models are being developed. A further limitation arises from the fact that we sampled only the five most important national newspapers. The German media system is highly diverse, with the majority of print media being local newspapers. However, the newspapers we analyzed belong to the ones most cited in other media sources, and thus serve as a reference for other journalists. We thus assume that framing of the EEG in local coverage will not diverge drastically from our findings. In the following, we will discuss our results from a domain-specific standpoint.

The Attention Cycle of the EEG

Reaching ambitious climate goals requires substantial political action on introducing technologies with lower greenhouse gas emissions. Media content analysis can provide essential insights into how political action and policy change are framed by the media and communicated to the public. In that regard, our results show that the media representation of the German EEG has witnessed a frameshift from positive accounts of the renewable energy industry toward the costs that the EEG imposes on society

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Table 1. Topics Assigned to Policy Goals and Political Action

Policy Goal/Category	No.	Topic	Topic Sentiment	Prevalence (%)
Energy industry[a]	5	conventional power plant profitability (C)	−0.0053	1.12%
	7	organic matter for energy production (B)	0.0029	1.48%
	8	wind power installations (W)	0.0026	2.02%
	10	business reports (M)	−0.0019	2.25%
	16	buildings and transport (BT)	−0.0023	1.37%
	20	bioenergy (B)	0.0008	1.84%
	22	SolarWorld (S)	−0.0008	1.00%
	29	innovative electricity technologies (RET)	0.0013	1.53%
	32	renewable energy shares and targets (RET)	0.0036	3.59%
	33	competitiveness of German solar industry (S)	0.0005	2.38%
	34	solar industry boom (S)	0.0079	2.00%
	36	wind energy market (W)	0.0060	2.04%
	37	offshore wind parks (W)	−0.0005	1.73%
	38	nuclear energy (C)	−0.0078	1.52%
	39	solar stocks (S)	−0.0027	1.89%
	41	siting of industry and energy plants (M)	−0.0011	1.57%
	43	international activity of energy industry (RET)	0.0075	1.27%
	46	investments in renewable energy projects (RET)	−0.0047	1.71%
	48	rooftop solar business models (S)	0.0023	2.31%
Energy cost	3	marketing of clean power	−0.0033	2.66%
	4	power price development	−0.0043	3.80%
	12	liberalization of electricity market	−0.0065	1.25%
	13	market integration	−0.0061	2.06%
	14	choice of electricity provider	−0.0039	1.61%
	19	EEG surcharge	−0.0028	3.88%
	23	industry exemptions from surcharge	−0.0128	3.47%
	26	energy utilities' market power	−0.0069	1.20%
	27	public charges and taxes	−0.0123	1.63%
	35	industries losing EEG-privileges	−0.0082	1.31%
	40	costs of energy transition	−0.0071	2.18%
	44	periodic reports on fiscal and financial regulation changes	−0.0066	0.85%
Politics	1	coordination of energy transition	0.0019	2.24%
	6	EU commission state-aid cases	−0.0126	2.47%
	11	EEG amendments 2014 + 2016	−0.0078	2.60%
	15	politics of the SPD and CDU/CSU political parties	0.0004	2.02%
	17	electricity price cap	−0.0093	2.35%
	18	energy concept 2004	−0.0102	1.87%
	24	political power structures	0.0022	1.43%
	25	election campaigns	−0.0039	1.80%
	28	legislative process	−0.0080	3.00%
	30	profiles of politicians and entrepreneurs	0.0046	2.05%
	31	EEG remuneration	−0.0014	3.33%
	42	EEG 2009–12 reforms–solar remuneration	−0.0209	2.51%
	49	complaints of interest groups	−0.0160	0.55%

(*Continued on next page*)

Table 1. ***Continued***

Policy Goal/Category	No.	Topic	Topic Sentiment	Prevalence (%)
Environment	21	emission trading system	−0.0101	1.87%
	45	climate change mitigation	−0.0025	1.31%
	47	sustainability transition	0.0003	2.35%
Energy security	9	grid extension	−0.0040	1.72%
Common speech	2	common speech	−0.0008	4.01%

Prevalence indicates the share of a topic in the entire corpus. The expected sentiment per topic is described as a number between −1 and 1. Topic 2 (common speech) is a particular case, as the topic is defined by the style of articles. Highly associated articles report interviews or letters that are not strongly edited and contain common speech. Within categories, topics are ordered by topic number that is assigned arbitrarily.

[a]For further analysis, energy industry topics have been attributed to different technologies (Figure 3): B, biomass; BT, building and transport; C, conventional; RET, renewable energy technologies; S, solar; W, wind; M, miscellaneous.

in 2011. Over time, attention to the industry declined, while that to the prevalence of costs increased. The decrease in interest in the energy industry can be attributed to the demise of German photovoltaics (PV) producers and increasing international competition. At the same time, other renewable technologies also lost attention. On the other hand, the EEG surcharge doubled in only a few years and let power prices rise. This can explain the increasing prevalence of costs during the same period. The shift of goal prevalence also entailed a fierce debate on how to limit the additional costs borne mostly by end consumers (topic 17).

Shifts of attention toward public issues along with changes in the framing from enthusiasm about new solutions toward the realization of costs have been acknowledged in the study of political communication repeatedly and popularly generalized as the *issue-attention cycle*.[41,42] However, the finding that public policies as the "object" of media attention may face similar patterns is new. The existing results on issue attention, together with technology hype[39,40] implying that new technologies often induce high expectations that are disappointed after a while, suggest that these patterns might generalize to other technology policy instruments applied worldwide to foster technological change. For sustainability transitions with their long time horizons of several decades,[5] such a change in framing may have severe consequences. Scholars have suggested that technological development opens up windows of opportunities for ambitious climate and energy policies, whereas usually, new technologies or policies are framed as expensive.[69] Our results indicate that such windows may also close and that policies in the long term may again be threatened by cost concerns, limiting political leverage. As media accounts of a policy are arguably only one part of the picture, and causal inference to political decisions or public opinion is difficult, we compare our findings with those of policy scholars and surveys of public opinion on German energy policy.

According to Schmidt et al.,[21] in the German parliament from 1998 to 2002, conservative parties argued against renewable technologies, referring to the cost of energy, while center-left parties who held the government at that time argued in favor of the policy based on positive industry effects.[21] Our research shows that during that time, the energy industry was most prevalent in media accounts. During the period between 2009 and 2013, the governing conservative parties also picked up the argument of positive effects for the industry.[21] However, the majority of conservative arguments were still negative and referred to the costs of the policy, while opposition parties argued in favor of renewable energy. Also, Lauber and Jacobsson[12] and Hoppmann et al.[23] observed that from 2009 onward, cost concerns increased in parliamentary and political debates, while benefits of the policy were more prevalent before that, in line with the change in media framing we observed. Our analysis of the coverage of specific political debates showed that the media closely monitor them, and framings of core policy concepts introduced by the government, such as the Energiewende, are adopted and reproduced quickly. From the comparison of policy studies and our results, we conclude that media framing of the EEG broadly mirrored the arguments of the governing parties, evidencing support for the indexing hypothesis in this case. Opposition arguments seem to be reflected less often in media coverage. However, we cannot conclude whether one side caused the other or the coincidence is a process of mutual reinforcement.

The public opinion of the German energy transition has also repeatedly been surveyed. A series of surveys from 2013, 2015, and 2017 shows that electricity costs have gained in importance over the years: in 2017, it was the most crucial aspect of the energy transition, while it was considered least important in 2013.[70] Yearly surveys from 2017 to 2019 show that this trend continued.[71] This is remarkable, as the EEG surcharge rose from 1.3 c€/kWh in 2009 to 5.28 c€/kWh in 2013, while its increase slowed down considerably afterward. Although the rapid increase has gone hand in hand with the prevalence of costs in newspapers, public opinion seems to lag behind both developments and even worsens while the surcharge is stable. The EEG's framing in media and politics as costly for end consumers has thus preceded the actual turn in public opinion that the energy transition is too expensive. In line with the agenda-setting hypothesis, one may speculate that the change in framing and the subsequent increased salience of the EEG and the surcharge between 2012 and 2014 (Figure 1) contributed to the shift of the public agenda.

The detailed assessment of industry goal topics revealed substantial differences in coverage of the different technologies. We have noticed that the solar energy industry received the most attention, even though it is argued to contribute less to the achievement of policy goals than wind energy.[72] The close attention can be attributed to at least four reasons: (1) Solar energy has a high appeal to large shares of the population, as it offers investment opportunities for household solar installations, but

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also in terms of solar company stocks. (2) The solar PV market was highly dynamic, and it was presumed that Germany had an advantage over international competitors, an assumption that turned out to be false.[62] (3) Compared with wind, solar PV technology development appears to be less complex.[73] (4) The rapid development in solar markets and technology induced high policy dynamics and political learning.[23] Those four factors contributed to the fact that media devoted more attention to solar PV in combination with the EEG. Interestingly, all technologies follow the same overall trend, while each technology follows discursive subcycles.

The analysis of the topics contributing to the media perception of energy costs shows that the EEG surcharge and power price development contribute most to the change in framing. It is likely that attention to both factors can be explained along the same lines as the greater attention to solar power: the EEG surcharge on the power prices directly affects the audience of newspapers. We also have shown that the framing of costs changed over time. In the early years of the EEG, EEG surcharge and grid costs were contrasted with the efficiency gains due to market liberalization, and the market power of the big utilities was blamed for being responsible for higher prices. Later, the high share of taxes and levies in the electricity price was emphasized.

Conclusions and Policy Implications

In general, our results provide insights into how frames changed over time in the media representations of an important piece of energy legislation. As the media is an important stakeholder contributing to political discourse by filtering political news for the larger audience[74] and informing policymakers,[75] policymakers should be aware of media effects when designing policies.

Our findings point to the question of how to refinance support schemes. Although surcharges might have positive effects on energy efficiency, as they increase electricity prices, on the other hand, they may increase friction with the public as they distribute costs to a high number of voters, an issue also faced by CO_2 taxes.[76] As a consequence of ongoing cost debates, Germany introduced renewable capacity auctions[19] and agreed on a gradual decrease in the EEG levy going hand in hand with the imposition of CO_2 charges on fuels from 2021 onward.[77] However, policies might face a phase of realization of costs either way.[41,42] If that is the case, then initial political support for industries must create actor and network effects strong enough to withstand upcoming societal and economic pressures.

Our results have shown that media coverage has shifted from a framing of the EEG that highlights industry spillovers to a framing that emphasizes the costs imposed on society. Our discussion showed that public opinion followed suit, thereby potentially limiting political leverage for politicians who aim to foster the future expansion of renewables, an expansion that will be needed to reduce the climate impact of energy provision. Thus, to maintain public support, media discussion should be redirected to focus on benefits for the industry instead of costs. The recently rising attention to new business models and technologies, such as rooftop solar self-consumption with batteries, electric vehicles, or hydrogen fuels, might point to a potential direction for policy making if cost narratives threaten transition policies. Geels et al.[4] argue that innovation policies (such as the EEG) can "galvanize public enthusiasm around positive visions, and build social and business coalitions that in the longer term may support stronger climate policies." As technology expectations often follow cyclic patterns,[39] these could be used to spur public enthusiasm for "conventional" renewables and policies by supporting combinations of renewable installations with storage facilities such as batteries or hydrogen production. It might be a way to kill two birds with one stone: on one hand, the innovative appeal of new technologies can rub off onto renewable technologies. On the other hand, storage technologies are desperately needed to balance intermittent resources and foster sectoral coupling.

Particularly for Germany, where the energy transition is perceived to have lost its momentum,[78] with new wind installations and auction participation decreasing in 2018 and 2019, while added capacity is needed to reach climate and energy goals, a new wave of dynamic technology development could be needed to "galvanize public enthusiasm around positive visions."

A remark concerning our assumptions can help to place our conclusions in the context of research on media effects with its various competing results on the causal relationships between the media, politics, and the public. The discussion of our results has shown that such relationships exist in this case, but by no means were we able to establish such links statistically. Our conclusions rely on the assumption that negative coverage also influences public opinion and, further, that public opinion affects political decisions in the long run. Occasionally, policymakers may act against public opinion, or public opinion might not follow the media agenda, but in general, research shows that it is reasonable to hold such assumptions.

EXPERIMENTAL PROCEDURES

To assess the legitimacy of the EEG, we analyzed 6,645 articles from five major German newspapers applying time-series change-point analysis[56] and structural topic modeling.[50] As a result, we obtain a fine-grained time series of the prevalence of topics. A qualitative content analysis of the different topics supports the time-series analysis.

Resource Availability

Lead Contact

Further information and requests for resources and materials should be directed to and will be fulfilled by the lead contact, Joris Dehler-Holland (joris.dehler-holland@kit.edu).

Materials Availability

This study did not generate new unique materials.

Data and Code Availability

All articles analyzed in this study are available through the newspaper databases. The data were used under license for the current study, and so are not publicly available for free. However, during the peer-review process, the data were available for the reviewers, according to German copyright law (§60d UrhG), from the corresponding author upon reasonable request. The results of the text modeling (STM) that constitute the base for time-series analysis are available from the corresponding author upon reasonable request.

All algorithms used in this study have been cited in this section, are publicly available, and are well reported. However, all scripts used for the analysis are available from the lead contact upon reasonable request.

Data Collection

The study is based on articles covering the period between January 2000 and December 2017 that appeared in five nationwide German newspapers. The period covers the enactment of the German EEG in 2000 as well as all of its major amendments at the time of writing this paper. The newspaper choice covers the five non-tabloid titles with the largest circulation in Germany. We did not include online versions, as readership and structures might have evolved drastically, given the time period covered. The political orientation of the newspapers covers all facets from moderately left to moderately right and includes a financial newspaper (*Handelsblatt*). By including different newspapers, we aimed at capturing as much as possible of the variance of the media agenda that might have reached the population, as opposed to concluding to a media agenda from a single source.[44]

The articles from two newspapers analyzed in this study were collected from the LexisNexis academic database (*Die Tageszeitung* and *Die Welt*), the *Handelsblatt* was collected from GBI-Genios (wiso-net.de), and the *Frankfurter Allgemeine Zeitung* and *Süddeutsche Zeitung* were retrieved from the newspapers' own databases. For all newspapers, the query "*Erneuerbare-Energien-Gesetz OR EEG OR Einspeisevergütung OR Stromeinspeisevergütung*" ("Renewable Energy Act OR EEG OR Feed-in remuneration OR power feed-in remuneration") was searched and the results were stored. The inclusion of the abbreviation EEG also conveniently captured word combinations such as EEG-*Umlage* (EEG levy) or EEG-*Vergütung* (EEG remuneration).

The results of the original search included 7,839 articles. A first analysis revealed that some articles did not cover the EEG, as EEG also is an abbreviation for *Elektroenzephalografie* (electroencephalography). The articles were filtered locally to exclude those articles. Further, the pre-analysis revealed that some articles in the databases were duplicates. Using proximity measures of text resemblance (Levenshtein distance), the database was consolidated further. In total, 6,645 articles were assessed in the final analysis.

Pre-processing

Texts of natural language contain a high number of words with different inflections. To obtain a meaningful model of the text dataset, pre-processing ensures that words containing the same information are, in fact, associated with each other.[54] Different options are available such as stop word removal, stemming, or lemmatization. Jacobi et al. argue that lemmatization (determining the canonical form of a word) tends to give better results for richly inflected languages such as German.[79] Following this argument, we applied an advanced probabilistic procedure called TreeTagger based on Markov chains, where transition probabilities are estimated based on decision trees that take into account the context of each word.[80,81] In addition to the canonical form of each word, the software also conveniently provides a part-of-speech (POS) tag indicating the function of each word within the sentence and is highly accurate for German texts.[81] The POS tags also have another advantage: to reduce the complexity of the collection of texts, many text mining approaches use lists of stop words that are to be removed. The POS tags serve a similar purpose in that we can precisely define which word classes we include in the analysis. To capture all meaningful information, we explicitly included all adjectives, adverbs, verbs, and nouns but excluded all particles. In addition, we excluded words that appeared in fewer than 10 articles, as the weight they contributed to the topics' distribution was negligible, to make the model estimation faster without losing statistical information.[54]

We used a change-point analysis to detect changes in mean and variance of the total newspaper coverage of the EEG and to separate different phases of attention.[56,57] The results provided a first overview and pointed out that there have been massive changes in coverage over the years (Figure 1B). The span lies between one article per working day up to an average of four articles per working day. A crucial step in change-point analysis is the choice of the penalty of the cost function. As is common practice, we manually chose the penalty by visual inspection of the results[57, p. 9]. The change-point analysis informs the choice of spline knots that we conducted in defining the STM covariate model structure.

Structural Topic Modeling

To assess the contents and temporal structure of the text collection, we built upon recent developments in automated content analysis or, to be more specific, topic modeling, herein referred to as an STM.[50] The STM extends the popular latent Dirichlet allocation and its successors[46,47] by including observed covariates as linear functions to the mean parameters of the assumed prior topic distributions.[50] Information on the choice of priors is available from Roberts et al.[50] The ability to include covariate information is central to the results of this study, as it provides a framework for the time-series analysis of newspaper coverage.

Structural topic modeling and latent Dirichlet allocation have been applied successfully in different fields such as political science,[45,48] innovation management,[82] or climate change perceptions.[51,83] Both models assume that a document comprises a mixture of k topics, where topic proportions in the STM can be correlated across documents, and prevalence is influenced by covariates such as time.[48] Formally, a topic consists of the distribution over all words in the vocabulary of the text collection. The distribution of topics and distribution of words within topics are estimated based on variational inference.[46,50] Both models are unsupervised; thus, given a predefined number of topics, the topics are inferred during the modeling procedure and not predefined by the analyst. This makes the models particularly suitable for exploratory research with limited *a priori* assumptions,[45] but comes with the necessity of careful validation and interpretation of the results and the difficulty of choosing a number k of topics. Comparative experiments with human coders show that topic modeling yields competitive results.[48]

Before the model can be evaluated, the functional form of covariate dependencies must be defined. As covariate, we included the quarter within which the article was published. For dynamic dependencies on time, the developers of STM propose the usage of splines in order to detect non-linear changes in the topic prevalence over time.[49,50] First, we used natural cubic splines, which means that the second derivative at the boundary knots is required to vanish; thus, the spline extends linearly outside of its domain. This makes sure that single points close to the boundaries do not have too much influence leading to erratic boundary behavior[84, p. 24]. In addition, during regression, fewer parameters have to be estimated. Second, we chose knots corresponding to the points in time when reforms of the EEG became effective that coincided with the change-point analysis conducted above. In addition, we set a knot in each phase that separated the phase into two phases of equal length. This allows for sufficient flexibility for detecting changes in prevalence. In total, nine knots and eight parameters were included in the model. The procedure was inspired by interrupted time-series analysis (e.g., McDowall et al.)[55] and is in line with general advice on the choice of knots when prior knowledge is available.[84, p.26]

After pre-processing and model configuration, analysts must make important decisions on the final model. To reduce the complexity of model choice, we decided on a fixed initialization strategy. Roberts et al.[85] showed that initializing the STM with a solution of a simplified problem using a spectral decomposition of the word co-occurrence matrix delivers favorable results. This reduced the model choice to a choice on the number of topics. Different procedures have been proposed and applied in the literature comprising the qualitative assessment of many different models with a different number of topics (e.g., Farrell)[82] or based on different statistical indicators that measure how well the topics can be interpreted by humans, such as *semantic coherence* (e.g., Mimno et al.).[85] In this study, we followed a hybrid approach.

With the above specifications of the model structure and functional form, we decided on the number of topics as follows: first, we assessed models for $k = 10, 20, \ldots, 100$ based on lists of most probable words and FREX (frequency and exclusivity) in order to get an overview of the topics that could potentially be related to the policy goals of the EEG. FREX is an indicator leveraging the exclusivity of words to a specific topic with the probability of occurrence and has been proven to yield favorable properties for providing word lists for topic interpretation.[86] The first analysis found that the number of topics should be larger than 20. Second, we estimated models with topics between 20 and 100. We evaluated the mean exclusivity based on the FREX indicator and mean semantic coherence against each other as proposed by the package authors of STM (Figure S1).[49] The analysis left us with three promising models with differing numbers of topics, k = 25, 31, and 49, that locally dominated the solutions. A closer investigation revealed that the models with k = 25 and 31 could not distinguish some issues sharply. The choice of the number of topics is also a qualitative decision on a certain perspective on the problem and thus depends on the research questions. Due to the delicacy of the topics contributing to policy goals of the EEG, we chose the model with k = 49, which allowed for a fine-grained analysis of the articles.

Model Validation and Interpretation

Two essential dimensions of the validity of topic models are semantic and predictive validity.[68] Semantic validity refers to whether topics have a coherent meaning and is considered the most important dimension of the validity of

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content analysis procedures. Standard procedures to assess the semantic validity of topic modeling are the assessment of word lists based on probability or FREX[87] or close reading of a subsample of texts.[45,68] For our case, predictive validity is also highly relevant, as it reflects the extent to which topic prevalence changes relate to external events. In the following, we describe the procedures we applied to assess validity.

After choosing the model and the number of topics, we validated the semantic content of the 49 topics. On one hand, we must ensure the internal semantic validity of the topics. On the other hand, it is necessary for interpretation to find meaningful labels for each category. In accordance with the literature,[45] the first two authors each read at least 10–15 of the articles most associated with each topic and reviewed topic distribution and word lists of the most probable terms and highest FREX. Each researcher documented the results as notes for each article and concluded an overall label of the topic and a short description independently. A comparison of the results showed an agreement of 80% between the two researchers. More precisely, 39 topics were interpreted identically; 6 topics were interpreted in parts differently and 4 topics substantially differently by the two researchers. The 10 topics on which there was disagreement were reconsidered jointly regarding the notes taken by the researchers to reach consensus on the topic label. The results are documented in Table 1 and, together with a short summary, in Table S1. Overall, we reached a consensus on all topics. Only a few topics contained documents that were not expected from the general tendency of the articles. For example, the sample of articles on topic 22 contained two texts that portrayed eccentric leaders of companies other than SolarWorld. The association of the articles can be explained by the many references to SolarWorld's eccentric leader.

The predictive validity of the model can be tested by comparing topic time series against real-world events.[83,88] The analyses presented in the paper and its comparison with political decision processes and outcomes show ample evidence of the external validity of the model results.[12,14,23] In the following, by way of example, we discuss the topic "liberalization of the electricity market" (Figure 4A) along with external events that are expected to affect its prevalence. In such a way, all topics can be discussed as long as they have some resemblance to external events. The German electricity market was liberalized with the enforcement of the Energy Industry Act in 1998. The graph shows that this event affects the coverage of the EEG, particularly at the beginning of our time horizon. However, while this event becomes more distant in the past, its effects on coverage also cease. The bump in the prevalence curve in 2005 can be explained by external events: In 2005, the Energy Industry Act was amended, leading to a temporal upsurge in market liberalization issues.

Research has shown that, within German energy policy, four policy goals have played a major role: environmental sustainability, limiting energy costs, energy security, and energy industry performance.[21] To understand how those policy goals are represented in media coverage, we coded topics according to the policy goal they contributed to most. This coding was done based on the more detailed descriptions provided in Table S1, rather than only on their short labels provided in Table 1. The coding procedure revealed that a set of topics was associated rather with concrete political debates between political stakeholders than directly with the policy goals. Arguably, policy goals are the main contents of those debates, but the model was able to distinguish them from the debates. We therefore further differentiated a category, "politics," from the four policy goals that represents, therefore, an indicator of the prevalence of political activity in newspaper coverage. A description of all five categories can be found in Table S2.

Sentiment Analysis

The approach we used for sentiment analysis can best be classified as an aspect-based one: based on the topic model we have developed above, we assessed the sentiment of each topic.[58] However, we were not interested in a measure that assigns a sentiment score to each document. The topic model we have developed gives rise to a simple way of defining topic sentiment based on the word distributions of each topic and a sentiment lexicon. For sentiment analysis, the lexicon is an important foundation.[58] For the German language, SentiWS provides an established lexicon for German, with more than 3,000 words and more than 16,000 inflected forms.[89] Based on this lexicon, we defined the topic sentiment ts_t as the weighted sum of all sentiment scores $s_{w\in[-1,1]}$ of words w from the vocabulary V. We weighed this with the word occurrence probability $\beta_{w,t}$ per topic t estimated by STM:

$$ts_t = \sum_{w \in V} \beta_{w,t} \cdot s_w .$$

The resulting topic sentiment gives a well-interpretable indicator for the overall sentiment of a topic: the higher the ts_t, the more likely the usage of words with a positive connotation in the context of this topic. The results are reported in Figure 2.

It is noteworthy that the vocabulary of our corpus consists of 12,217 words, of which 1,662 (or 13.6%) are also in the sentiment lexicon. This is to be expected, as most of the words of natural language do not carry sentiment per se. The ratio implies that the actual range of topic sentiment will be much smaller than $[-1,1]$. It is bound by the sum of the word occurrence probabilities per topic of the words from the lexicon. Furthermore, positive and negative sentiment annul each other in the definition above. Those facts contribute to the expectation that topic sentiment values will be small and centered around zero. However, we argue that this does not affect robustness for comparative usage and affects only the scale of values. This scaling effect could be offset by normalization, but we think that the definition in terms of the statistical expectation is more intuitive.

Presentation of Results

For interpreting the resulting time series of topic prevalence, we estimated linear models with the spline structure described above. Confidence intervals were obtained by drawing from the posterior distribution of topics as implemented in the *estimateEffects()* function of the STM package.[49] We aggregated the topics to four policy goals and political activity. Aggregation was conducted manually, taking into account the qualitative topic descriptions provided in Table S1. Linear models are provided in Tables S3 and S4.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.patter.2020.100169.

AUTHOR CONTRIBUTIONS

J.D.H. designed the study, analyzed and interpreted data, and wrote the draft. K.S. contributed to the analysis and interpretation of data and writing of the draft. W.F. contributed to the interpretation of results and revised the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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Paper B

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

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From Virtuous to Vicious Cycles – Towards a Life Cycle Model of Technology Deployment Policies

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"Now that we know policy choices have political consequences, however, what needs to be determined is precisely how, when, and where particular effects are likely to occur." *(Pierson, 1993, p. 597).*

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 life cycles to the policy feedback framework that is 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 and supported by the literature, this paper proposes an ideal-typical technology deployment policy life cycle model that describes how TIS development, sectoral configurations, and the focal policy co-evolve in a reciprocal process. The model discussion brings to light the role of the TIS not only for policy enactment but also for policy maintenance or succession. We further discuss aspects of policy design and preconditions of such life cycles. 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.

Keywords:

Technology deployment policy; Policy feedback; Innovation systems; Technology life cycle; Sustainability transitions; Renewable energy

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, 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 phase of rapid acceleration of adoption 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 possibilities for stakeholders and interest groups to influence the policy process toward particular interests (Jordan and Matt, 2014, 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; Edmondson et al., 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, 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 to combine the framework of policy feedback in socio-technical systems (Edmondson et al., 2019; Edmondson et al., 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 more general temporal patterns of deployment policies from the case study results, informed by cases from 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. Section 3 introduces the methods employed to assess the EEG and the related policy processes. Section 4 presents the EEG case study. Section 5 proposes and discusses five phases of an ideal-typical *technology deployment policy life cycle*. Section 6 discusses the prospects of the TDP life cycle and points out possible directions for future research. Section 7 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 (Geller et al., 2006). Technology deployment policies are an essential measure to increase the uptake of technologies at the "middle of the experience curve" after initial costs have been brought down by policies such as, for example, R & D programs or supply-side subsidies (Breetz et al., 2018). All such programs have in common the inherent inertia of the systems to change that increases political friction and calls for stringent, long-term policies to improve the sustainability of the respective sectors.

The literature on sustainability transitions is increasingly considering theories of policy processes (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; Edmondson et al., 2020; Rosenbloom et al., 2019; Schmid et al., 2019).

Also the TIS literature early on included references to politics (Markard et al., 2015). 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 also been criticized for paying insufficient attention to agency and therefore requires a more detailed view of the policy process (Kern, 2015).

Within this context, this paper seeks to contribute to both literature streams for the case of technology deployment policies. The literature on policy feedback in sustainability transitions has had great success in laying the foundations to understand the effects of policies on subsequent developments. However, it has not spelled out hypotheses on the relations between technological (TIS) development stages and politics. On the other hand, we contribute to a more elaborate understanding of the TIS relations to its political context by discussing how policy feedback can describe such relations in more detail.

This section proposes to rely on the TIS framework, specifically the TIS functions, contexts and the TIS life cycle, and policy feedback to assess the co-evolution of policy and technology. 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 acknowledged that TIS relations to its context structures such as political systems are essential to understand its development (Bergek et al., 2015).

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, it makes sense to focus the analysis on the TIS constrained by national borders ('focal TIS') embedded into its (national) sectoral context. 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 produce policy feedback.

2.1 Policy feedback in socio-technical systems

A vital aspect of the feedback metaphor 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.

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 a crucial driver of policy effects on society, affecting the distribution of coalitions concerning the 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).

Table 1: Policy effects and feedback (Edmondson et al., 2019; Edmondson et al., 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, surcharges; Reallocation of resources can affect the behavior of target groups towards more sustainable modes, but can also have unintended consequences.
Interpretive Effects (IE)	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

However, it must be emphasized that policy feedback is not sufficient for policy change (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 or 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, the conceptualization of the emergence of policy effects within the socio-technical system and its translation into feedback has remained vague. Therefore, in the context of technology deployment policies, the following sections propose to link feedback to the literature on technological innovation systems.

2.2 Technological innovation systems and the TIS life cycle

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 is generated.

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.

A classical perspective for understanding TIS dynamics is that certain processes or functions are 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 (Hekkert et al., 2007; Suurs and Hekkert, 2009). On the other hand, vicious cycles can prevent successful development. Societal problems (such as environmental issues) can ‘guide the search’ and thereby start the development of a TIS (Hekkert et al., 2007). Also, entrepreneurs that lobby for market formation or better economic conditions for a technology can start virtuous cycles of TIS development (Hekkert et al., 2007). 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' contextual structures and interactions. TIS-context interactions are described as a continuum between 'external links' and 'structural couplings' dependent on the degree of mutual interdependency. Structural couplings manifest in TIS elements that are embedded into multiple contexts simultaneously, such as a firm in a TIS that must satisfy a specific sector's demand while responding to political developments (Bergek et al., 2015, p. 53).

Early on, TIS scholars have focused on the impact of politics on the legitimation of new technologies, but 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. Therefore, the characteristics of the political system actors are situated in, play a central role in shaping their political strategies and behavior (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.

When considering a sectoral innovation system of all the elements involved in the production and distribution of a particular function or service (Malerba, 2002), such as energy provision, it becomes clear that it is difficult to think of the TIS isolated from the institutionalized context a sector provides. A TIS may have mostly external links with the sector or be structurally coupled with the industry extensively in the form of actors active in the TIS and the sector simultaneously (Bergek et al., 2015).

Therefore, sectoral actors can shape the development of a TIS by influencing the direction of search and cooperation or by de-legitimizing a competing TIS. 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 (TIS). TIS life cycles emphasize the growing or loosening ties of the TIS and its environment in different stages (Markard, 2020). 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. In the *formation phase*, a low number of actors can base their activities on limited funding, mainly from public R&D support, and different technological ideas compete (Markard, 2020, p. 8). In the *growth phase*, sales rise, new firms enter the market, the number of actors grows, and actors specialize. They form industry associations, and institutions such as formal regulations and standardization emerge while technology diversity decreases and ties to its context grow stronger (Markard, 2020, 8ff). In the *mature phase*, sales are high, but growth rates are low. The TIS is stable with low entries or exits. The context and TIS are highly co-dependent, and their ties are stable (Markard, 2020, p. 10). In the *decline phase,* sales decrease, and firms leave the TIS. Struggles of actors increase, the TIS and institutions destabilize, and ties to the TIS's context loosen. 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; Suurs and Hekkert, 2012). A motor of innovation comprises a combination of system functions particularly 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 (Table 2).

From that perspective, in the early formation phase of a TIS, knowledge development and diffusion are essential for TIS development, together with resources for R&D and initial guidance of the search. When the TIS develops further, entrepreneurial and legitimation activities increase to extend initial political support on a project basis. Within the growth phase, 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. When system building was successful, legitimation and advocacy coalition building lose in importance in the mature phase. For potential phases of decline, the original work of Suurs (2009, 226ff) could not identify precise 'motors of decline'.

Table 2: TIS life cycle, innovation motors, and TIS functions (Markard, 2020; Suurs, 2009; Suurs and Hekkert, 2009).

TIS life cycle phase	Characterization	Motor	Driving Functions
Formation	• Low technology maturity • Reliance on R&D support and dependency on context	Science and Technology push motor	Knowledge development, Knowledge diffusion, Guidance of the Search, Resource mobilization
		Entrepreneurial Motor	Knowledge development, Knowledge diffusion, Guidance of the Search, Resource mobilization, **Support from advocacy coalitions/Legitimation, Entrepreneurial activities**
Growth	• High entries, increasing sales • Growing interdependency with context • Technology matures • Actors specialize and build networks	System building motor	All functions
Maturity	• High sales, low growth • Stable context relations • Low entries and exits	Market motor	All functions without legitimation
Decline	• Sales decreasing • Actors exit • Context ties loosen	Motors of decline	Diffuse patterns; any function failure could lead to TIS malfunctioning

From this discussion, two important conclusions can be made. First, the discussion showed that the development of the TIS relates to the strength of its context relations, for example, its relations to policy subsystems or sectors. Therefore, when considering the development of the relations between a deployment policy and the TIS, it is plausible that these may change over time. Second, the TIS functions serve the description of TIS performance, and functional patterns may vary over TIS stages. The following section discusses how the TIS framework can be used to explain the emergence of policy effects and feedback.

2.3 On the emergence of policy effects and feedback for TDP

Policy feedback in socio-technical transitions has come with a stylized conceptualization of socio-technical systems, which was the motivation for mobilizing the TIS framework, its functions, contexts, and life cycles to allow for a thorough understanding of processes at play within the socio-technical systems. This section draws on the TIS framework's elements to outline how policy effects and feedback materialize.

The first question is whether and how deployment policies affect an innovation system. Beyond addressing market failures, deployment policies have helped foster technological learning. Deployment policies have been argued to be used to break technology lock-ins (Malerba, 2009); however, they might also cause lock-in effects (Jaffe et al., 2005). In order to stimulate niche market developments, fostering demand-pull policies have been found essential (Walrave and Raven, 2016), and their absence has been associated with lower TIS performance (Andersson et al., 2017; Suurs and Hekkert, 2009). For technologies with a certain maturity, deployment policies can foster innovation activities, where price-based instruments have a more significant impact than quantity-based instruments (Costantini et al., 2015) related to their potential to mitigate risks (Klessmann et al., 2008). Therefore, deployment policies are often implemented in a stage where some learning has occurred, but substantial additional learning can only be reached by an upscaling of production (Breetz et al., 2018). In this context, it is interesting to note that the implementation of deployment policies is often preceded by TIS activities toward legitimacy creation (Suurs, 2009). Additionally, deployment policies can affect the balance between explorative and exploitative innovative activities (Hoppmann et al., 2013). Summarizing, the literature suggests that deployment policies may have resource and interpretive effects onto innovation systems. Their effects on TIS' exceed the creation of markets and resource mobilization. They guide the search toward niche market segments or the exploitation of innovative achievements. Indirectly, resource and interpretive effects to be expected are the expansion of entrepreneurial activities and knowledge creation and diffusion. However, a policy may also affect audiences in the larger context of the focal TIS.

One crucial feature of deployment policies is their effect on the distribution of financial resources. As we have seen, increased resources provided to the TIS may foster its development. However, the resources provided to the TIS must be collected or saved elsewhere. Therefore, a deployment policy may lead to resource effects also in the context of the focal TIS. Depending on the policy design, resources may be taken from the national budget or redistributed via taxes or surcharges, leading to potential adverse resource effects. Additionally, the new distribution of resources may also affect the sector, as new technologies may increase competition in the provision of sectoral services. On the other hand, increased activities within the TIS and its context emit policy feedback.

A critical determinant for the emergence of socio-political feedback is the likelihood of the formation of advocacy coalitions or opposition that may realize in interest group activities due to the distribution of incentives (Edmondson et al., 2019; Pierson, 1993). The TIS functions framework contributes to the analysis of feedback, as the success of a TIS in fulfilling a specific function usually relies on scrutinizing the activities of actors or networks, their alignment, and structural changes over time (Suurs and Hekkert, 2009). Successful fulfillment of 'entrepreneurial activities', for example, is related to the entry of new actors and their increasing activities in the field. Likewise, active 'knowledge development' increases the actor base by activities of, e.g., universities, research institutes, or cooperations between companies, and successful resource mobilization may draw in additional actors from government, banks, or investment funds who must develop skills to rate credit risks related to the new technology. Therefore, the successful fulfillment of TIS functions is related to the actors of the focal TIS. Such actors develop an interest in the well-being of the focal TIS, as they have dedicated resources to it and therefore are likely to support the focal policy publicly. Particularly when the expansion of a TIS goes in hand with job creation, it delivers a welcomed political argument (Fankhaeser et al., 2008; Lockwood, 2013;

Stokes and Warshaw, 2017). The emergence of explicit negative feedback from the TIS appears unlikely[1] as long as the TIS context does not threaten the legitimacy of the focal technology and policy.

Besides the political system, two crucial context structures are relevant sectors and other TIS (Bergek et al., 2015). Such context structures are said to relate to the focal TIS in positive (supporting) or negative (hindering) ways (Ulmanen and Bergek, 2021). For this study, the sector within which the focal technology is applied is a key context structure that may emit policy feedback due to interests in either further deploying the technology within the sector or not. One determinant of sectoral reactions might be whether the new technology and its deployment modes align well with sectoral companies' competencies or not, which determines how readily a technology can be adopted by incumbent sectoral actors (Tushman and Anderson, 1986). The 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). To articulate their interests, companies have a broad set of strategies at their disposal (Oliver and Holzinger, 2008). Within the sector, also other sources of feedback can be expected. A crucial question in this regard is how the focal technology aligns with already existing infrastructure (Weber and Rohracher, 2012). However, also beyond the sectoral and technological contexts, feedback can be expected from the broader socio-technical system. An important source of feedback the literature identified is the mass public, where it is crucial how the focal policy distributes benefits and losses (Campbell, 2012; Larsen, 2018). Interestingly, "voters need not themselves arrive at the opinion that the status quo must go: Elites can make the case for change *for* them." (Jacobs and Weaver, 2015, p. 448). Thus, stakeholders might use alleged mass public effects of a policy to argue for or against it.

[1] As long as the technology or TIS do not face any threats to their legitimacy, expansion of the TIS should create positive feedback due to its positive externalities for politics. Even the failure to fulfill certain functions might be considered as feedback, as policymakers might be inclined to address such weaknesses in the system to foster development.

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

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 (2021), 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 the purpose of translation, this study uses the 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

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

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. This procedure resulted in Table 3 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 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 and structured according to whether the original studies predominantly provided information on *external conditions*, *sectoral and TIS dynamics,* or developments in the *policy subsystem*. This structure largely preserves the three literature streams that the synthesis builds upon and acknowledges the importance of external events in the policy feedback literature.

Additionally 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 similar pattern to the one presented with some notable differences. In section 5, these results help to refine the notion of a deployment policy life cycle, along with findings from other cases.

4 Case study - The German EEG (1999-2017)

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 (1999-2000; 2000-2004; 2005-2010; 2010-2014; 2014-2017). We summarize external conditions, the dynamics within the electricity sector and the TIS, and the policy subsystem for each stage[4]. Policy feedback, effects, and critical variables are described in Table 3, sometimes in more detail than the body of text allows.

[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]**.

4.1 EEG - Phase I (1999-2000)

External conditions. In 1998, the energy industry act (Energiewirschaftsgesetz, EnWG) was enacted, implementing EU requirements toward a common internal market. The EnWG liberalized the German electricity market and was meant to dissolve the prevailing monopoly structures and allow new entrants access to the electricity grid with fair conditions (Kungl, 2015, p. 16). After the elections in September 1998, a coalition of social-democrats and the green party came into government. In 2000, the new government agreed with utilities to phase out nuclear power within the next three decades (Kungl, 2015, p. 16).

Sectoral and TIS dynamics. Wind installations doubled between 1998 and 2000 and increased from 2.9 to 6.1 GW (AG Energiebilanzen e. V., 2019). The growth during the preceding decade had established the second-largest wind turbine industry in the world (Jacobsson et al., 2004, p. 19). It created strong political networks of the wind energy industry (Bergek and Jacobsson, 2003), that supplied policymakers with arguments for the positive effects of renewable energy support, such as industry and job creation **[+SPF]**.

Between 1998 and 2000, the world market for solar panels was already growing (Jacobsson and Lauber, 2006). The TIS showed already increasing activities across all functions, including increasing entrepreneurial activities and knowledge development (Table A. 2). Additionally, after 1996, the German Solar industry association promoted introducing a 100,000-roofs-program, and solar panel producers threatened to produce their panels abroad if no further steps for market expansion are taken **[+SPF]** (Jacobsson et al., 2004, p. 18). After negotiations with policymakers, two companies expanded their production capabilities in Germany in 1998, and policymakers were already able to convince large producers of prospective policy intentions (Jacobsson et al., 2004, p. 18).

The utilities evaluated the liberalization of the electricity sector 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 **[absence of -SPF]** (Kungl, 2018, p. 190).

Within the industry, positions towards the EEG were ambiguous. While the "BDI [Bundesverband der Deutschen Industrie, Federation of German Industry] condemned the bill for exorbitant costs" **[-SPF]** (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 **[+SPF]** (Hirschl, 2008, p. 145).

Policy subsystem. The new government meant a change in the support coalition of renewables, as mainly the green party had renewable energy expansion on its agenda since its foundation (Hake et al., 2015; Hirschl, 2008, p. 140). In 1999, the government implemented the 100,000-roofs-program to support the installation of rooftop solar panels. 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 **[+SPF]** (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 **[-FF]**, finally, a small group of members of parliament initiated a bill in parliament (Stefes, 2010). The directorate generals (DGs) of the EU for energy and competition opposed the bill **[-instE]** (Lauber and Jacobsson, 2016, p. 151).

The new EEG, enacted in April 2000, introduced a fixed remuneration differentiated by technologies. The new remuneration scheme was now able to create a market for solar power **[+RE]**. The amendment was well-aligned with the earlier introduced 100,000-roofs-program **[+instE].**

4.2 EEG - Phase II (2000-2004)

External conditions. The elections in 2002 allowed for a second term of the coalition of social democrats and the green party. The greens could win a higher share of votes, while social democrats lost, and the minor partner gained political leverage. In 2002, the nuclear phase-out became formal law.

Sectoral and TIS dynamics. The guaranteed remuneration for 20 years reduced investment risks. Wind and solar installations increased, and markets developed further (Figure 1). The solar TIS grew, new entrants along the whole value chain entered the TIS, and networks within the TIS tightened **[+intE, +RE]** (Quitzow, 2015, p. 131). In 2003, most large module producers had entered the market (Quitzow, 2015, p. 131). Compared to the preceding phase, TIS activities increased along all functions (Table A. 2).

The EEG also further expanded the social composition of electricity producers. 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). This broad actor base made MPs more susceptible to lobbying by renewable energy associations, as local initiatives and citizens increased pressure on MPs **[+SPF]** (Seibt, 2015, p. 180).

Utilities 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 interests 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).

Policy subsystem. Within the government parties, solar, wind, and biomass are generally evaluated positively in the debates on the amendments of 2004 (Seibt, 2015, pp. 181–183). An essential theme of parliamentary debates is the market creation and the chances to create jobs in a growth industry **[+SPF]**, but also costs for society and industry enter the discussions (Hoppmann et al., 2014, pp. 1427–1429).

However, in the beginning, the new law was challenged by various circumstances. High uncertainties arose from the state-aid inquiries of the European Commission **[-AF]**, which the European court of justice finally resolved in 2001 (Hirschl, 2008, p. 149). The elections in 2002 strengthened the political position of the green party. Based on previous struggles with the EEG and the BMWi, the greens managed to transfer responsibilities for renewable policies to the green-led ministry for the environment (BMU). While the BMU was more positive concerning renewable energies, the new constellation led to complicated debates on the EEG 2004, with the economic ministry trying to lower wind remuneration and introduce industry exemptions from the EEG surcharge **[-intE, -FF]** (Hirschl, 2008, pp. 157–162). Within the controversy between BMWi and BMU, the scientific advisory board of the economics ministry even proposed to altogether terminate the law due to the introduction of CO_2 certificates in Europe **[-instE]**, increasing uncertainty on the maintenance of the EEG **[-intE]**. Industry exemptions, supported by the BMWi, were accepted and traded off against introducing a regulatory agency for the electricity market in the new EnWG (Hirschl, 2008, p. 156).

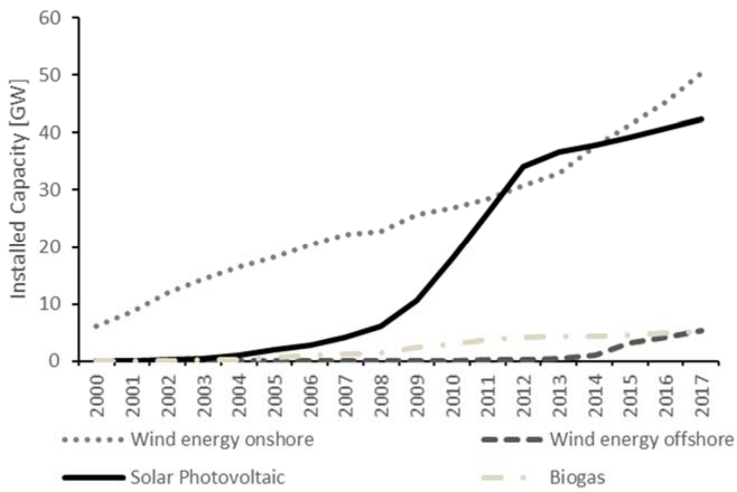

Figure 1: Cumulative installed capacity of renewable energy technologies in Germany (2000-2017) (AG Energiebilanzen e. V., 2019).

4.3 EEG - Phase III (2005-2010) Enthusiasm, growth, and realization of costs

Exogeneous conditions. Within the elections of 2005, a coalition of the largest German parties came into government: conservatives and social democrats. Also in 2005, the first trading period in the European emissions trading scheme (EU-ETS) started. The world market for silicon faced a shortage and led to supply issues for the growing photovoltaics industry. In 2008, the financial crisis hit the world economy, entailing decreasing electricity demand.

Sectoral and TIS dynamics. The EEG amendments of 2004 reinsured the expansion of renewable energy production (Figure 1). Marketwise, removing the cap for solar power production eliminated uncertainties for future developments (Quitzow, 2015). The TIS functions show a high activity level **[+RE&+intE]** (Table A. 2), although some observers remarked the slow expansion of module production capacity related to increased silicon prices (Quitzow, 2015, p. 134). Growing employment, particularly in the solar industry, increased renewable energies' political leverage **[+SPF]** (Quitzow, 2015, p. 133). Industry associations of wind, solar, and renewables in general (BWE, BSW, BEE) are increasingly seen as professional organizations, and their activities increase **[+SPF]** (Seibt, 2015, p. 186).

Innovative activity in the solar TIS increased **[+RE&+intE]** (Figure 2). Private R&D expenditure soon surpassed public spending, and new knowledge diffused fast (Quitzow, 2015). Q-Cells and Solarworld emerged as important actors while additional equipment suppliers entered the German market. In this phase, the expansion of the solar TIS is only limited by the shortages in silicon supply, and module prices rose, soon being compensated by efficiency improvements (Quitzow, 2015).

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, they started to oppose the EEG, 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]** (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).

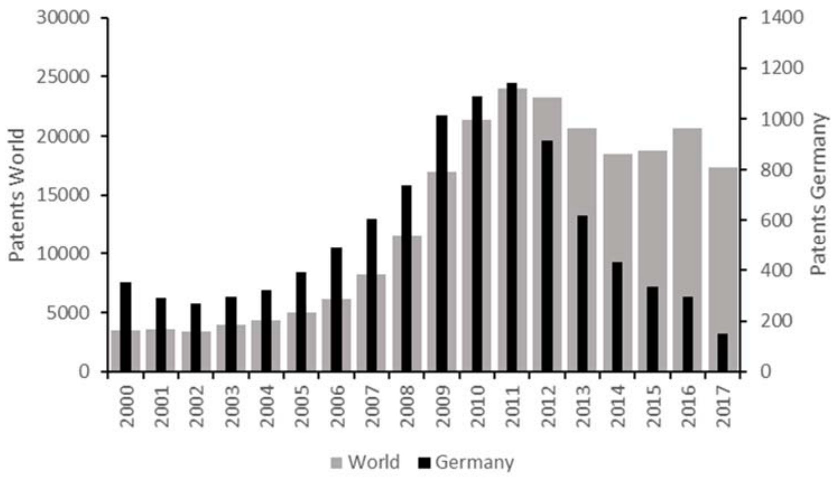

Figure 2: Patents for solar technologies worldwide and in Germany (IRENA, 2021).

Policy subsystem. 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). Concerning PV, social-democrats and greens highlighted positive economic, social and environmental side effects of the EEG, while conservatives and liberals voiced concerns regarding its social costs, while there was an overall consensus supporting PV (Hoppmann et al., 2014, p. 1429). The conflict between the environmental and economics ministry decreased **[+instE]** (Lauber and Jacobsson, 2016, p. 151).

Decreasing module prices created windfall profits for PV investors. Within parliamentary debates, solar energy was increasingly seen as costly, while wind energy still enjoyed strong approval (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 **[-RE]** (Hoppmann et al., 2014, pp. 1429–1430).

4.4 EEG - Phase IV (2010-2014) – Political struggles and solar industry collapse

Exogeneous conditions. In the elections of 2009, a coalition of conservatives and liberals was formed, which held office until 2013. In 2009, the financial crisis prevailed, and electricity demand lowered, putting pressure on utilities. The production of PV modules increased internationally (Quitzow, 2015). The nuclear incidents in Fukushima, Japan, in 2011 induced a phase-out of nuclear power in Germany until 2022.

Sectoral and TIS dynamics. Despite the financial crisis, the strong growth in PV installations continued from 2009 onwards. Dropping silicon prices and increasing production capacity worldwide contributed to lowering module prices (Quitzow, 2015), decreasing faster than the German FiT remuneration. The intense competition for the German PV module producers increased the pressure on the German PV TIS, German module producers lost market shares, and entrepreneurial activity decreased, along with knowledge creation and diffusion (Table A. 2). Investment from solar companies shrunk, and new entries in the market stagnate (Quitzow, 2015). After 2011, the industry was hit by massive shakeouts: while the business climate index of the German PV industry decreased **[-intE]**, the number of employees in the industry dropped from 140,000 in 2011 to about 40,000 in 2014 (Figure 3), and several module producers went bankrupt (O'Sullivan et al., 2018). Societal expectations toward PV turned negative **[-intE]** (Kriechbaum et al., 2017). Due to reduced remuneration, market development slowed down (Figure 1). The PV TIS specialized in production equipment necessary to produce PV modules (Dewald and Fromhold-Eisebith, 2015). The massive loss in competitiveness and jobs led to an erosion of TIS structures and the PV industry's political leverage; however, the German solar industry association (BSW) increased lobbying activities and was regarded as successful in limiting cutbacks for the PV TIS **[+SPF]** (Seibt, 2015, p. 197). Interestingly, within disputes over introducing duties for modules produced in China, the German PV industry appeared to be divided due to diverging interests undermining policy feedback (Meckling and Hughes, 2018).

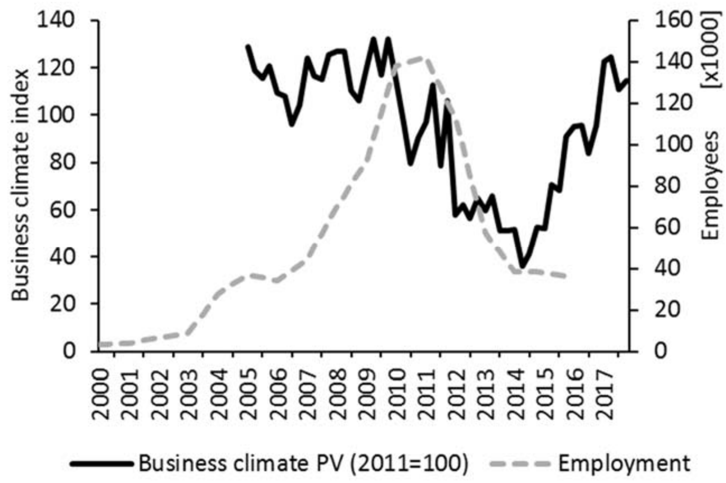

Figure 3: Business climate index of the PV industry in Germany (BSW-Solar, 2019) and employment in the PV industry (O'Sullivan et al., 2018).

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, utilities were not affected strongly by those external pressures (Kungl and Geels, 2018). They continued their defensive strategies concerning the EEG, but their activities regarding nuclear lifetime expansion and carbon capture and storage (CCS) 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 (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 against renewables changed from their allegedly general technological and economic infeasibility to the threats to the security of supply that renewables pose and the costs of the support scheme (Kungl, 2018, p. 356). Utilities seized the rising EEG surcharge as an argument against the EEG and its increasing burden on (vulnerable) households **[SPF]** (Kungl, 2018, pp. 360–361).

In the German industry, costs became a key topic politically **[SPF]** (Leiren and Reimer, 2018). The increasing EEG surcharge was seen as dangerous for the competitiveness of the German industry. 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 **[-AF]**, 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).

Policy subsystem. The new coalition of conservatives and liberals brought along a shift in the political discourse toward the costs and affordability of renewable energies (Lauber and Jacobsson, 2016, p. 152). In the run-ups to the EEG's 2009 amendments, PV had lost political capital, and the government's attitude towards PV worsened (Seibt, 2015, p. 181). While prices for PV modules plummeted, several EEG amendments were implemented during 2010 and 2011, meant to reduce deployment speed and control costs by aligning the EEG remuneration with falling module prices **[-RE]** (Hoppmann et al., 2014). German solar industry association's (BSW) communication strategy turned defensive: Before 2009, BSW emphasized positive aspects of PV; from 2010, it turned to highlighting adverse employment effects of policy change (Seibt, 2015, p. 168).

While arguments in favor of the renewable energy industry had gained ground also in conservative and liberal parties (Leipprand et al., 2017; Schmidt et al., 2019), also the opposing coalition grew stronger with utilities, influential industry stakeholders, and government aligning behind the increasing EEG surcharge to argue against increasing social costs of renewables **[-SPF]**. However, the ties of the PV industry to federal states where the German PV module production was located helped to mitigate stronger cutbacks in 2011 and 2012 **[+SPF]** (Lauber and Jacobsson, 2016; Quitzow, 2015; Strunz et al., 2016).

The EEG amendment of 2012 introduced a market premium instead of the former fixed feed-in tariff to bring renewables closer to the market and introduced targets corridors for PV installations between 2.5–

3.5 GW to limit expansion (Lauber and Jacobsson, 2016). Target corridors were enforced by reducing remuneration for electricity from solar PV if installations in previous months exceeded thresholds **[-RE]**.

In early 2013, when the EEG surcharge increased again **[-RE]** (Figure 4), a controversy broke loose within the government. Liberals and conservatives disagreed about the extent of measures to limit the rise of the EEG surcharge, while the social-democratic opposition internally disagreed on the necessity to protect the domestic industry's competitiveness due to the potentially rising grid and storage costs **[-intE]** (Lauber and Jacobsson, 2016, p. 153). Also the European Commission intervened, challenging the EEG 2012 based on its state-aid guidelines, particularly concerning extended industry exemptions in the EEG 2012 **[-AF]** (Leiren and Reimer, 2018, p. 37).

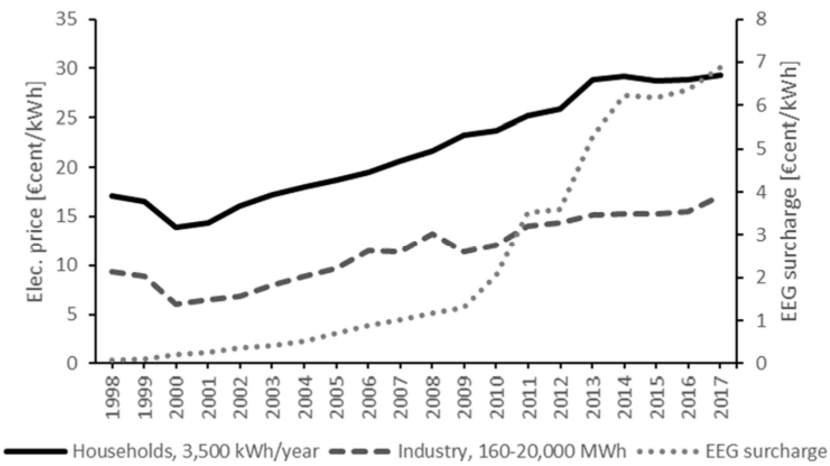

Figure 4: Development of electricity prices and the EEG surcharge (BDEW, 2021).

In the forerun of the elections of September 2013, the costs of renewables became a key topic (Leiren and Reimer, 2018, p. 37). All major German parties agreed that reforms were necessary (Messing, 2020, p. 172). Conservative parties won the majority and settled for introducing renewable energy auctions in their coalition agreement with social democrats. (Messing, 2020, p. 174). Social-democrat leader Sigmar Gabriel became Minister of economic affairs, and all responsibilities for the EEG were transferred to his ministry. The new government introduced a pilot phase for renewable auctions with the target to introduce auctions for wind power and PV by 2017 **[-RE]**. Additionally, the EEG amendment 2014 implemented target corridors for all technologies. The decisions were well-aligned with the European Commission **[instE]** (Leiren and Reimer, 2018; Strunz et al., 2016).

4.5 EEG - Phase V (2014–2017)

Exogeneous conditions. After the elections in September 2013, a coalition of conservatives and social democrats was formed. The European Commission amended its state-aid guidelines in 2014 that increasingly emphasize competitive and market instruments **[instE]** (Strunz et al., 2016).

Sectoral and TIS dynamics. The reduction of remuneration in 2012 led to a slowdown in PV market uptake **[-RE]**. Since 2012, the feed-in remuneration for solar electricity has been lower than the household electricity price[5], wherefore the business model for household PV changed (Dehler et al., 2017). The price level for ground-mounted PV decreased further within the newly introduced auctions. After the rapid drop in the business climate, companies became more optimistic about their future, and employment in the solar industry stabilized (Figure 3).

Decreasing wholesale prices, increased shares of renewables, and reduced electricity demand compromised the profitability of conventional power plants (Kungl, 2018, p. 336). Additionally, from 2015 onwards, utilities faced an increasing debate on the future of German coal power plants (Leipprand and Flachsland, 2018). Between 2013 and 2015, the four large utilities made significant value adjustments in their business reports (Kungl, 2018, pp. 338–340) and reacted with efficiency measures and disinvestment (2010 – 2014). In mid-2013, EnBW announced restructuring its business towards renewables (Kungl, 2018, pp. 388–390). In 2014 and 2015, E.on and RWE announced restructuring measures and split up conventional power generation, renewables, and services (Kungl, 2018, pp. 383–388), while Vattenfall sold its lignite plants in 2016 (Kungl, 2018, p. 392). The introduction of auctions, particularly for offshore wind energy, was advantageous for large companies (Leiren and Reimer, 2018, p. 37; Stefes, 2020), and utilities expanded their activities in renewable energies.

For the energy-intensive industry in Germany, the EEG 2012 expanded exemptions of the EEG surcharge. While these exemptions became a part of the dispute between the European Commission and

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

the national government, they stayed untouched in the EEG 2014, and surcharge exemptions prevailed (Leiren and Reimer, 2018). what even seems to undermine the willingness to pay of households for the EEG surcharge (Andor et al., 2018).

Policy subsystem. After the amendments of the EEG in 2014 pointed the way toward renewable energy auctions, political attention turned to the configuration of the final auctioning scheme to be introduced in 2017 (Messing, 2020, p. 174). The increase of the EEG surcharge came to a halt, decreasing immediate pressure on policymakers (Figure 4). 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 that cannot diversify investment risks with a higher number of bids **[-SPF]** (Messing, 2020, p. 145). Additionally, missing electricity grid capacities were addressed in the debates (Messing, 2020, p. 174). While the BMWi implemented platforms to discuss details of the reforms with various stakeholders, 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). The concentration of responsibilities within the BMWi was further seen as limiting the possibilities to intervene, as controversies on the EEG were now internal to the responsible ministry (Messing, 2020, 187f). The EEG 2017 finally introduced auctions for wind power, biomass, and PV.

Table 3: Summary of the main developments of the EEG divided by five phases.

EEG	I (1999-2000)	II (2000-2004)	III (2004-2010)	IV (2010-2014)	V (2014-2017)
Socio-political Feedback [SPF]	- strong political networks of wind power industry, "prototype" of renewable energy industry [+SPF] - Support coalition for EEG of environmental groups, industry unions, labor unions [+SPF] - Liberalization keeps utilities busy and opens up opportunities [no - SPF] - BDI opposes EEG due to expected costs [-SPF], but VDMA supports proposal [+SPF]	- Growth of solar TIS, creation of jobs [+SPF] - Growing PV market with a high number of diverse investors [+SPF] - Utilities press for market integration of renewables [-SPF] - Industry associations lobby for surcharge exemptions [SPF]	- Growing employment in the solar industry [+SPF] - Increasingly professional solar industry associations [+SPF] - A high number of beneficiaries of the EEG [+SPF] - 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] - Ties of PV industry to federal states mitigate stronger cutbacks [+SPF] - Utilities seize rising surcharge as argument [-SPF] - Pressure of utilities on BMWi in favor of auctions [SPF] - BDI active opponent of EEG surcharge [-SPF]	- Auctioning scheme criticized for adverse effects on smaller investors - 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] - Responsibilities for energy policy bundled at BMWi in 2013	- Slow grid expansion and conflicts with Bavaria
Resource Effects [RE]	- 100,000 roofs programme implemented for PV [+RE] - EEG implemented [+RE]	- EEG remuneration differentiated by technology [+RE] - 100,000 roofs program expired [-RE]	- Cap on solar power installations removed [+RE] - Increased remuneration for solar power [+RE]	- Various adjustments of the solar remuneration [-RE]	- Target corridor for all technologies [-RE]
Interpretive Effects [intE]	-	- Fixed EEG remuneration and long-term perspective increase investment security [+intE] - 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] - No protection of national solar industry [-intE]	-

Institutional effects [instE]	- EEG and 100,000 roofs programme well-aligned [+instE] - EU DG energy and competition oppose bill [-instE]	- BMWi advisory board proposes to terminate EEG due to potential conflicts with EU ETS [-instE] - 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' - Increasing misalignment with grid infrastructure - European Commission inquiry based on state-aid guidelines [-AF/-instE]	- Amendment of state-aid guidelines, emphasis of market instruments - 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 - The world market for PV already growing, expand production in Germany	- German solar TIS grows, new entrants	- Strong market development, installed capacity grows fast - Module prices decrease due to technological learning - High R&D expenditure	- German PV module producers lose market shares, entrepreneurial activity decreases - After 2011, several German manufacturers file bankruptcy - Employment decreases, expectations turn negative - Slowdown of market development from 2012	- Solar TIS stabilizes: employment and business climate
Sectoral change	- Liberalization promises profits for conventional plants - Renewables share 2000: 6.3% of electricity consumption	- Liberalization promises profits for conventional plants - Renewables share 2004: 9.4% of electricity consumption	- High profits of utilities due to ETS and alleged market power - Expansion of conventional power plant fleet - Utilities lose legitimacy - Utilities diversify and invest in renewables, but only outside of the home market - Renewables share 2010: 17% of electricity consumption	- Economic crisis, reduced electricity demand, increased competition from renewables - Nuclear phase-out increases pressure - Wind offshore as business opportunity - Value adjustments of utilities - Renewables share 2014: 27.4% of electricity consumption	- Utilities restructure and spit up or sell conventional power assets and renewables - Offshore auctions offer investment options for large-scale investments - Renewables share 2017: 36% of electricity consumption
Exogeneous Conditions [ExC]	- EnWG enacted in 1998 - Agreement on nuclear phase-out in 2000	- Nuclear phase-out becomes law	- The first trading period of EU ETS starts 2005 - Changes of the EnWG and introduction of a regulatory authority for electricity markets (Bundesnetzagentur) - Shortage of silicon on the world market - Financial crisis in 2008	- Financial crisis - Increasing worldwide production of PV modules; dropping silicon prices - Nuclear incidents in2011 in Fukushima, Japan, and German nuclear phase-out until 2022	-
Policy change (focus on solar)	- 100,000 roofs program EEG enacted 2000: - Technology-specific remuneration of renewable electricity for 20 years	2004: - "Solarstrom-Vorschaltgesetz" initiated by the parliamentary factions of social-democrats and greens	2009: - Dynamic degression of remuneration depending on annual installed capacity - Support of self-consumption	2010: - One-time degression of remuneration in July and October - Increased regular annual degression of solar remuneration 2011:	2017: - Introduction of auctions for all technologies - "Netzausbaugebiete" should limit wind expansion with high curtailment from 2017

	- Cap for installed PV capacity - Fixed annual degression - Remuneration is added to electricity bills via the EEG surcharge	- Cap on PV capacity removed, remuneration increased		- Adjustments of degression rates due to high solar deployment 2012: - Introduction of (voluntary) market premium - Increase of industry exemptions - Monthly degression of solar remuneration if target corridors exceeded - Cap for funding of a maximum of 52MW installed solar capacity 2014: - Pilot phase for auctions for ground-mounted solar - Obligatory market premium for all technologies - Monthly degression for all technologies	
Policy subsystem change	- Social-democrats and greens form a coalition (1998) - BMWi responsible (minister Müller) but reluctant to propose the bill - Members of parliament propose bill	- Social-democrats and greens reelected (2002), shift weights towards greens - Responsibility for EEG passed to BMU - Conflicts between BMU and BMWi	- Conservatives and social-democrats form coalition 2005 (Chancellor Merkel) - Solar power is increasingly seen as costly in parliamentary debates	- Conservatives and liberals form coalition 2009 (Chancellor Merkel) - Conservatives and social-democrats form coalition 2013 (Chancellor Merkel) - Responsibility for EEG passed from BMU to BMWi after elections in 2013 - Influential actors/ministers: Rösler (economic affairs, 2011-2013), Röttgen (environment, 2009-2012), Altmaier (environment, 2012-2013), Gabriel (economic affairs, 2013-2017) - Secretaries of state: Baake	-

5 Towards a life cycle model of technology deployment policies

The previous section has 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 the pattern. 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). A natural question to ask, therefore, is whether and to what extent the observed patterns might also be found in other cases of deployment policies. This section seeks to address this question.

As a starting point, we identified the main policy effects and feedback throughout the five phases (Table 4, Figure 5). We shall refer to these as the phases of a *technology deployment (TPD) policy life cycle*. Such 'ideal-typical' (Penna and Geels, 2012) characterizations of temporal patterns have been proposed in various fields, for example, to describe the dynamics of long-term change processes of issue attention (Downs, 1972; Peters and Hogwood, 1985), of industries (e.g., Klepper, 1997), of industry responses to issues (Geels and Penna, 2015; Penna and Geels, 2012, 2015) or technological innovation systems (Markard, 2020). All such models have in common that, while proposing a specific sequence of events or phases, they do not strictly assume that the life cycle pattern is the only possible outcome. It should be understood as a point of departure to explain deviations from empirical findings, where empirical examples might pass the phases in different orders or get stuck in a particular stage.

The following sections discuss the five phases of the proposed cycle and seek to provide evidence from literature and other cases that help to support the case of a more general life cycle pattern and refine some of the observations made.

Table 4: A technology deployment policy life cycle model.

Phase	Characterization	TIS stage	Effects	Feedback mechanisms
I	*Pre-enactment & Enactment*	Formative, early growth with emerging political networks	• Policy not yet enacted	• Initial +SPF from the TIS • Underestimation of incumbents • Issue attention to certain societal problems
II	*Post-enactment and interaction with existing policy and institutions*	Formative or early growth	• InstE due to embedding of focal policy into existing institutional arrangements • RE due to the focal policy • intE: uncertainty whether the policy will be maintained	• AdF • FF less likely; low costs • -SPF from incumbents, closed industry fronts against technology • +SPF increasing political ties of TIS
III	*Technology and policy enthusiasm, and realization of costs*	Growth	• +RE due to the focal policy • intE: policymakers appear committed to technology and policy • instE: policies well-aligned	• +SPF: industry associations and TIS actors increase political ties • Increased positive externalities: job creation, technology leadership • -FF/-SPF: policy costs increase
IV	*Political struggles and increased uncertainty*	Growth, maturity or decline	• intE: increasing uncertainty whether the policy will be maintained or changed • Reduced RE	• Stage of the TIS determines continued or decreasing +SPF • -FF/-SPF: High policy costs • -SPF: incumbents seize policy costs as an argument; shape policy to meet their demands • -AdF is possible due to technology side effects
V	*Political consolidation, loss of interest, reorientation*	Growth, maturity or decline	• intE uncertainties resolved • RE depending on the previous phase • instE: adaption of institutional arrangements towards technology	• Low attention to policy, feedback declined • Sensitive to events that rekindle attention

5.1 Phase I: Pre-enactment & enactment

The case of the EEG has shown that the solar TIS in Germany was already active in all dimensions. Notably, actors actively lobbied for the introduction of 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 can 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 of 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.

5.2 Phase II: Post-enactment and interaction with existing policy and institutions

After enactment, the EEG created a market for solar applications, and the solar TIS started to grow faster. New actors entered the TIS, strengthening its political weight. However, the EEG was contested by the European Commission due to alleged misalignment with state-aid rules and within government. 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). Such struggles may contribute to the uncertainty of actors 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.

5.3 Phase III: Technology and policy enthusiasm, realization of costs

In this phase, the German EEG emitted strong effects on all levels: Market support drove the adoption of PV panels, political conflict decreased, and policies appeared to be committed to achieving goals. On the other hand, the solar TIS grew fast with highly active TIS functions, and the political leverage of the TIS due to economic spillovers such as job creation increased, leading to positive feedback. TIS development and focal policy develop a virtuous cycle of mutual reinforcement. 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 got 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[6].

Ironically, the virtuous cycle inducing TIS expansion nourishes the roots of subsequent vicious cycles (Figure 5). Within the policy process of the EEG, policy costs redistributed by the surcharge became more prominent, and utilities mobilized against the EEG. Ample 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 the electricity sector, the economic crisis in 2008 was a critical exogenous driver of increasing opposition (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 (negative 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 (negative resource effects), fiscal feedback may arise from financial ministries or treasury (e.g., Edmondson et al., 2020).

Apart from policy costs and competition, other sources of increasing negative feedback with increasing deployment can also be observed. For example, biogas and biofuels production brought along increasing concerns about the competition for food (Markard et al., 2016b; Pilgrim and Harvey, 2010; Suurs and

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

Hekkert, 2009), and wind power in Germany was challenged increasingly by acceptance issues (Dehler-Holland et al., 2022).

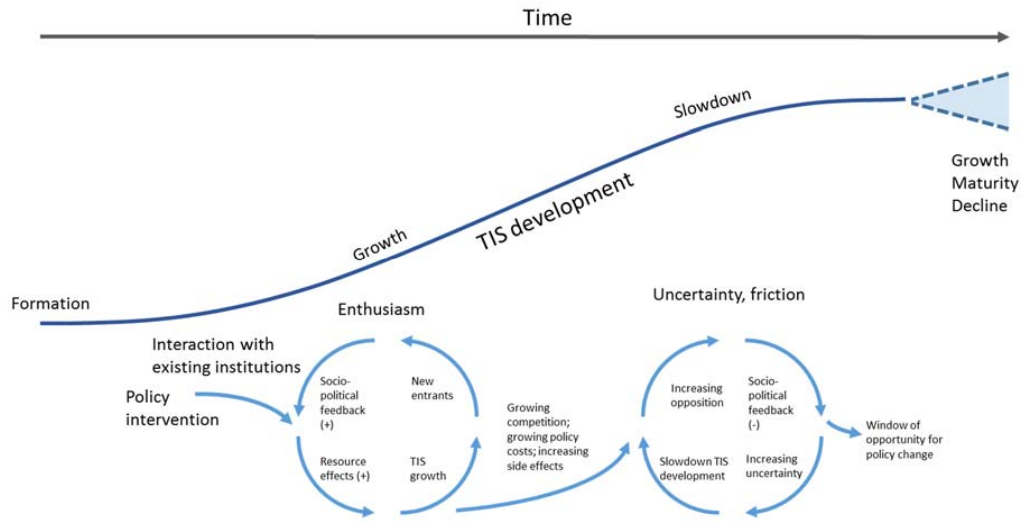

Figure 5: Illustration of the technology deployment policy life cycle model.

5.4 Phase IV: Political struggles and increased uncertainty

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 was struggling with intense international competition and dropping module prices, while solar investors could reap windfall profits in light of the high remuneration. In rapid succession, the government lowered the remuneration, ultimately achieving a slowdown of market expansion and introducing renewable tenders for PV in 2014, which has been considered to accommodate utilities' calls for market integration and favor larger projects (Leiren and Reimer, 2018). The political capital of the solar TIS helped to mitigate stronger cutbacks.

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; 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 side effects of technology may become apparent. In the case of solar energy in Germany, grid integration and security of supply entered the stage. Other examples comprise 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 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 (Figure 1), 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 was able to 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).

5.5 Phase V: Political consolidation, loss of interest, reorientation

Within the fifth 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 leaving little space for debate. 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 developments of this phase depend on the policy outputs of the previous phase. For example, after policy dismantling in Spain, the Czech Republic, and Italy, markets for renewable energy collapsed (Gürtler et al., 2019; Prontera, 2021).

6 Discussion

The previous sections analyzed the co-evolution of the German EEG and the photovoltaics TIS and attempted to generalize an ideal-typical life cycle of technology deployment policies. The results have consequences for successful policy design, which shall be discussed. Furthermore, model boundaries, methodological limitations, and possible avenues for future research are pointed out.

The literature on policy sequencing has forcefully brought forward the point that transition policy, in order to be successful in the long term, needs to continuously build up supporting coalitions that may be backed by sequentially increasing policy goals and stringency (Meckling et al., 2017; Pahle et al., 2018). This study substantiated these calls by describing how feedback from TIS, supported by deployment policies, can develop into a forceful voice in policy discourse. However, it also showed how negative feedback increases with growing policy costs and sectoral competition. From a policy design perspective, this brings to the fore four critical considerations: (1) the importance of the creation of a successful national TIS for policy feedback; (2) the distribution of benefits and losses affects policy feedback; (3) the fast technological developments call for increased policy robustness; (4) from a transitions perspective, the alignment of the focal policy within the broader policy mix. The following will discuss each of those prospects.

The literature on national innovation systems proposes that institutional settings influence technology development. National networks, education, scientific institutions, and cultural traditions may affect the potential for innovation (Freeman, 1995). Therefore, it was argued that when deployment policies are enacted, technology characteristics and national capabilities should be carefully analyzed to derive realistic expectations of to which extent a deployment policy can spur the creation of a successful TIS (Schmidt and Huenteler, 2016). Here, it is important to note that Schmidt and Huenteler (2016) do not assume that the complete value chain for technology production can be expected to establish in any jurisdiction. Instead, the national innovation system's institutions and technology's design and manufacturing complexity determine the expectations of which parts of the value chain may be established successfully. These expectations then may inform policymakers towards a policy design and instrument combination focused on the respective parts of the value chain, and successful TIS development can contribute to policy maintenance or succession. However, these considerations also raise the question of how the proposed life cycles unfold in countries with less favorable institutional structures. One may conjecture that in such cases, the potential to create supporting policy feedback is lower, potentially rendering deployment policies more vulnerable to opposition. Further comparative research could shed light on the relationships of national institutional settings and the development of policy feedback over time.

Furthermore, the way resources are distributed influences the feedback a policy receives. In the case of the EEG (and many other feed-in schemes), costs are redistributed to the public as a surcharge on the electricity bill. Alternatively, costs might be covered by the state's budget. A surcharge is more visible to the public and may be exploited in public discourse, triggering socio-political feedback. Leaving budget responsibilities to financial ministries may, on the other hand, increase friction within governments and budget committees (fiscal feedback) and leave the program at risk of dismantling when political tides shift towards economic austerity, for example, during times of crisis (e.g., Edmondson et al., 2020; O'Neill and Gibbs, 2020). The mode of reimbursement of deployment policy expenditures influences feedback structures over time and exposes the focal policy to different risks.

Additionally, the results show that rapid technological progress, be it in the national industry or internationally, triggered a series of rapid policy adjustments to limit costs and windfall profits for investors. However, rapid and unplanned policy adjustments may adversely affect the focal TIS, increasing uncertainties over the field's future prospects. The literature has discussed the ability of policies to adapt to changes by design under the labels 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). Also a switch from price-based to quantity-based support mechanisms when technologies have developed sufficiently may be advised (Kitzing et al., 2020), which could be envisaged already in the original policy design for the case when regulatory monitoring concludes towards sufficient technology maturity.

Certainly, a deployment policy may be considered part of a more comprehensive instrument or policy mix toward sustainable transition. (Kern et al., 2019; Rogge and Reichardt, 2016). This perspective has prominently brought forward the idea that the support of niches should be complemented by 'elements of creative destruction' that destabilize the existing regime (Kivimaa and Kern, 2016). While the study at hand was primarily constrained to a single instrument supporting the establishment of a niche, it is informative on when such additional regime destabilization is needed most. One may hold that the early phases of the TDP life cycle are not critical to the additional establishment of destructive policy instruments, as TIS growth can provide positive feedback to the transition. However, over time, contestation increases, and policies become more exposed to critical feedback. Therefore, in the cycle's later stages, the introduction of regime destabilization instruments becomes more critical. As a matter of fact, the case at hand shows that the German coal phase-out debate started in 2015 (Leipprand and Flachsland, 2018), and in 2020, a coal phase-out until 2038 passed parliament. Together with the observation that implemented policy instruments vary along the technology's experience curve (Breetz et al., 2018) and the functions active in the different phases of the TIS life cycle, the policy mix perspective provides an exciting route for future research to extend the proposed model towards a conceptualization of policy mix succession. The initial phase has shown that often, technology-push instruments are already in place when the focus shifts towards increasing technology deployment. Later phases link to the subsequent introduction of regime destabilization measures. However, it should be made clear that such an extended model would not presuppose that the different measures are exclusive to each stage and tend to coexist, having synergistic effects.

An important question to be discussed is the circumstances under which the proposed patterns may be expected. First, technology characteristics and their relationship to incumbent regimes may be contributing to the likelihood of the emergence of the life cycle patterns. The case study relied on a technology that has characteristics of a mass-produced product (Huenteler et al., 2016). As such, economies of scale and widespread deployment influence its development intensely. Compared to more complex technologies such as wind power, we presume that policies supporting the adoption of mass-produced products might be particularly prone to the feedback patterns observed in this paper. The evidence from the literature seems to support that claim, where wind power rarely became the focus of negative feedback due to costs[7]. LED lighting is an interesting example of deployment policies leading to a fast transition from one technology to another. Incumbents even seemed to have supported the phase-out of incandescent light bulbs; however, they could influence new regulations and standards heavily and quickly adapt their production facilities to the new technology (Markard, 2020; Smink et al., 2015). This example may indicate that policies for competence-enhancing innovations (Tushman and Anderson, 1986) might follow different development routes. Given that the dichotomy of competence-enhancing and destroying innovation is weakening (Bergek et al., 2013), exploring deployment policies for different innovation characteristics and related development pathways may be fruitful for future research.

The case study and literature discussion have shown that context events influence policy feedback dynamics. Particularly the financial crisis in 2008 increased economic pressures on policymakers and sectoral actors, reinforcing undermining policy feedback. Also the fast developments in the global PV TIS affected the need for political responses. However, the case of wind power and the StrEG (Table A. 1) and evidence from other cases provide evidence for similar patterns in the absence of such events. For these reasons, the model did not attempt to propose TIS development stages for the later phases of the TDP life cycle (see Table 4).

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

[7] However, the examples of Spain, the Czech Republic and Italy show that wind power was also strongly affected by retrenchments (Gürtler et al., 2019; Prontera, 2021).

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 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. 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 already have advanced furthest.

7 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. A case study of the German renewable energy act and the PV TIS brought to light a temporal pattern whose characteristics were compared to other cases in the literature and led to the proposal of an ideal-typical *technology deployment policy life cycle model*.

To fully appreciate the contributions of this paper to the understanding of the co-evolution of policies and technologies, it might be worthwhile to take a step back and consider what delineates models from more generic frameworks. Frameworks are used to identify core elements and their relationships that scientific inquiry of a particular topic should consider; they provide a common language to assess phenomena of interest (Ostrom, 2007, p. 25). On the other hand, models are more specific in making more precise assumptions on variables to test and explore the outcome in more tangible cases (Ostrom, 2007; Schlager, 2007). While much of the work to understand the policy processes of sustainability transitions have provided analytical frameworks (e.g., Edmondson et al., 2019; Markard et al., 2016a), we proposed a model for a specific set of policies (technology deployment), taking into account technological and TIS development.

Therefore, the proposed model takes 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. 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 support the likelihood of policy maintenance or succession.

We think the technology deployment policy life cycle model will be useful to scholars and policymakers. It provides an essential 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.

8 APPENDIX

Table A. 1: Summary of the main developments of the StrEG (1990-2000) and wind power in Germany, divided by 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] - Renewable associations propose feed-in law [+SPF]	-	- Increased political leverage of wind power associations [+SPF] - 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] - 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 potential for [FF]	-	-	- BMWi proposes to lower remuneration due to increasing costs [-FF] -	-
Administrative Feedback [AF]	-	-	-	-	-
Resource Effects [RE]	1989: - Introduction of support programs (1,000 roofs program, 100MW program) - 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 - Support reduced in some regions [-RE]	- Introduction of 100,000 roofs program in 1999
Inerpretive Effects [intE]	-	- Feed-in law reduces risk and uncertainty for investors	-	- Political struggles increase uncertainty for investors [-intE]	- Uncertainties for investors 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, StrEG becomes 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 - German reunification challenges the energy sector and integration of east German power plants necessary	-	-	-	- Introduction of EnWG - 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 (Figure A. 1).	- Market expansion increases
Sectoral change	- Eastern and Western German electricity systems are merged - 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 - The "Big Four" utilities emerge - Renewables share 1999: 5.2% of electricity consumption

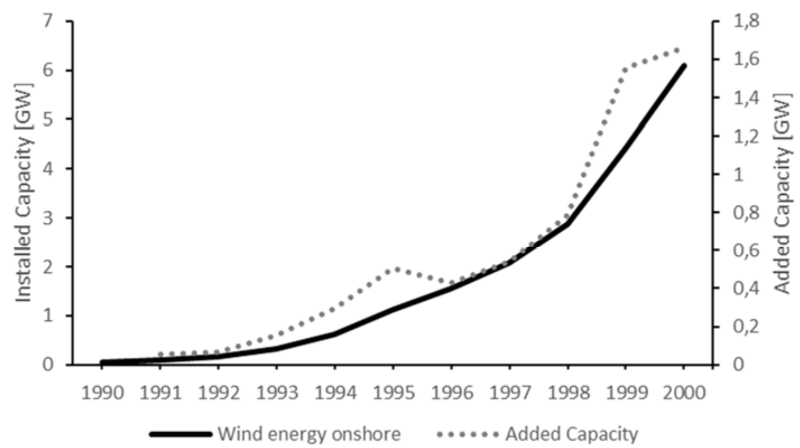

Figure A. 1: Installed wind energy capacity and yearly added capacity in Germany (1990-2000) (AG Energiebilanzen e. V., 2019).

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

Function	Phase I (1999-2000)	Phase II (2000-2004)	Phase III (2004-2010)	Phase IV (2010-2014)	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) - 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) - Incumbents leave market, medium-sized companies dominate (Dewald and Fromhold-Eisebith, 2015) - Slow increase in employment - Firm entries and capacity extension could not keep pace with demand development (Quitzow, 2015, p. 132) - Capacity expansion not as large as in Japan and US (Quitzow, 2013)	- Increased level of new entries, low exits in cell and module manufacturing (Hipp, 2021, p. 573) - Ineffective in reducing costs; Capacity expansion only when silicon shortage over (Quitzow, 2015, p. 134) - Strong increase of employment - First signs of decline in 2009, lower investments, financial crisis (Quitzow, 2015, p. 139)	- Exits exceed entries, almost no new entries in cell and module manufacturing (Hipp, 2021, p. 573) - Collapse of employment - Decline and insolvency of producers (Dewald and Fromhold-Eisebith, 2015) - Still strong in production equipment (Dewald and Fromhold-Eisebith, 2015)	- Exits exceed entries, almost no new entries in cell and module manufacturing (Hipp, 2021, p. 573) - Stabilization of employment
Knowledge development	- Dominant design already emerged in early 1990s, increase in patents (Huenteler 2016) - Strong knowledge base in German universities (Jacobsson et al., 2004, p. 21)	- Patents slightly decrease (Figure)	- Patents increase fast (Figure) - Increased private and public expenditure (Quitzow, 2015, p. 134)	- Patents drop after 2011 (Figure)	- Patents still drop (Figure)
Knowledge diffusion through networks	- R&D collaboration increases (Hipp, 2021, p. 575) - Collaboration of industry and universities (Jacobsson et al., 2004, p. 21)	- R&D collaboration higher level (Hipp, 2021, p. 575) - Intense collaborations between industry and research (Dewald and Fromhold-Eisebith, 2015)	- R&D collaboration increases steadily (Hipp, 2021, p. 575) - 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)	- FiT, however, caps for maximum solar capacity - 100,000 roofs program	- High business climate index, starting to drop	- Dropping business climate index	- Stabilization of business climate

	- 100,000 roofs program guides search towards rooftop systems - Wind power as example for success		- High silicon prices encourage development of thin-film technologies (Quitzow, 2015) - Increasing uncertainty due to industry and market developments and policy goals (Quitzow, 2015, p. 143) - Guidance toward production equipment	- Dropping societal expectations (Kriechbaum et al., 2017) - Guidance toward production equipment	
Market formation	- 100,000 roofs program - Local feed-in laws (Jacobsson et al., 2004, p. 19)	- Increased adoption - FiT remuneration - New market segments: rooftop, roof-integration (Jacobsson et al., 2004, p. 19) - Industry very vulnerable to market decline (Jacobsson et al., 2004, p. 21)	- Increased adoption - FiT remuneration even higher - Entry of ground-mounted system market segment (Dewald and Truffer, 2011, pp. 296–297) - High business climate index, but dropping by the end of the phase	- Extreme increased adoption and slowdown - FiT remuneration high, and cutbacks - Dropping business climate index	- Linear path of adoption - FiT remuneration adapted to growth - Stabilization of business climate
Resource mobilization	"Collective forms of project financing (citizen solar plants – Bürgersolaranlagen)" (Dewald and Fromhold-Eisebith, 2015) 100,000 roofs program 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) 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) Half of installations profited from low-interest loans (KfW), Commerzbank, local banks, state-owned banks (Quitzow, 2015, p. 133) Public investment subsidies available, but not used excessively, moderate growth of supply side investment (Quitzow, 2015, pp. 134–135) - 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 no of employees 2004 compared to later - Strengthened industry associations by new entrants (Jacobsson et al., 2004, p. 21) - Industry and jobs strong argument for amendment in 2003 (Quitzow, 2015, p. 133)	- Seibt 143: Increase of employees of BSW, 151: Increase empl. for lobbying and PR; 157: increased press releases; fusion of UVS and BSi in 2006 (Seibt, 2015) - Support of eastern states governments prevents stronger cutbacks (Quitzow, 2013, p. 20) - 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 succesful, can use high public acceptance, despite critique (Seibt, 2015) - Fragmented value-chain undermines common position of solar industry (Meckling and Hughes, 2018)	-

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Paper C

Assessing technology legitimacy with topic models and sentiment analysis – The case of wind power in Germany

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Assessing technology legitimacy with topic models and sentiment analysis – The case of wind power in Germany

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ABSTRACT

Legitimacy is a crucial factor determining the success of technologies in the early stages of development and for maintaining resource flows as well as public and political support across the technology life cycle. In sustainability transitions that unfold over long periods of time, the maintenance of legitimacy of technologies identified as vital for sustainability becomes a key challenge. In the energy sector, wind power contributes to the transition to an energy system with low greenhouse gas emissions. In Germany, wind power recently faced a series of lawsuits and decreasing investment activity. Therefore, we assess the legitimacy of wind power in Germany by analyzing newspaper articles from four national newspapers from 2009 to 2018. A large amount of articles motivates the use of topic models, sentiment analysis, and statistics to shed light on the changing alignment of wind power with its context. The results show that various issues temporarily gain prominence on the agenda. Lately, the legitimacy of wind power in Germany has been increasingly challenged by adverse effects on humans, animals, and landscapes. Policymakers and project developers may address aspects of pragmatic legitimacy, such as civic participation and the local distribution of profits.

1. Introduction

1.1. Motivation and contributions

Climate change and the need to reduce greenhouse gasses call for rapid transformations of national systems of energy generation and usage. Often termed sustainability transitions, research acknowledged that transitions unfold over long periods and are subject to intense societal and political conflicts (Meadowcroft, 2009). Within sustainability transitions, technology deployment and technological change play a key role (Markard et al., 2012).

A key factor linked to technology's success within society is legitimacy (Bergek et al., 2008b; Markard et al., 2016). Whether a focal technology is perceived as aligned with societal values and beliefs is vital to maintain resource flows, political support, and deployment (Hekkert et al., 2007). An essential aspect of legitimacy is its processual character: over time, the legitimacy of technology may change (Markard et al., 2016). Such temporal dynamics become particularly relevant in long-term transitions when the legitimacy of technologies commonly identified as crucial for a more sustainable future must be continuously reproduced.

A technology that is pivotal for reducing greenhouse gas emissions in the energy sector is wind power. While its first deployment for electricity generation dates back several decades, large-scale deployment only took off in the 1990s, with Germany being one of the lead markets (Bergek and Jacobsson, 2003). While potential conflicts with societal norms and values have been pointed out early on by acceptance research (Rand and Hoen, 2017), renewable energies were awarded an "exceptionally high degree of legitimacy […] in German society" (Jacobsson and Lauber, 2006, p. 272). Recently, wind power projects in Germany have been hampered by a series of lawsuits (Fachagentur Wind an Land, 2019) while investment activity slowed down. Therefore, this article's first contribution is a detailed account of the legitimacy of wind power in Germany and its development over the last decade.

To pursue this research question, we investigate a large set of newspaper articles from four national German newspapers from 2009 until 2018. As the number of articles available is high, we make a second contribution to the research on technology legitimacy and the relations of technology and society in general. We propose employing methods from the toolboxes of natural language processing to explore the context structures and institutional (mis-)alignment of the focal technology. With the proposed approach, we can assess technology legitimacy's key

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elements: the technology's context and sentiment and salience of the various topics or issues that contribute to cognitive, normative, regulatory, and pragmatic legitimacy. The methodology is designed to account for temporal dynamics and change in newspaper coverage; therefore, it adds to the method sets of socio-technical transitions, where long time horizons and discursive changes are of particular concern.

The results draw a rich picture of the political struggles emerging in the face of a gradual delegitimation of a technology pivotal for energy transitions. While wind power in Germany today still must be considered a legitimate source of electricity generation, alleged health, environmental, and landscape conflicts have become an important topic in the discourse. Together with missing options to participate in the benefits of wind power, such issues became a barrier in the deployment of wind power, causing the need for policy adjustments. Conceptually, this process of delegitimation, which starts on a local level and diffuses to the broader public, resembles the process of legitimation (Johnson et al., 2006).

The remainder of the paper is structured as follows: Section 1.2 gives an overview of the case of wind power in Germany. Section 2 introduces the technology legitimacy framework, discusses the role of media, and provides a literature review of existing media studies on wind power. Section 3 discusses the available data and describes the usage of Structural Topic Modeling (STM, Roberts et al., 2016a) to assess large text corpora and statistical methods to assess STM output. Section 4 discusses the results of our analysis by first delineating the context structures of wind power and topics relevant to legitimacy. Section 5 concludes the paper.

1.2. Wind power in Germany

The support of wind power development in Germany dates back to the oil crisis in the 1970s when the R&D expenditure for renewable energy sources was raised to about DM 20 million and increased throughout the following decade (Jacobsson and Lauber, 2006). However, market expansion was still limited – until 1989, 20 MW of wind power capacities were installed (Jacobsson and Lauber, 2006). At the end of the 1980s, the first deployment policies were enacted that guaranteed payments for wind power produced and fed to the common grid from demonstration projects (Jacobsson and Lauber, 2006). Finally, in 1991, the first feed-in law ensured grid connection and viable payments for electricity from wind turbines. When in 2000 the renewable energy act (*Erneuerbare-Energien-Gesetz, EEG*) was introduced, about 6.1 GW of wind power was installed (AG Energiebilanzen e. V., 2019). The feed-in law was flanked by several industry policies on the federal and state level. Additionally, the states' explicit land allocation for wind turbines supported the development of a large national wind power industry (Bergek and Jacobsson, 2003). The EEG enacted in 2000 introduced fixed feed-in tariffs for electricity from renewable sources (Hake et al., 2015). In the following decade, installed wind capacities rose to 25.7 GW in 2009 (AG Energiebilanzen e. V., 2019), and capacities continued to grow afterward. In 2011, after the nuclear accidents in Fukushima, Japan, the German government decided to phase out nuclear power, an event that is often associated with the term "Energiewende" (energy transition) and a regime shift towards renewable sources (Strunz, 2014). However, concerns over the costs of renewable energies increased, and measures to limit uncontrolled renewable capacity expansion were introduced (Lauber and Jacobsson, 2015). In the EEG amendment in 2017, tenders for wind power capacities were introduced (Leiren and Reimer, 2018). In general, the EEG is inclined to favor large-scale wind turbines and wind parks due to economies of scale and the remuneration per kilowatt-hour produced (Nordensvärd and Urban, 2015), a trend that might be even reinforced by the introduction of renewable energy tenders that fosters competition and further price declines in the wind power market. By the end of 2018, 6.4 GW offshore and 52.6 GW onshore wind power capacities were installed (AG Energiebilanzen e. V., 2019), but participation in onshore wind auctions decreased, and new installations of wind turbines decreased below political targets. A trend that prevails until today (2020). These developments may be linked to issues of local acceptance and legal conflicts (Fuchs, 2020). Already in 2017, critical voices claimed that the German energy transition had lost its momentum (Kemfert, 2017).

2. Theoretical background and literature review

This section summarizes the technology legitimacy framework employed to understand the usage of wind power in Germany and its context relations. Furthermore, we motivate why media accounts are an essential source of legitimacy worth close investigation. We close with a review of what is known from previous research on wind power in media studies.

Markard et al. (2016) framework of technology legitimacy rests upon a systemic view of technology production and deployment. It draws on Technological innovation systems (TIS), whose core constituents are actors such as producers, users, vendors of a focal technology, networks in which actors connect by knowledge exchange or coalitions, and institutions such as regulations, social values, and norms (Markard, 2020). For example, wind power's TIS consists of several turbine manufacturers, project developers, and investors that operate in a market majorly determined by renewable support schemes. The TIS literature further acknowledges that innovation systems cannot be fully understood without considering their context (Bergek et al., 2015). The TIS framework also includes notions of change and dynamics. It aims at showcasing how, by the complex interplay of actors in networks, certain institutions and developments are produced in feedback loops of cumulative causation (Hekkert et al., 2007). A fruitful line of conceptualization has identified seven core functions of a TIS that help describe dynamic processes within the TIS (Bergek et al., 2008a; Hekkert et al., 2007). The creation of legitimacy is a core function of a TIS that governs its relations to its (institutional) environment (Hekkert et al., 2007; Markard et al., 2016).

2.1. Technology legitimacy

The relation of a focal technology to its institutional environment has been termed technology legitimacy (Markard et al., 2016). Legitimacy has a long tradition in organization theory (e.g., Aldrich and Fiol, 1994; Deephouse et al., 2017). Legitimation understood as a set of activities leading to legitimacy, is a crucial function of innovation systems, particularly in the formation phase (Bergek et al., 2008b). In later phases, legitimacy helps maintain political and public support, and a loss of legitimacy can contribute to the decline of technologies and industries (Geels and Verhees, 2011). Within sustainability transitions, maintaining legitimacy is particularly important, as transitions require long-lasting societal support (Geels et al., 2017; Geels and Verhees, 2011). The decisive role of policy and the long-term orientation of sustainability transitions elevate the relevance of the maintenance of technology legitimacy.

Markard et al. (2016) define technology legitimacy as the "[…] commonly perceived alignment (or misalignment) of a focal technology with institutional structures in its context." (Markard et al., 2016, p. 333), and we adopt this perspective within our study. In the following, we discuss the main concepts of this definition.

In contrast to the organization theory literature that focuses on organizations striving for legitimacy, technology legitimacy emphasizes the *focal technology* as the main object of inquiry (Markard et al., 2016). Manufacturers, technology companies, installers, or other organizations involved in the technology innovation system can take actions to maintain their legitimacy strategically. Technology legitimacy can be seen as contributing to the legitimacy of actors involved in the TIS. It can thus be expected that those actors will also engage in maintaining technology legitimacy. However, it is essential to note that technology legitimacy focuses on the technology instead of actors' legitimacy and

Table 1
Dimensions in the technology legitimacy framework (adapted from Markard et al., 2016).

Dimension	Content	Diagnostic questions	Specifics
Cognitive	Understanding and purpose of technology	What is wind power? What is its purpose, what problem can it solve?	
Normative	Major design principles	What is a 'good' wind power plant? What are unwritten rules or guiding principles for building and operating wind power plants?	
Regulatory	Socio-technical materialization	How do wind power plants look like? What are typical technology characteristics? How are they operated?	Plant size, construction, ownership, and operation
Pragmatic	Self-interest and participation	Do stakeholders of wind power profit from the technology? How can they participate?	

actions within the TIS (Markard et al., 2016, p. 333).

Institutional structures comprise societal norms, values, beliefs, traditions, or regulations that apply to actors active within the socio-technical system. Institutions give structure to social interactions and are themselves socially constructed (Markard et al., 2016). Institutions are part of the context of the focal technology. Common frameworks of legitimacy regularly divide the institutional structure into different dimensions[1] (Table 1) (Binz et al., 2016; Geels and Verhees, 2011; Markard et al., 2016; Suchman, 1995). The cognitive dimension refers to the knowledge about a technology and its purpose in general, and, in its highest form, may reach a state of taken-for-grantedness, where the deployment of technology is beyond questioning (Aldrich and Fiol, 1994). The normative dimension refers to the alignment with informal rules such as norms and values. The regulatory dimension refers to formal standards and regulations that the focal technology can be misaligned with (Markard et al., 2016). To Markard et al. (2016) legitimacy framework, we add pragmatic legitimacy that refers to stakeholders' self-interest and the possibilities to participate in its deployment (e.g., Harris-Lovett et al., 2015; Suchman, 1995). Staying in terms of Markard et al. (2016) 'diagnostic questions', such questions could be "Do stakeholders of the technology profit from the technology? How can they participate?" (Table 1). Pragmatic legitimacy has been described as the dimension most susceptible to change by policies or stakeholder behavior (Jansma et al., 2020; Suchman, 1995). Particularly participation has been repeatedly identified as an essential element of the acceptance of local wind power projects (Langer et al., 2018; Sonnberger and Ruddat, 2017). Therefore, a detailed account of pragmatic legitimacy can enhance the usefulness of the technology legitimacy framework for policymakers.

An essential factor of legitimacy is the *context* of the focal technology. The TIS literature has identified various context structures relevant to shaping innovation and the operation of a TIS (Bergek et al., 2015). Such context structures can be political systems, sectors, other technological systems, and the like. It is important to note that each context element comes with its own institutional structure of regulations, norms, or rules that shape a context element's operations. An electric vehicle may, for example, need to comply with traffic regulations of the transport sector, while at the same time, it must obey the rules of the electricity system in order to recharge batteries. Therefore, the alignment of a technology with institutions from different contexts is vital for legitimacy. It is also here, in the context, where actors, such as politicians or customers, are situated that "need to be convinced that something is appropriate, right or desirable" (Geels and Verhees, 2011, p. 913) and whom themselves contribute to the creation of legitimacy.

Another aspect of legitimacy is that it can be described as a social process and is thus construed by different actors such as policymakers, companies, or end-users (Johnson et al., 2006). The processual character is also reflected in the fact that legitimacy might be contested and supported repeatedly over time, and technology struggles for legitimacy (Geels and Verhees, 2011). *Commonly perceived alignment* thus refers to this characteristic as it defines legitimacy "[…] as an overall or integral perception of how well a specific technology is aligned to the context, or not" (Markard et al., 2016, p. 333), where alignment and misalignment can happen at the same time. Technology can comply with individual institutions while not being aligned with others. For example, nuclear energy has the prospects of delivering electricity with low CO_2 emissions while at the same time bearing the risks of radiation exposure. Therefore, legitimacy is the product of a weighting process of different aspects of a focal technology. A further implication of describing legitimacy as a social process is a link to the temporal dimension: Within the legitimation process, actor coalitions and institutions can change, inducing alterations of commonly perceived alignment and changes of the weights of different aspects.

While this process of legitimation has been described through four stages of (1) innovation, (2) local validation, (3) diffusion, and (4) general validation (Johnson et al., 2006), a comparable description of the process of delegitimation is missing in the literature. Delegitimation, understood as an increasing perception of misalignment of the focal technology with specific institutions (while the perception of other relationships may remain stable), can have consequences for policymakers in the pursuit of necessary technological change. Empirically, the technology legitimacy literature has described periods of delegitimation. Geels and Verhees (2011, p. 920) describe how nuclear energy became delegitimated in the Netherlands by an anti-nuclear movement whose roots can be traced back to initiatives against a specific nuclear energy project. Markard et al. (2016) sketch how the legitimacy of biogas technology in Germany became increasingly challenged, first in professional circles and by local initiatives; only later the perception of misalignment diffused to the broader public. Both cases entailed a limitation of political support for the focal technologies. These empirical examples suggest that delegitimation follows a processual structure similar to legitimation. The perception of misalignment first emerges on a local level or in specialized societal groups. From here, it may diffuse to other situations, until eventually, the technology is regarded illegitimate in general. From the perspective of policymakers and technology managers, this processual conceptualization of delegitimation highlights the importance of legitimacy management starting from every single local project, even if the technology is generally validated. Drastically speaking, every single project may be the starting point of a spiral of delegitimation.

It is also important to note that technology legitimacy acknowledges that the context or external conditions can change. Changes in the context of a focal technology can contribute to (mis-)alignment and contribute to technology legitimacy (Markard et al., 2016).

2.2. Technology legitimacy and the media

In order to analyze technology legitimacy, it is crucial to understand how legitimacy is produced. The technology legitimacy framework identifies three mechanisms of the creation and change of legitimation: (1) technological change to comply with institutions; (2) changes in the

[1] The distinction between the dimensions of legitimacy should be understood analytically, meaning that in real-world arrangements, an event or action affecting legitimacy likely affects several dimensions. Deephouse and Suchman (2008, p. 68) provide the example of the regulatory approval of a new pharmaceutical, which, apart from regulatory legitimacy, provides evidence of alignment with health (normative l.), enhances 'cognitive' comprehensibility, and showcases that the new product is useful (pragmatic l.).

institutional environment itself; and (3) the framing of the focal technology concerning its relations to the institutional structure (Markard et al., 2016, p. 332). It should be evident that the mechanisms of de-legitimation are the same. Particularly concerning the latter two, media coverage is a well-suited indicator to assess legitimacy. This section aims to point out the role of media in the production of legitimacy without neglecting that other sources of legitimacy exist and may add to our results.

Organizational scholars have recognized different sources of legitimacy, such as the state, regulatory agencies, interest groups, public opinion, or the media (Deephouse et al., 2017, p. 14). Particularly state authorities decide on the provision of resources or conduct evaluations, and such activities have been used as indicators for the legitimacy of organizations (Deephouse, 1996). Surveys of public opinion have been conducted to understand the legitimacy of organizations (Dowling and Pfeffer, 1975). However, media coverage has become an important indicator of legitimacy in the studies of organizations (Deephouse and Suchman, 2008) and, more recently, of technology legitimacy (Binz et al., 2016; Geels and Verhees, 2011; Jansma et al., 2020; Markard et al., 2016; Weiss and Nemeczek, 2021). This interest in studying media accounts is related to the fact that public opinion and media both influence each other mutually, making media both an indicator and a source of legitimacy (Deephouse and Suchman, 2008). Furthermore, media influences the political process (Walgrave and van Aelst, 2006), and therefore has an effect on the evaluation of technology by political actors who themselves are an important source of legitimacy. Additional arguments can be found in the framing literature that argues that media accounts are produced in the exchange of political and social elites with journalists and continuously emphasize certain issues over others (Carragee and Roefs, 2004; Entman, 2007; Vliegenthart and van Zoonen, 2011). We, therefore, expect that positions of actors from the technology's context and TIS are reflected in media accounts of technology. This perspective is also adopted in the study of technology legitimacy that "emphasizes that collective sense making takes place on public stages (e.g., public debates, media, newspapers). Social movements, industry associations, policy makers, and special-interest groups perform on these public stages and engage in discursive struggles that aim to influence collective discourses" (Geels and Verhees, 2011, p. 913). In the public discourse, actors from different contexts compete on the framing of technology and, indirectly, on the prospective provision of resources (Geels and Verhees, 2011; Jansma et al., 2020).

The manifold relations of media to public opinion and political and societal stakeholders motivate us to conduct a thorough newspaper content analysis to assess the legitimacy of wind power. While we do not strive to delve in detail into which actors shape technology legitimacy, we target at analyzing the manifestation of this discursive process which is assumed to have consequences for the legitimacy of technology. The commonly used definition "To frame is to select some aspects of a perceived reality and make them more salient in a communicating text, in such a way as to promote a particular problem definition, causal interpretation, moral evaluation, and/or treatment recommendation for the item described." (Entman, 1993, p. 52) provides first guidance for our analysis of newspaper content. For our study, we are therefore particularly interested in the salience of problems, interpretations, and evaluations that point to (mis-)alignment of wind power with institutions in its context. Furthermore, general sentiment towards the focal technology has been regularly assessed in the study of technology legitimacy in newspapers (Jansma et al., 2020; Markard et al., 2016). However, we propose a more refined assessment of sentiment of specific topics emerging in the coverage of a focal technology (see Section 3.5). As we shall see, this refined notion of sentiment helps to identify issues that pose threats or support legitimacy.

When it comes to sentiment and the directionality of newspaper contents, it is noteworthy that there is a general tendency of journalists to report societal problems and negative events rather than positive stories, a fact that can be traced back to psychological factors of the readership (Soroka et al., 2019). This could be a potential caveat to the legitimacy assessment via newspapers, as a technology could be generally framed more in light of problems than by positive accounts of its deployment. However, the literature suggests that positive expectations towards technologies are a regular part of news reporting (e.g., van Lente et al., 2013), and societal problems (e.g., climate change) also motivate the deployment of new technologies, particularly when it comes to renewable energies. These arguments show that also positive aspects of technologies make the news, and some societal issues contribute to legitimization. However, the general tendency to report on conflicts and problems should be kept in mind when interpreting the results. In the following, we provide some insights that the framing literature has produced on wind power in various national contexts.

2.3. *Framing of wind power*

Most renewable energy media studies use deductive approaches to scrutinize how renewable energy technologies are framed along economic, technological, environmental, and social dimensions (Rochyadi-Reetz et al., 2019). For the period between 2010 and 2012, Rochyadi-Reetz et al. (2019) find that renewables, in general, are primarily framed in (positive) economic terms, while countries with higher penetration (including Germany) also tend to report negative societal and environmental consequences.

Wind power frames have been analyzed with cross-sectional (multi-country) approaches (Djerf-Pierre et al., 2016; Fischlein et al., 2014; Rochyadi-Reetz et al., 2019; Stephens et al., 2009). In general, the cross-sectional studies emphasize the contingency of wind power frames. In the US, state-level wind discourses vary between states (Fischlein et al., 2014; Stephens et al., 2009). Djerf-Pierre et al. (2016) show that while discourse in Sweden was ambiguous, negative economic frames governed the agenda in Australia. In both countries, political and economic elites dominated the discourse.

Another set of studies provides insights into local specifics of public wind power discourse. In Australia, local wind projects encounter fierce debates while the government is little aware of such local conflicts (Hindmarsh, 2014). Zukas (2017) showed that wind energy discourse is primarily determined by politicians and industry stakeholders in Wisconsin, USA. In the discourse on German offshore wind, arguments on negative environmental impact are rarely used, although a survey showed them to be effective in influencing acceptance (Schmidt, 2017). Offshore wind has also been scrutinized in Norway, where economic frames, both positive and negative, were most frequently employed (Heidenreich, 2016).

Furthermore, few studies assessed media coverage of wind power with longitudinal sampling strategies or linked context changes to media accounts. In Ontario, Canada, Deignan et al.; Deignan et al. (2013; 2015) assessed the effect of policy changes on the coverage of public health issues concerning wind power and found increased negative coverage. Gearhart et al. (2019) assessed US television coverage of wind power between 2001 and 2016, where coverage decreased over time and primarily displayed wind power as a political issue. Remarkably, also the reporting of positive environmental effects of wind energy decreased over time. A further study suggests a bidirectional relationship between media and policymaking (Smith et al., 2016). Finally, Pralle and Boscarino (2011) analyze how climate change mitigation is traded off against local environmental and esthetic concerns in wind power coverage.

Concluding this brief literature review, we found considerable variation in the findings of the different studies, indicating that the framing of wind power is strongly dependent on its context. Economic and political frames seem to dominate agendas, while environmental and esthetic concerns are raised less frequently in media coverage. Hence, according to these studies, the legitimacy of wind power may be primarily determined by economic and political issues, but also environmental concerns may play a role, and legitimacy may vary between different national contexts and times. In general, media has rarely been scrutinized for changes in wind power coverage over long periods, a shortcoming that might be related to the difficulties arising from the large amount of data that must be processed. Furthermore, the wind power framing literature does not consider the importance of media for the legitimacy of wind power. With the paper at hand, we contribute to the literature by assessing wind power's legitimacy and proposing a statistical approach to analyze a high number of newspaper articles described in the following.

3. Methodology

A quantitative assessment of newspaper content to assess the legitimacy of wind power is an inherently data-intensive process. Within this section, we outline the collection of data and, due to the high amount of data available, we outline how we use Natural Language Processing (NLP) methods for detailed content analysis. We identify the Structural Topic Model (STM, Roberts et al., 2016a) as a suitable tool for our endeavor. Various preprocessing steps, model configuration, validation, and final data analysis have to be taken into account to make such an analysis operable. Different aspects of the methodology we followed in this article have recently been proposed (Dehler-Holland et al., 2020). As automated content analysis is a relatively new field, a detailed discussion of data collection, preprocessing, and method choices is necessary to understand the findings provided in this study and enhance reproducibility (Antons et al., 2020).

3.1. Data

In order to assess the legitimacy of wind power as comprehensive as possible, we collected newspaper articles from four national German newspapers: *Die Welt, Die Tageszeitung (TAZ), Frankfurter Allgemeine Zeitung (FAZ)*, and *Süddeutsche Zeitung (SZ)*. While Welt and TAZ were retrieved from the LexisNexis academic database, FAZ and SZ were collected from the newspaper's archives. The newspapers were chosen based on their national coverage and their high circulation. Additionally, the four newspapers are well distributed geographically in Germany: The editorial offices of the SZ, FAZ, TAZ, and Welt are located in Munich, Frankfort, Berlin, and Hamburg, respectively, and local sections cover those regions. As the temporal scope of our analysis, we chose the period between 2009 and 2018. During those ten years, the support regime has changed substantially, and wind onshore and offshore capacities have been expanded.

After different combinations of words had been tried, we consistently used "Windenergie* OR Windkraft*" (wind energy OR wind power) in all databases. Other search terms such as "Windrad" (windmill) did also include irrelevant articles. The terms ensure that wind power is discussed in the article, and articles that mention only wind are excluded.

First, duplicates were removed using the Levenshtein distance (Levenshtein, 1966) for measuring text similarity. Duplicates expose text classification to the risk of biased results, as they may inadvertently put excessive weight onto specific categories. Second, texts were screened for sections such as *letters to the editors* or *table of contents* that have been excluded from the analysis.

After these two preparatory steps, 9840 articles entered the analysis. The articles' length shows a broad distribution between 13 and 4594 words, while the average article contained 593 words. Articles are not distributed evenly over the different news outlets (Table 2). The FAZ published most articles during the time, while in SZ, the fewest articles appeared, while, in turn, the average article discussing wind power was the longest.

3.2. Content analysis

Content analysis methods usually comprise quantitative methods to assess contents of communication, e.g., newspaper articles. The quantitative methods used to assess content can further be subdivided into manual and automated approaches. The latter have the advantage that large bodies of text can be evaluated at once, while manual methods are constraint in the number of texts that can be assessed for a specific research question by the number of researchers and time available. Given the large amount of data collected for our study, there are two options in pursuing a quantitative content analysis. First, one could reduce the number of texts by focusing only on the texts most relevant to the relevant research question and conduct a manual content analysis of a significantly smaller subset of texts. Second, we could use an automated approach to assess the entire dataset. Given that a thorough analysis of legitimacy should assess all context structures within which a focal technology is assessed, we opted for the latter.

Broadly, automated methods can be divided by whether categories of text are already known or not (Grimmer and Stewart, 2013). This distinction is essential, as different methods are available in each case. Based on this distinction, supervised or unsupervised methods can be applied (Grimmer and Stewart, 2013; Quinn et al., 2010). Supervised methods are used to learn categories predefined by the researcher, but large training sets are necessary to carry out meaningful research, and substantial knowledge is needed to provide those (Quinn et al., 2010). For example, Hughes, 2018 categorizes more than 11,000 one-minute speeches in the American House of Representatives manually to train different supervised algorithms up to an acceptable level of error. Unsupervised methods can be applied relatively fast, with minimal a-priori assumptions and low costs (Quinn et al., 2010). On the other hand, findings must be validated with care, and automated methods cannot replace careful manual validation (Grimmer and Stewart, 2013).

As the foundation of this study is a large number of texts that need to be classified, and categories of analysis have not been fixed, we have decided to follow an unsupervised modeling approach to define categories for the underlying texts. A popular class of unsupervised learning for text classification are topic models (e.g. Blei et al., 2003; Blei and Lafferty, 2007). Topic models are well in line with framing concepts (DiMaggio et al., 2013). Topic models have undergone rapid development within the last decades, and a recent achievement has been the consideration of meta-data within models. The Structural Topic Model (STM) allows the topic model to leverage information from covariates, such as time, in the classification step. This feature is the main reason for us to apply this technique, besides the rising number of accounts of its ability to produce valid results (Roberts et al., 2014, 2016a, 2016b). Furthermore, STM is a mixed membership model and allows that the occurrence of topics within a document follows systematic patterns across the whole set (Blei and Lafferty, 2007; Roberts et al., 2016a). This feature allows the researcher to endeavor relationships between different topics across all documents that help to delineate the different

Table 2
Descriptive statistics of newspaper data per source.

Newspaper	Number of articles	Average article length [words]	Median article length [words]	Max article length [words]	Min article length [words]
Die Welt	2141	610	545	2829	25
Die Tageszeitung	2639	483	391	4594	13
Frankfurter Allgemeine	3154	620	566	4523	20
Süddeutsche Zeitung	1906	681	605	3807	14
All	**9840**	**593**	**506**	**4594**	**13**

contexts of wind power.

Automated content analysis has high requirements concerning the format in which text data is provided to classification algorithms. Texts from different sources cause the need for normalization in order to be comparable without introducing bias. Various steps are required to ensure that texts have the same encoding, that words with the same meaning are mapped onto each other, and to reduce the dimensions of the data set as much as possible to speed up model estimation (Lucas et al., 2015). Thus, preprocessing is a time-consuming task in our content analysis endeavor.

3.3. Preprocessing

As the text data used in this study stems from different sources, the texts had to be brought into a standard format. Documents were imported into an R data frame. Once in a standard format, normalization procedures can be applied. Fig. 1 provides an overview of all the steps necessary to analyze the results.

To derive a meaningful text model, words inflected from the same base form (such as singular and plural of a noun, or *use* and *used*) must be associated with one another. Two major approaches exist. The simple approach is to "chop off" the end of each word and including only the stem of words for later analysis, and for many languages such as English, stemming yields satisfactory results (Lucas et al., 2015). However, as German is more richly inflected, lemmatization is preferable (Jacobi et al., 2015). Lemmatization is the task of inferring the canonical form of a word from the inflected form and its context (Manning et al., 2009). For this study, we used the Treetagger, a well-tested software that provides lemmatization and Part-of-Speech (PoS) tagging for German and can be coupled with R (Schmid, 1994, 1999). The algorithm is based on the classical language model that assumes that texts are created as Markov chains (Schmid, 1994). For Markov chains, the derivation of transition probabilities plays a significant role. Schmid (1994) addresses this problem by using decision trees that decide on the size of the context that should be taken into account when assessing a specific word (such as analyzing trigrams, bigrams, or unigrams) and PoS tags of previous words. The algorithm has been improved to assess German texts and achieves highly accurate results (Schmid, 1999). The PoS tagging results were used to reduce the corpus to include only words adding semantic meaning to the texts. Furthermore, classical stop word removal based on a comprehensive lexicon has been applied (Diaz, 2016). Lemmata are included in the reduced corpus whenever they are available. If unknown to the lemmatization algorithm, we included the term how it appeared in the original text.

The reduced corpus is the foundation for any further classification efforts. The corpus was translated to a document-term matrix consisting of 9840 documents and 17,418 terms to be assessable by numerical text models. Based on the preprocessing of textual data, a Structural Topic Model was developed that explicitly considers the temporal dynamics of discourse by leveraging the patterns of overall attention to wind power.

3.4. Structural topic modeling

In general, topic models and other unsupervised learning algorithms infer the contents of a set of texts rather than presuppose categories beforehand (Roberts et al., 2014, p. 1066). A fundamental assumption is that categories or, in our case, topics are defined by the frequent usage of the same vocabulary. Based on this assumption, word counts per document and their distributions give essential information on documents' content. This concept is also referred to as "bag-of-words", as the order of words is not considered. The algorithm must "know" how a document is generated to estimate the underlying distributions of words; thus, topic modeling assumes an a-priori mechanism that produces texts (Blei et al., 2003). Topic modeling assumes that a corpus contains a fixed

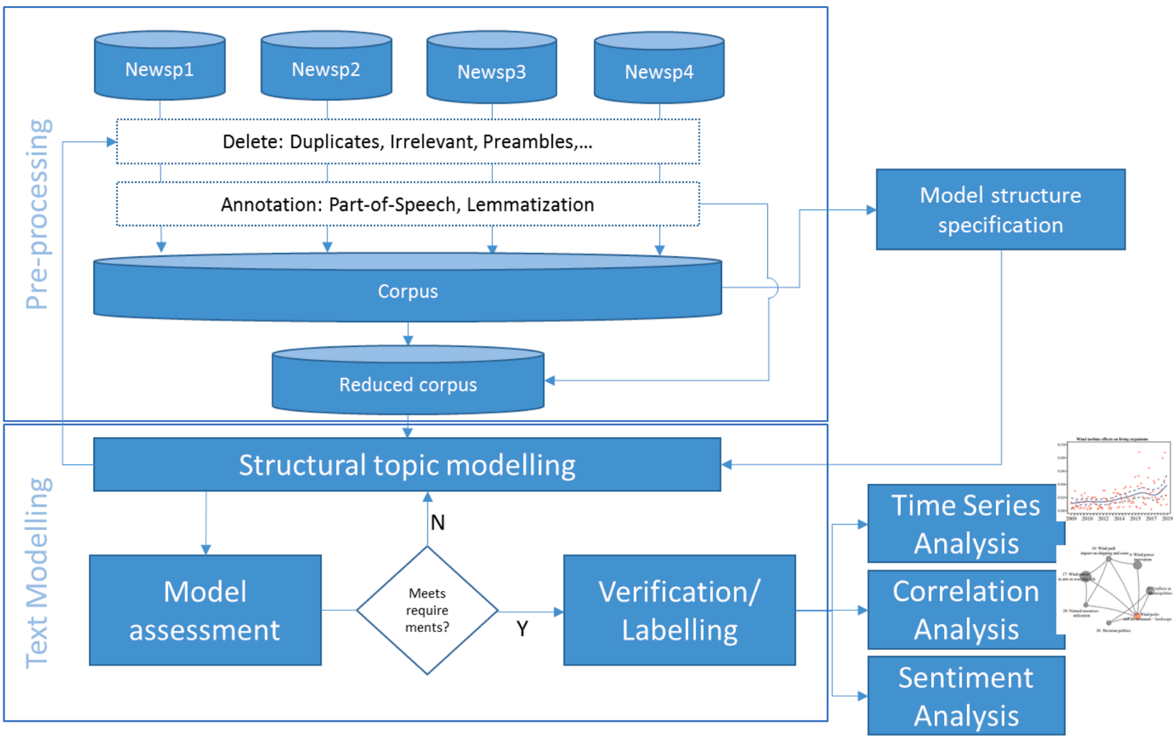

Fig. 1. Schematic representation of preprocessing, modeling, and analysis steps.

number of k topics, where each topic is defined by a distribution of words. Each document is composed of those k topics to varying shares. Each document now is assumed to be produced by a process that (1) draws a document length and then, (2) word-by-word, draws a topic from the distribution of k topics, (3) draws a word from the associated distribution, and (4) goes on with the following word (Blei et al., 2003). The underlying distributions can be estimated using Bayesian statistics techniques given a set of documents (Blei et al., 2003).

The specific innovation of structural topic models is that the distribution of topics (*prevalence*) may depend on covariates, such as time or publisher (Roberts et al., 2014, 2016a). This is the main feature we will exploit in our analysis of technology legitimacy, as legitimacy, as conceptualized above, is highly dynamic or time-dependent (Johnson et al., 2006; Markard et al., 2016). Thus, a crucial step of our analysis is to decide on the STM's structural specification, namely how to include the temporal dimension. First, we chose the month of publication of articles as a covariate so that the model can infer common features from an appropriately sized number of articles. Second, the leading developers of STM propose spline models to include temporal variables into the model structure (Roberts et al., 2019), and we follow this advice. The basic assumption of STM is then that the *mean prevalence* $\mu_{\tau,t}$ (the share of a topic τ in all documents at a given point in time t) can be expressed by piecewise third-degree polynomials to allow for non-linear changes over time as follows:

$$\mu_{\tau,t} = \sum_{i=1}^{N} b_{\tau,i} \cdot bs_i(t),$$

given a base of splines bs and $N = \#knots = degrees\ of\ freedom$ when we use natural splines to avoid erratic behavior at the domain bounds. In defining a spline model for our text model specification, choosing the number and placement of the knots (i.e., the points where two polynomials meet) is the next critical step.

Often, the choice of knots is made based on separating the data in quantiles, and a low number of knots is generally enough to represent the data adequately (Harrell, 2015). However, if prior information is available, the choice of knot positions according to expected data changes can improve the model quality (Harrell, 2015, p. 26). Therefore, to get a first idea of the temporal dynamic of newspaper coverage, we assess the time series of document counts per month. We apply a changepoint analysis algorithm that detects changes in mean and variance of time series by testing data distribution changes (Killick et al., 2012; Killick and Eckley, 2014). The analysis reveals that data can be separated into contiguous phases, and we set the knots accordingly to the phase bounds (compare Fig. 3 in Section 4.1) and between bounds to bestow sufficient flexibility to the model.

Another fundamental decision concerns the number of topics that suffice to analyze the corpus. The decision can be formulated as a trade-off between the different topics' separability and their semantic coherence. The decision ultimately requires a judgment call by the researchers based on the research question at hand but can be guided by statistical measures. The above trade-off can be formalized by measuring, for a given model, the exclusiveness of terms in a given topic compared to other topics (Airoldi and Bischof, 2016). Semantic coherence can be formalized by the co-occurrence of words (Mimno et al., 2011). We estimate models with $k = 20, \ldots, 100$ and assess the models based on statistical measures (Figure A. 1 in Appendix). Solutions that locally dominate other solutions are investigated manually based on frequently occurring terms. Finally, we decided on a model including 44 topics, which appears to be a reasonable trade-off that enables us to investigate our research questions but does not lead to a high number of topics that increases validation need and introduces topics that do not contribute to the research questions.

3.5. Statistical analysis of context structures and topic sentiment

We performed time series modeling, graph analysis, and sentiment analysis of topics to explore the contents and their changes over time. In the following, we provide insights into the procedures applied to assess technology context and sentiment.

Essential aspects of technology legitimacy are the different contexts in which the focal technology is embedded. We strive for empirically identifying wind power's context structures by assuming that they are inherently represented in the topic model structure by the way topics are discussed alongside each other regularly. This factor can be measured by the correlation of topic prevalence time series. To analyze the relations of topics within the corpus, we assess correlations as a graph structure. The edges in the graph are given by the Pearson product-moment correlation between the topic time series. As the individual topic distributions are strongly skewed and show high kurtosis, we apply a rank-based transformation to normality. The transformation has been found to have favorable properties, and the Pearson correlation coefficient may underestimate the relationship between variables (e.g., Bishara and Hittner, 2012, p. 408; Kowalski, 1972). To understand the context structures of wind power, we divide the graph structure induced by correlations into sub-graphs of highly correlated topics. More technically speaking, we assess the graph's modularity to identify context elements that showcase higher correlations internally but lower correlations to external elements. Given the relatively low number of vertices (i.e., topics) in our graph, we can maximize modularity without falling back to heuristics (Brandes et al., 2008). The procedure delivers both the optimal number of sub-graphs and the topics each sub-graph contains. We use the igraph package in R to estimate graph structures (Csardi and Nepusz, 2005).

Another critical property of text in analyzing technology legitimacy is the sentiment expressing texts' emotional content. In legitimacy analysis, negative sentiment has been used as an indicator for legitimacy being challenged, while positive sentiment is associated with higher legitimacy (e.g., Binz et al., 2016). Sentiment analysis is an important subfield of NLP in fast development (Pang and Lee, 2008). Often, the sentiment of a text, sentence, or aspect is expressed as a polarity score, e.g., in $[-1, 1]$ (Feldman, 2013). In that regard, our approach to assessing the sentiment associated with topics originating from a topic modeling procedure does not differ. We recently proposed analyzing topic sentiment by assessing the expected sentiment of topics given a specific sentiment lexicon (Dehler-Holland et al., 2020). For German, SentiWS provides a comprehensive sentiment lexicon with more than 3000 words (Remus et al., 2010).

Based on a sentiment lexicon W, we define the *topic sentiment* ts_τ per topic τ as the weighted sum of all sentiment scores $s_w \in [-1, 1]$ of words w from the vocabulary V of the entire corpus and the word occurrence probabilities $\beta_{w,\tau}$ estimated by a topic model. We rescale the expected value to $[-1, 1]$, as not all words in the vocabulary V are necessarily also to be found in the lexicon and define

$$ts_\tau = \frac{\sum_{w \in V} \beta_{w,\tau} \cdot s_w}{\sum_{w \in V \cap W} \beta_{w,\tau}}.$$

This definition allows us to assess the different topics' emotional content to better understand their relations to legitimacy. In our case, 8.9% of the words from the corpus vocabulary are also part of the sentiment lexicon, as naturally, many words of natural language do not carry unambiguous sentiment. This percentage is in line with previous studies using the same lexicon (Dehler-Holland et al., 2020; Remus et al., 2009). In order to assess the development of sentiment over time t, we evaluate the time series of $ts_\tau \cdot \mu_{t,\tau}$, where $\mu_{t,\tau}$ denotes average prevalence of topic τ in time t, as an indicator of the contribution of a single topic to the entire corpus's sentiment. Henceforth, we refer to $ts_\tau \cdot \mu_{t,\tau}$ as *weighted sentiment*.

Now that we have formally introduced the concept of topic sentiment, it is important to develop an intuition for it and how it can inform the study of technology legitimacy. We note that topic sentiment appoints a sentiment value to each topic instead of individual texts. We remind the reader that each topic is, in fact, a distribution of words (Section 3.4), and topics differ in that some words are more likely to appear than others. Topic sentiment is essentially an average of the lexicon's sentiment scores weighted by the probability of words to appear within a specific topic. The value of topic sentiment indicates whether the topic predominantly comprises words associated with positive (e.g., 'good', excellent', 'perfect') or negative (e.g., 'bad', 'wrong', 'harmful') sentiment scores. We emphasize that topic sentiment is linked to the emotional content of the topic and not necessarily to sentiment directly associated with the focal technology.

From this discussion, it also should become clear that positive (negative) topic sentiment alone is not sufficient to conclude towards legitimation (delegitimation) of the technology. As a broader societal issue may determine the topic's content, it is crucial to understand further the positioning of the technology towards that issue, i.e., whether it amplifies the issue at hand or possibly contributes to its resolution. As an example from our results, the topic *nuclear energy* (#43, $ts = -0.09$) discusses a technology highly controversial in Germany, where public opinion is critical about its deployment. In this discourse, wind power is framed as an alternative to nuclear energy, wherefore the topic contributes to the legitimacy of wind power, despite or because of its negative sentiment.

To showcase the trend of prevalence of a specific topic or wind power's context elements, we performed regression on the non-linear time trend formalized by natural splines as defined in Section 3.4. Combining the above procedures allows for a rich analysis of the underlying data, highly informative on trends and relations in newspaper coverage of wind power.

3.6. Validation

The use of an unsupervised content analysis method makes careful validation of the final model indispensable (Grimmer and Stewart, 2013), even though STM has a remarkably high accordance rate with human coding procedures (Roberts et al., 2014). We remind the reader that STM identifies topics not predefined by the researchers, and the content of these topics must be assessed qualitatively to derive meaning from the purely statistical results. While topic modelers often use word lists of the most probable terms for each topic to derive labels for each topic, we have additionally assessed a sample of articles on top of analyzing statistical measures of semantic coherence to ensure that topics do properly account for semantic regularities of the whole set of articles. For each topic, the first two researchers independently read (at least) the ten articles that showcase the highest topic proportions. Both researchers independently formulated a label for the topic based on close reading and the word lists of most probable terms per topic and wrote a short description of its content. Then, the results were compared, and common labels and descriptions were formulated. In general, there was already a high agreement on most of the topics from the start. In 73% (32 of 44) of the cases, both researchers agreed on topic labels and descriptions already in the first step. In nine cases, the label's wording deviated, but both researchers agreed on the content and its description. Therefore, consensus could be found quickly. For three topics, both researchers assessed additional articles from the sample and rediscussed labels and topic descriptions until consensus on the topics' content was reached. The consolidated labels and topic descriptions are summarized in the Appendix in Table A. 1. The validation results build the foundation of the interpretation of time series, correlation analysis between topics, and topic sentiment.

3.7. Operationalization of technology legitimacy

The preceding sections have clarified how we perform a content analysis of newspaper articles concerning wind power. First, we use topic modeling to delineate different topics within the corpus. Second, natural splines are used to model changes in the prevalence of topics over time. Third, we aim to analyze the context structures of wind power with correlation graphs, thereby formalizing a key concept in the definition of technology legitimacy. Fourth, we defined topic sentiment to assess the emotional content of topics. In this section, we lay out how we use the results of the content analysis exercise to assess the legitimacy of wind power.

As we have already argued in Section 2.2, newspaper articles provide a good proxy to assess legitimacy that is produced in the continuous exchange of actor positions. However, we have not yet addressed two critical issues of how the content analysis can inform technology legitimacy: (1) the identification of topics relevant for the legitimacy of wind power; and (2) the evaluation if a topic indicates (mis-)alignment of wind power with certain institutions. We discuss our approach to both issues in the following.

From our theoretical discussion (Section 2.1), we learned that relevant institutions are situated within the broader context structures of the focal technology. The literature proposes four dimensions that are relevant in the assessment of legitimacy: cognitive, normative, regulatory, and pragmatic legitimacy. After we assessed the context via correlation graph partitioning, we formulated broad assumptions on the institutions relevant in each context (Section 4.1). To refine this first analysis, we assessed the topics provided by the model by referring to the four legitimacy dimensions with the help of diagnostic questions as proposed by Markard et al. (2016) in Table 1 and the topics' qualitative descriptions (Table A. 1). This approach sheds light on two different aspects of legitimacy: first, it addresses the context, where each context also relates to a specific set of actors, infrastructure, and related interests (Fig. 2). Second, the legitimacy dimensions analytically help pinpoint why a specific topic impacts legitimacy, e.g., because the content of a specific topic reveals that the deployment of wind power is related to costs, which conflicts with stakeholders' self-interest (pragmatic legitimacy).

In order to evaluate whether a topic indicates (mis-)alignment with relevant institutions, we used the topic's qualitative descriptions derived during validation (Section 3.6), their prevalence over time, and topic sentiment. In general, we took high prevalence and a topic sentiment strongly diverging from zero as the first indication that a topic might represent a legitimacy issue. This was further qualified by the qualitative assessment of the topic's content and explorations of the topic's correlation graph neighborhood. A high correlation with a topic that pointed at societal or political conflicts (e.g., the topic *legal conflicts and law-making*, #33) was taken as an additional indicator for (mis-)alignment. Together, topic prevalence, sentiment, correlation with conflict topics, and qualitative assessment allow the conclusion that a particular topic contributes to or undermines legitimacy. In order to identify the timing of (mis-)alignment, we used weighted sentiment that provides a composed indicator of prevalence and sentiment over time.

Based on this operationalization of technology legitimacy with the help of detailed automated content analysis, we can draw a rich picture of the legitimacy of wind power in Germany. The nature of the unsupervised topic modeling procedure, where topics are determined automatically and not by the researchers' prior knowledge, inevitably also produces topics that are uninformative on legitimacy. However, it also allows minimizing potential bias in the coding procedure and costs (Quinn et al., 2010).

4. Results and discussion

In this section, we present the results of the change-point analysis of the number of articles and discuss the results of the content analysis using a structural topic model with 44 topics in detail. We start with an

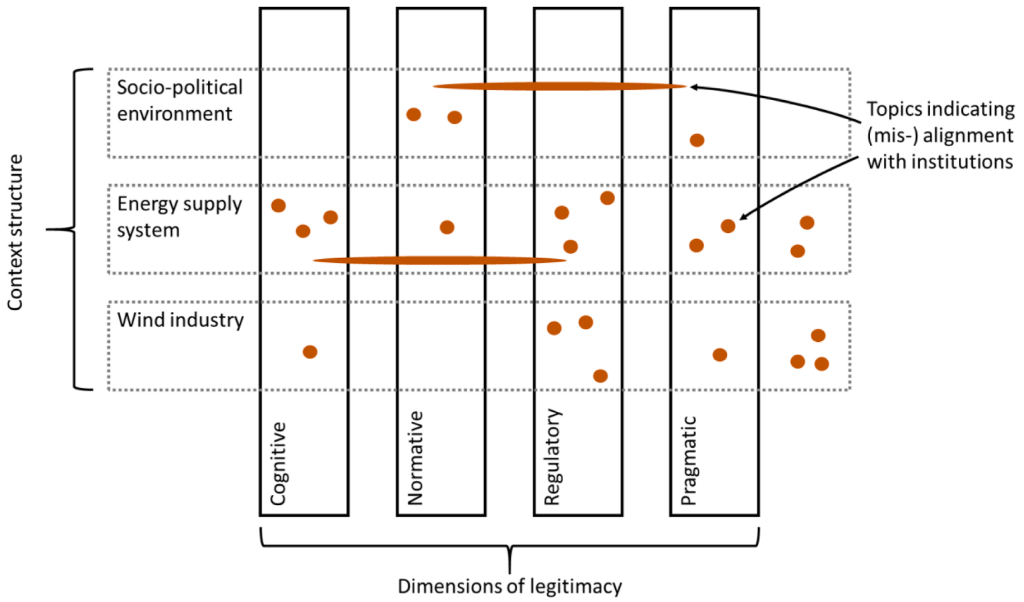

Fig. 2. Illustration of the identification and matching procedure of legitimacy dimensions and topics.

Table 3
Topic labels, context, and measures of sentiment and prevalence.

Context	#	Topic	Sentiment	Prevalence [%]
Energy supply system	6	Climate change and climate policy	−0.096	2.16%
	7	EU energy policy	−0.052	1.57%
	8	Electro-chemical energy production and storage	0.001	1.86%
	9	Share of energy carriers in energy demand	−0.007	3.80%
	10	Offshore wind parks	0.029	4.71%
	12	Electricity prices and EEG surcharge	−0.118	3.36%
	13	Wind power capacity development	−0.064	2.86%
	25	Grid expansion between north and south Germany	−0.052	2.72%
	30	Marketing of sustainable energy	0.052	2.13%
	34	Federal energy politics	−0.043	3.95%
	38	Transition of the energy system	0.028	3.01%
	39	Transformation of large electricity companies	−0.017	2.33%
	41	Security of supply	−0.103	2.23%
	43	Nuclear energy	−0.088	2.11%
Socio-political environment	3	Regional conflicts with wind projects	−0.048	2.17%
	4	Innovation in energy generation	−0.005	2.18%
	15	Offshore-Cluster North Sea	−0.005	1.56%
	16	Wind park impact on shipping and coast	−0.011	1.39%
	17	Wind power in culture and everyday life	0.046	2.84%
	20	Natural resources utilization	−0.083	1.18%
	21	Regional elections and coalitions	−0.006	3.21%
	23	Wind energy exhibition location	0.015	2.13%
	24	Private wealth building and taxation	−0.018	1.00%
	26	Education	0.077	1.79%
	28	Wind turbine effects on humans and animals	−0.221	1.71%
	31	Concepts of societal progress	−0.011	3.00%
	33	Legal conflicts and law-making	−0.198	2.36%
	35	Sustainable urban development	0.053	1.54%
	36	Bavarian politics	−0.014	1.22%
	37	Wind turbines' interaction with physical environment: landscape, weather, infrastructure	0.028	1.66%
Wind industry	1	Alternative fuels for transport	0.028	1.20%
	2	Investment in wind projects and the wind industry	−0.008	2.15%
	5	Prokon insolvency	−0.123	2.42%
	11	SMEs in the German industry	−0.044	1.26%
	14	Wind turbine world market	0.021	2.51%
	18	Digitalization of industry	0.068	1.36%
	19	Profit reports	−0.074	4.10%
	22	International politics and cooperation	0.010	2.52%
	27	Miscellaneous international news	−0.032	1.64%
	29	Acquisition of company shares	0.004	2.11%
	32	Stock market developments	−0.121	2.72%
	40	Shipyards demise	−0.084	1.92%
	42	Restructuring technology engineering companies	−0.008	2.69%
	44	Innovation in industry	0.046	1.67%

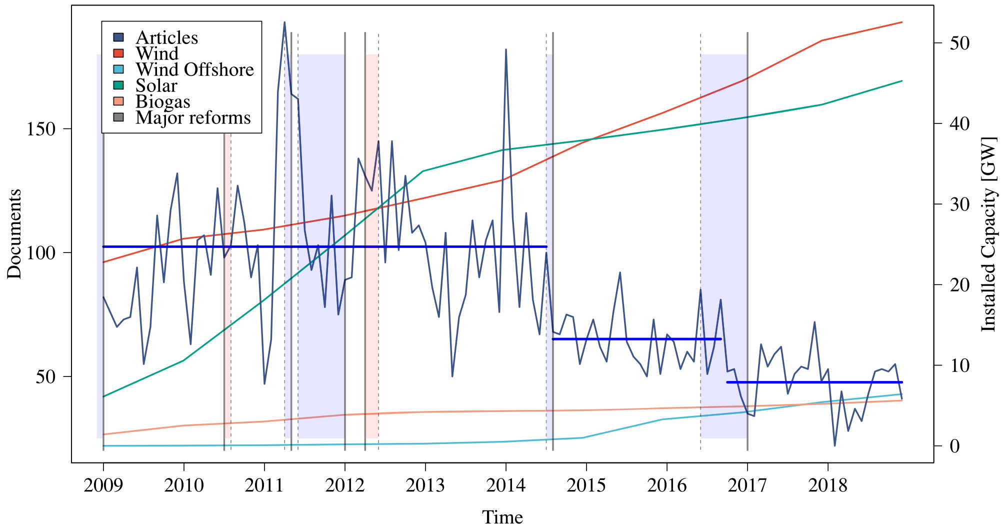

Fig. 3. Changepoint analysis of the number of documents per month. Vertical lines indicate EEG amendments. Dashed vertical lines indicate when the amendment passed parliament. The time between parliamentary approval and commencement is shaded blue or red. On the right axis, installed renewable energy capacities of different technologies are plotted (AG Energiebilanzen e. V., 2019).

overall assessment of the salience of wind power in four national newspapers. We delineate three context structures and discuss the changing prevalence of the three context structures over time. Furthermore, we assess topic sentiment across the entire corpus and derive the weighted sentiment of the three context structures as a first indication of where legitimacy issues might come into play. Afterward, we discuss selected topics and their contributions to the perceived alignment of wind power with institutions in its context structures – i.e., wind power's legitimacy in Germany. We close this section with reflections on the framework of technology legitimacy and some remarks on our methodology. Because it is, admittedly, not an easy task to follow the 44 topics through the results section, we usually refer to the topic number (#) and topic sentiment (*ts*) in the text for quick reference in Table 3.

4.1. Change points and the context of wind power

The analysis of change points in the newspaper coverage of wind power serves two goals. While we use the results to inform the text model on the temporal structure of coverage, we also learn that coverage has decreased since 2014 (compare Fig. 3). Generally, coverage is characterized by long periods of relatively stable attention towards wind power. Interest in wind power drops in 2014 and 2016. At first appearance, the drop in attention coincides with significant amendments to the renewable energy act (EEG). However, delving more into the details of coverage reveals that the salience of wind power in 2014 is strongly driven by the insolvency of Prokon, a wind power project planner and investor that issued profit participation rights to a large number of small investors (Topic #5, Table 3). The attention to this case ceased fast in the same period.

The context of the focal technology is vital to understand institutions that play a role in the legitimacy of a technology. To explore the context of wind power in newspaper accounts, we analyze the topic correlation graph (Fig. 4). As described in Section 3.5, we identify sub-graphs by optimizing modularity. We find that three contexts are particularly important in reporting wind power. Based on the sub-graphs, we distinguish wind power's context as its *socio-political environment*, the *energy supply system*, and the *wind industry*[2] (Table 3). We now discuss the three context structures in more detail, emphasizing context institutions related to wind power.

The *energy supply system* context comprises topics that are related to the provision of energy. Several topics are associated with centralized energy production and the transition to renewable energy generation (#10, 39, 43, and 38). Two topics are associated with the share of energy carriers in energy demand and developments of wind capacities (#9 and 13). Wind power is associated with topics related to the security of supply (#25 and 41). Two topics address the costs and the marketing of renewables and wind power (#12 and 30). Storage of electricity by, for example, the production of hydrogen (#8) is closely related to several key topics in the energy supply system. Federal, EU, and international climate politics (#6, 7, and 34) appear to be more associated with issues in the energy supply system context than the socio-political environment. The topics indicate that the often perpetuated goals of the energy supply system of affordability, minimization of environmental impact, and security of supply (Helm, 2002; Schmidt et al., 2019) play a role in shaping the relationships of this context and wind power.

Within the *socio-political environment* of wind power, topics associated with wind power's relation and conflicts with its social and natural environment are clustered. The socio-political environment comprises topics associated with wind power interaction with its environment (#16, 20, 28, and 37). Several topics are associated directly with legal and regional conflicts (#3, 15, 23, and 33). Wind power also relates to the population's everyday life (#17, 24, and 26). Two topics are associated with a (sustainable) development of society as a whole and, more practical, on a regional level (#31, 35). Interestingly, state-level policymaking is embedded in wind power's socio-political environment (#21, 36). The topics point show that, in general, issues of local projects and wind power deployment shape the relationship between the socio-political environment and wind power.

The *wind industry* context comprises topics associated with various

[2] Remarkably, the context structures we identified by optimizing modularity resemble the environments in the triple embeddedness framework proposed by Geels (2014).

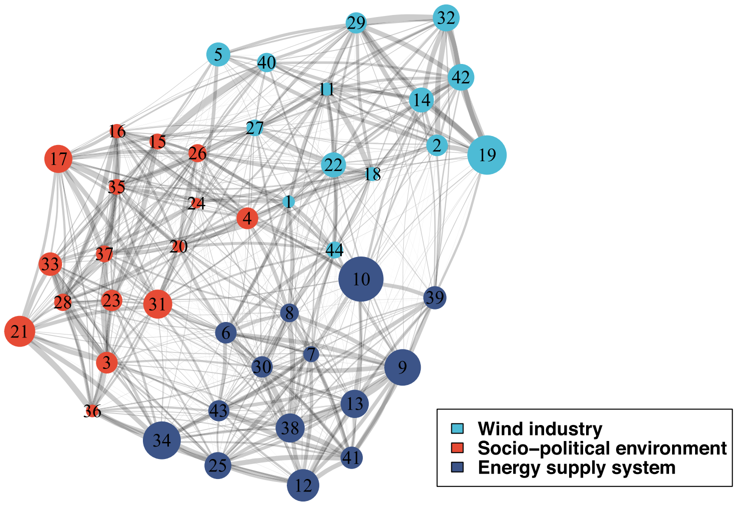

Fig. 4. Topic correlation graph. Community structures as identified by optimal modularity. Vertices scaled proportionally to topic prevalence. Edges are scaled proportionally to the correlation coefficients. Please refer to Table 3 for more detailed information on the context and topics.

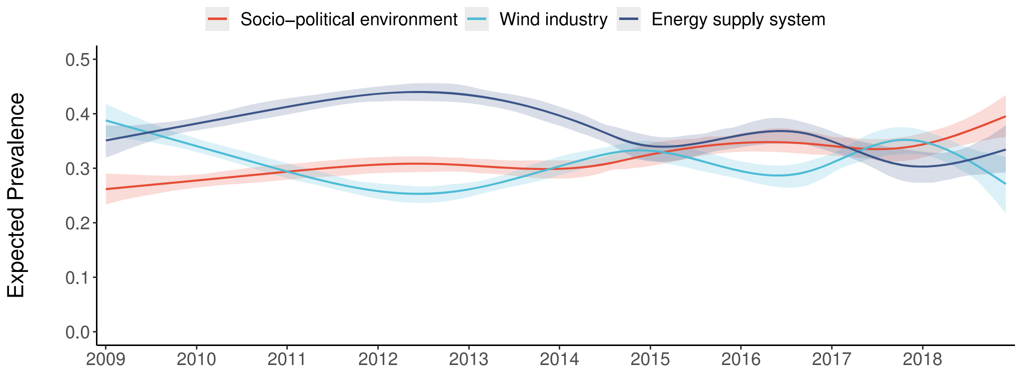

Fig. 5. Prevalence of the three context structures. Prevalence is modeled by the spline model described in Section 3.4. The shaded areas depict model uncertainty (0.95 confidence intervals).

aspects of the production and marketing of wind turbines. A large proportion of topics is devoted to economic aspects of the wind industry, such as investments (#2, 5), the performance of wind power companies (#32, 19), or market dynamics and company restructuration (#29, 42, 14). Wind power is regularly a topic in international affairs (#22, 27). An interesting set of topics is associated with the relations of the wind industry to other sectors and technology spillovers from other industries. Digitalization and innovation in chemical industries contribute to the production of wind power plant components and remote maintenance (#18, 44), as well as a multitude of small and medium-sized companies in Germany (#11). The German shipyards are in crisis and may profit from wind offshore installations (#40), while electricity from wind has the prospects of producing alternative transport fuels (#1). The topics indicate that economic performance and industry relations are important in the wind industry context.

To understand the contributions of the different contexts to the media agenda over time, we assess the development of prevalence of all three contexts (Fig. 5). The analysis shows that the socio-political environment has become most prevalent over time. The energy supply system was intensely covered between 2010 and 2015 after the government announced the German energy transition.

4.2. Sentiment

The tone of newspaper coverage has been argued as an essential variable to understand a technology's legitimacy. Based on the above notion of topic sentiment, we assessed the weighted sentiment of the wind power corpus over time (Fig. 6). Overall, the topic sentiment is negative for 29 out of 44 topics (Fig. 6a). Two negative outliers are remarkable: *wind turbine effects on humans and animals* (#28, $ts = -0.22$) and *legal conflicts and law-making* (#33, $ts = -0.2$) display distinctively negative topic sentiment. We notice that the weighted sentiment has a decreasing trend between 2009 and 2014 (Fig. 6b). After 2014, the trend of sentiment seems to increase. However, it should be noted that the Prokon insolvency already discussed has a substantial impact on the topic sentiment's temporal development and is majorly responsible for the dent in 2014. Without topic #5 (*Prokon insolvency*), the weighted sentiment is decreasing steadily.

When splitting up weighted sentiment by the three context structures, we find that weighted sentiment of the socio-political environment constantly decreases over time (Fig. 7). The weighted sentiment associated with the energy supply system reaches its lowest level around 2013, when costs related to the deployment of renewable energies were heavily discussed (*Electricity prices and EEG surcharge*, #12, $ts = -$

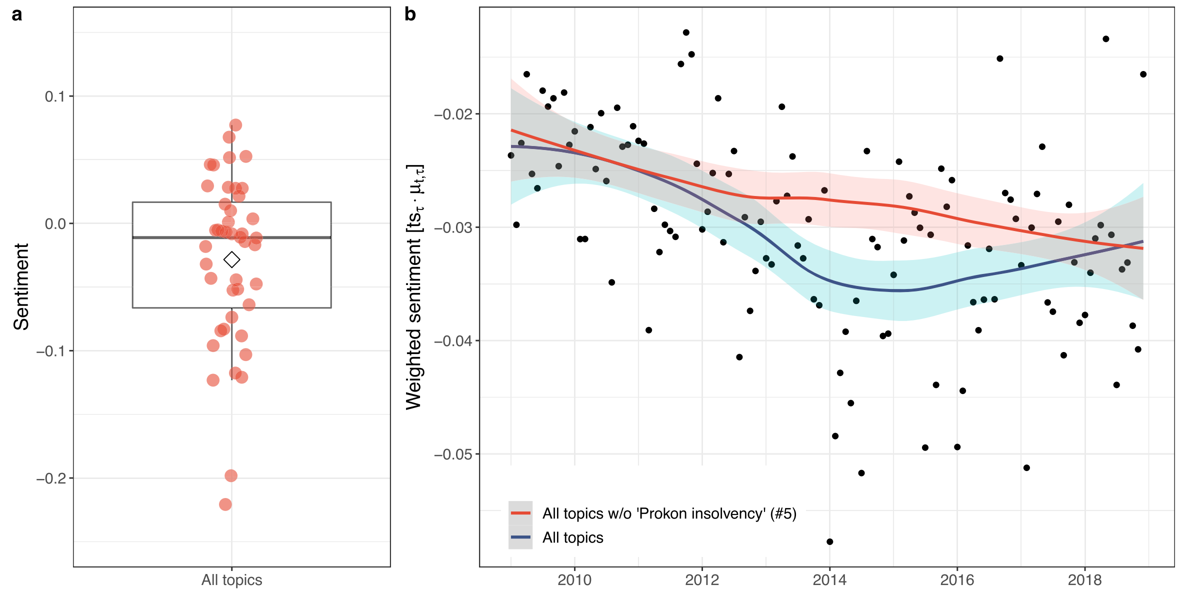

Fig. 6. Sentiment analysis of the 44 topics. a) Topic sentiment of all 44 topics. b) Topic sentiment weighted by topic proportions over time. To depict the trend, we fitted a LOESS model with 0.95 confidence intervals. Black dots are monthly weighted sentiment. The blue line depicts the trend of weighted sentiment in all topics, the red line is the trend of weighted sentiment with topic #5 Prokon insolvency removed.

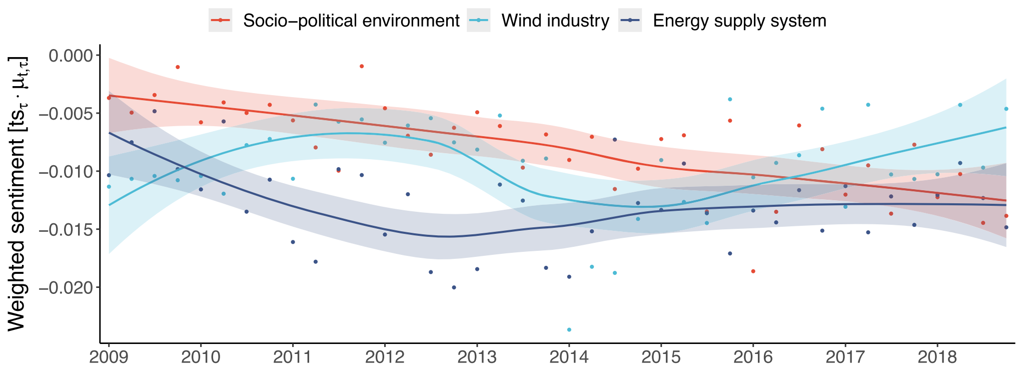

Fig. 7. Weighted sentiment of the three context structures. For visualization, data points are fitted with a LOESS model. The shaded areas depict model uncertainty (0.95 confidence intervals).

0.12). The weighted sentiment associated with topics from the wind industry context appears relatively volatile on an aggregated level. However, a closer analysis of drivers of these changes in sentiment reveals that exceptional topics such as the *Prokon insolvency* (#5, $ts = -0.12$) is responsible for the low sentiment in 2014, and negative *profit reports* (#19, $ts = -0.07$), as well as the *shipyard demise* (#40, $ts = -0.08$) in the aftermath of the financial crisis in 2008/2009 decrease sentiment in 2009 and 2010.

These results, taken together with the previous analysis of the prevalence of the three context structures, show that the weights of newspaper coverage have changed over time: Where early attention was dedicated to the energy supply system, later, wind power is primarily discussed within its socio-political environment. Together with the constantly decreasing sentiment of the socio-political environment, one might be inclined to think that this already indicates upcoming issues within this context, possibly related to the legitimacy of wind power. However, as we have discussed in Sections 3.5 and 3.7, linking the results of our analysis to legitimacy requires a more detailed analysis of the topics' content and its contributions to the four dimensions of legitimacy. Therefore, the next section is dedicated to scrutinize how different topics contribute to the four dimensions of legitimacy.

4.3. The legitimacy of wind power

Surveys on wind power in Germany have repeatedly shown high approval rates (above 80%) (Fachagentur Windenergie, 2019). Wind power generation is supported by the German renewable energy act (EEG), and market development only slowed down in 2018 at the end of the observational period. These indicators suggest that wind power, in general, is considered a legitimate source of electricity, mainly due to its low carbon emissions. However, this section develops a more fine-grained understanding of legitimacy by scrutinizing the four dimensions of cognitive, normative, regulatory, and pragmatic legitimacy.

The previous section showed how the trend of newspaper coverage sentiment developed in the observational period and how wind power is embedded in its context. In this section, we scrutinize the model in more detail and analyze which topics contributed to different dimensions of legitimacy. We close the section by discussing these findings along the temporal dimension (Section 4.3.5).

4.3.1. *Cognitive legitimacy*

Cognitive legitimacy refers to the purpose of wind power and the problems it may be able to solve in general (Table 1). In that regard, within the newspaper corpus, wind power is promoted as a solution or alternative to address environmental problems arising in the context of the energy system: *Nuclear energy (#43)* and *climate change and climate policy (#6)* show negative sentiment ($ts = -0.09$ and $ts = -0.10$ respectively). Nuclear energy has been a controversial issue in the German energy system for decades, and climate change entered political debates in the 1990s (Hake et al., 2015). Wind power is framed as contributing to a power system with low carbon emissions and without nuclear power. Both topics support the cognitive legitimacy of wind power, where the purpose of wind turbines surpasses mere electricity production and aligns well with climate and nuclear energy policy. These topics also show that the interpretation of sentiment as an indicator for legitimacy must be made cautiously, as negative sentiment may also be associated with issue reporting, of which the focal technology is supposed to be a solution.

Additionally, the increasing prevalence of *wind power in culture and everyday life* (#17, $ts = 0.05$) shows that depictions of wind power plants increasingly enter media as a "normal" part of life and landscapes. Wind turbines are described in movie and book reviews and descriptions of everyday life. Such "taken-for-grantedness" positively contributes to cognitive legitimacy (Suchman, 1995).

However, there are also challenges of cognitive legitimacy on the grounds of misalignment of wind power with energy security aspects as in most developed countries, security of electricity supply is taken for granted in daily life (Yergin, 2012, p. 347). Intermittency of electricity production from wind plants is a regularly reported issue concerning the *security of supply* (#41) with negative sentiment ($ts = -0.10$; *Fig. 10*). Increasing installations of wind parks in the windy northern part of Germany make grid expansions necessary, a fact that further challenges alignment of wind power with its energy system context, as grid expansions become a cause for regular protests (*grid expansion between north and south Germany*, #25, $ts = -0.05$).

4.3.2. *Normative legitimacy*

Normative legitimacy refers to the guiding principles of what a 'good' wind power plant is (Table 1). As described in Section 3.7, we assume that topics covering conflicts are an indication of the misalignment of technology and institutions. We identified four topics associated with legal and regional conflicts (#3, 15, 23, and 33). Siting decisions concerning offshore wind infrastructure and the venue of a large wind power exhibition have been local issues in northern Germany (#15 and 23). *Legal conflicts and law-making* about wind power are reported regularly (#33). Within *regional conflicts with wind energy projects* (#3, $ts = -0.05$), local councils, state governments, and residents struggle over local wind projects during planning and installation. A correlation analysis (Fig. 8) reveals two major normative conflict lines we discuss in the following.

In the newspaper coverage of wind power, reports on *wind turbine effects on humans and animals* (#28) increase in prevalence over time. Wind power is reported to affect bird and bat life and human well-being by, e.g., infrasonic sound or shadow flicker. Ranking topics by prevalence reveals that their importance grew tremendously: ranked 39th out of 44 in 2009, the topic was ranked 5th in 2018 (Fig. 9). Additionally, its sentiment is the lowest among all topics ($ts = -0.22$). *Fig. 10* shows that in 2018, wind turbine effects on humans and animals have become the most substantial source of negative sentiment in wind power coverage. Negative topic sentiment, increasing prevalence, and its correlation to conflict topics indicate that wind turbines are perceived increasingly to conflict with societal and environmental values of preventing harm from humans and animals.

Another conflict line concerns wind turbines' placement in the physical environment (*Wind turbines interaction with physical environment: landscape, weather, infrastructure;* #37; $ts = 0.03$). The analysis of topic ranks shows that landscape issues have grown in importance over time (Fig. 9). Topic sentiment and close-reading of a subsample of texts show that framing of landscape conflicts is more delicate than potential effects of wind turbines on humans and animals that can refer to specific

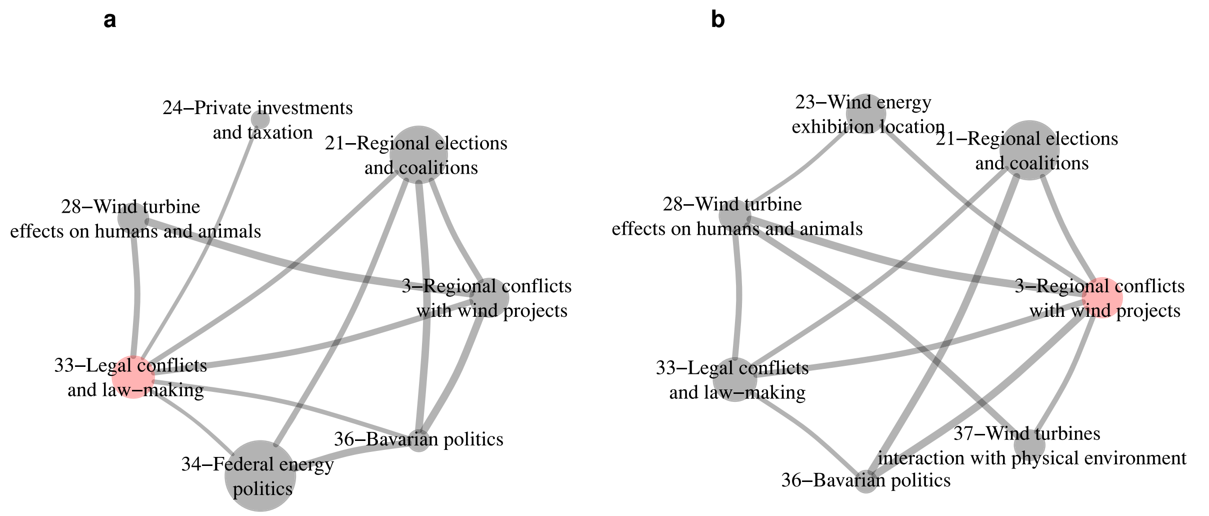

Fig. 8. Neighborhood graphs of two conflict topics. a) Legal conflicts and law-making (#33) relates to various political topics and to wind turbine effects on humans and animals (#28). b) Regional conflicts with wind projects (#3) relates to political topics as well as Wind turbines' interaction with physical environment: landscape, weather, infrastructure (#37), and wind turbine effects on humans and animals (#28). Only correlations higher than 0.5 are depicted.

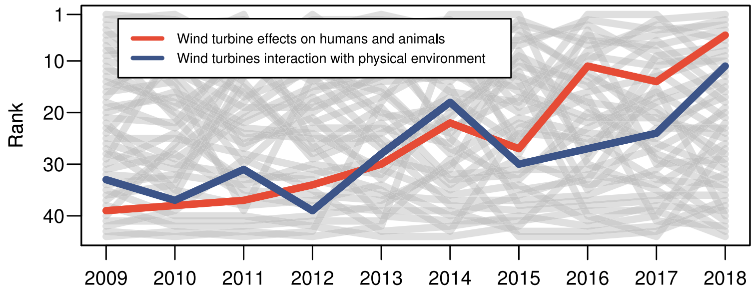

Fig. 9. Rank of the topics wind turbine effects on humans and animals (#28) and wind turbines interaction with physical environment: landscape, weather, infrastructure (#37) in the wind power agenda over time.

adverse health effects. Negative impacts of wind turbines on landscapes are often conveyed by contrasting wind turbines' placement to poetic descriptions of landscapes, contributing to a moderately positive topic sentiment. This finding aligns with findings from acceptance research that the perception of landscape issues is more ambiguous and depends on individual characteristics (Ellis and Ferraro, 2016, pp. 34–35). However, the topic's growing importance in the corpus and its relation to regional conflicts on wind turbine projects show that wind turbines are increasingly perceived as misaligned with landscapes and infrastructure.

Both topics point to increasing normative conflicts of wind turbines with their environment. They also indicate that legitimacy issues increase on a local level, where particular projects are materialized. Adverse effects on animals and humans and perceptions of landscapes are already known for a long time from the acceptance literature (Rand and Hoen, 2017). Misalignment with societal values is therefore not a challenge of legitimacy per se, but only becomes an issue when society acts upon it or the misalignment is "commonly perceived" (Geels, 2014; Markard et al., 2016). These results point to an increasing violation of norms by growing wind installations. In a densely populated country, space that can be used uncontroversially to install wind power plants is scarce. The growing number of wind turbines installed in forests since 2011 contributes to this argument (Bunzel et al., 2019).

4.3.3. Regulatory legitimacy

Regulatory legitimacy refers to the technical characteristics, and formal and regulatory standards wind power has to be aligned with (Table 1). In Fig. 8, we have seen that health, environmental, and landscape issues (#28, 37) in the deployment of wind power described above relate to *legal conflicts and law-making* (#33, *ts* = − 0.2), indicating that not only societal values are challenged by wind power, but also regulatory issues in moderating stakeholder interests come to the fore: The legal conflicts topic is associated with texts on lawsuits against regional wind power projects, but also general court rulings concerning wind power, including the rights of municipalities or environmental protection agencies with regard to the protection of wildlife, air traffic control, as well as conflicts between federal assembly and the federal parliament. In line with the increased prevalence of lawsuits, a recent study found that a large fraction of wind power projects is currently sued (Fachagentur Wind an Land, 2019). The largest fraction of lawsuits are filed by environmental protection organizations, citizens' initiatives, and private citizens (Fachagentur Wind an Land, 2019). These findings indicate that the increasing wind power expansion leads to frictions of local wind power projects with planning regulations that are within the responsibilities of municipal and state-level governments in Germany. However, it is difficult to precisely pinpoint a general regulatory misalignment, as projects are approved on a case-by-case basis by regional authorities.

This increasing misalignment of regional planning regulations and wind power also manifests in the links of *legal conflicts and law-making* to the different layers of national policymaking (Fig. 8) In *regional elections and coalitions (#21, ts* = − 0.01*)*, wind power is a conflict topic in coalition talks between parties. Many state governments have implemented distance regulations for wind power plants (Fachagentur Windenergie and Land, 2019), with the strictest regulation implemented in Bavaria in 2014 having substantial impacts on wind capacity development (Stede and May 2020). *Bavarian politics* (#36, *ts* = − 0.01) has even been identified as a separate topic. *Federal energy politics* (#34, *ts* = − 0.04) is often debated with the states in energy summits and through the legislative process in the federal assembly.

In the discussion of regulatory legitimacy, it is important to notice that we strived to delineate the underlying normative components of the political conflicts (normative legitimacy) from the related legal and political disputes. We distinguish between underlying societal norms (e.g., adverse effects on humans and animals) and the enforced laws and regulations to balance the conflict between norms and wind power.

4.3.4. Pragmatic legitimacy

Pragmatic legitimacy refers to the stakeholders' self-interest and the possibilities to participate in its deployment (Table 1). *Fig. 10* shows that from 2012 to 2014, *Electricity prices and EEG surcharge* (#12) played a decisive role in the newspaper coverage of wind power and showcased a low sentiment score (*ts* = − 0.12). The increasing numbers of installed renewable capacities led to an increase in the surcharge added to electricity bills to refinance the renewable support scheme. Our results show that wind power is associated with increased costs affecting the self-interest of a large share of the population and industry. While benefits of wind power manifest on an abstract level, such as its contribution to an emission reduction of electricity production, its costs become visible for electricity consumers on the annual bills. During that time, an analysis of political debates shows how renewable energy was framed as a burden to electricity consumers (Lauber and Jacobsson, 2015, pp. 154–155).

Furthermore, conflicts over participation in wind power are a common topic of articles associated with *legal conflicts and law-making* (#33). A significant event that showed the risks of profit participation for small investors was the case of the *Prokon insolvency* in 2014, with more than 75,000 persons holding profit participation rights (#5, *ts* = − 0.12). The Prokon insolvency also triggered a new law for the protection of small investors (*Kleinanlegerschutzgesetz*) that has been accused of severely limiting participatory options for civic engagement in renewable energy projects (Janzing, 2014). Cooperatives and regional energy concepts are only covered peripheral in the topic we labeled as *marketing of sustainable energy* (#30), whose prevalence decreased over time, even though such citizen groups have been described as a success factor of the German "energy democracy" (Morris and Jungjohann, 2016). Taken together, these three topics indicate that over time, the perception of options to participate in wind power development became more dominated by risks and conflicts, wherefore we conclude that pragmatic legitimacy decreased compared to the beginning of the observational period.

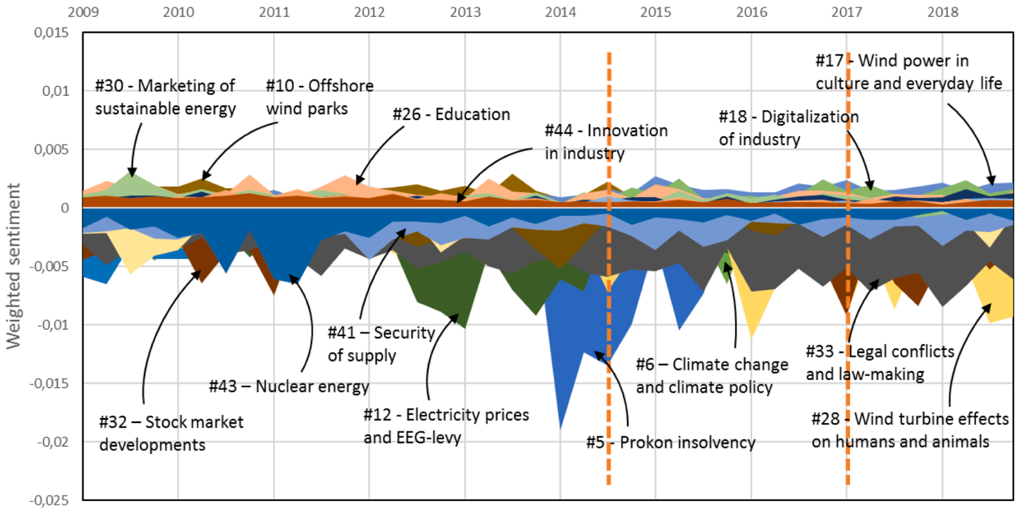

Fig. 10. Area graph of topic sentiment weighted by topic prevalence over time ($ts_\tau \cdot \mu_{t,\tau}$). Topic labels of topics contributing most to the development of sentiment are highlighted. We discuss three periods delineated by orange vertical lines in Section 4.3.5.

4.3.5. Discussion

In this section, we discuss the presented results collectively and interpret them along with historical events concerning their contribution to the legitimacy of wind power. In line with the results of the changepoint analysis, we distinguish three periods that structure the discussion (Fig. 3). The area graph (Fig. 10) depicts topic sentiment (ts), weighted by topic prevalence ($\mu_{t,\tau}$) over time (t).

4.3.5.1. 2009–2014. From the beginning, the wind power support by the EEG favored the development of wind power plants with increasing hub height, larger rotor diameters, and higher turbine capacities. Therefore, wind turbine projects increased their alignment with the centralized energy system. In this period, the prospective role of wind power in replacing nuclear energy after the nuclear incidents in Japan (2011), when fears about nuclear safety were highly prevalent that caused the decision for the German nuclear phase-out and a faster shift to renewable energies, contributes to the cognitive legitimacy of wind power by expanding the purpose of the technology (#43, *Fig. 10*). A source of misalignment with the centralized energy system are increasing wind turbine installations in the north, necessitating grid extension. Therefore, in 2011 a new legislation to align grid extension and renewable energy development was enforced (*Netzausbaubeschleunigungsgesetz, NABEG*).

Our results show that by the end of this period, two critical challenges to pragmatic legitimacy arose. The fast expansion of renewable electricity production increased the costs that electricity consumers bore via the EEG surcharge (#12, *Fig. 10*). Therefore, in 2014 the new government limited the expansion of wind power to target corridors and announced the introduction of auctions for wind power by 2017. Additionally, the financial issues and the final insolvency of Prokon in 2014 (#5, *Fig. 10*) vividly showcased the risks of participation in wind power, threatening pragmatic legitimacy.

4.3.5.2. 2014–2016. In this period, the Prokon case rumbled on and finally triggered the introduction of a law that limited possibilities of participation in 2015. Also, the prospective introduction of tenders might have contributed to the disappearance of cooperatives and citizen groups from the media agenda after the first period. Participation has always been an essential source of pragmatic legitimacy of the German energy transition (Morris and Jungjohann, 2016).

In newspapers, the newspaper coverage weights started to shift, and the adverse effects of wind power on humans and animals (#28, *Fig. 10*) and environmental impacts became more prominent on the agenda (Fig. 9), indicating increasing normative misalignment. As local planning law is the responsibility of state and municipal governments, wind power becomes controversial in state-level election campaigns (#21, 33, 36). The most prominent regulation arising on the state level is the so-called 10H-rule introduced at the end of 2014 in Bavaria that enforced a minimum distance of wind turbines to dwellings of ten times the height of the turbine (Stede and May 2020).

On the other hand, during that period, wind power was framed as part of climate change mitigation strategies around the Paris agreement 2015. As climate change faced decreasing attention until 2015, the Paris agreements seem to have contributed to the cognitive legitimacy of wind power (#6, *Fig. 10*).

4.3.5.3. 2016–2018. The EEG amendments in 2016 introduced tenders for wind power to increase economic efficiency, and to decrease technology costs further. However, tenders were seen as critical, particularly concerning their effects on the participation of civic groups or cooperatives. Their lower ability to diversify risk and lower economies of scale was seen as increased barriers for successful participation in tenders (Leiren and Reimer, 2018). In the pursuit of higher economic efficiency, the amendments risked pragmatic misalignment. However, governing parties were aware of such issues, and their coalition contract aimed at increasing participatory options (CDU, CSU, SPD, 2018).

In this period, adverse effects of wind power on humans and environmental interaction remain high on the agenda (Fig. 9, *Fig. 10*). The increasing prevalence of legal conflicts (#33, *Fig. 10*) contributes to the increasing perception of normative misalignment. A survey with wind project developers showcased a high fraction of wind turbines are being complained in court (Fachagentur Wind an Land, 2019), the majority due to alleged species protection issues.

When in 2018, the participation in tenders was well below the auctioned capacities, and wind expansion slowed down, an intense political debate broke loose in which court proceedings related to resident and environmental objections against wind power projects were held responsible for the slow-down. Therefore, a general distance of wind turbines to dwellings of 1000 m was proposed to reduce friction with local residents' interests (BMWi, 2019a). After the fierce intervention of wind industry associations, the draft was stopped before it became law. Subsequently, the responsible ministry issued an action plan to increase local acceptance and to speed up the permission processes for individual projects (BMWi, 2019b). Legitimacy issues of wind power, therefore, contributed to institutional change in its context.

4.4. Methodological reflections

In this section, we take a step back and reflect upon our approach's strengths and weaknesses to explore newspaper coverage and legitimacy. Specifically, we discuss which kind of information on legitimacy can be expected by assessing newspaper accounts of a focal technology. Furthermore, we discuss the prospects of the statistical methods employed to assess technology legitimacy.

First, we have already discussed why we think that newspapers are a particularly useful source to analyze legitimacy. From our results, we find that particularly issues in wind power's socio-political environment currently challenge the legitimacy of wind power. However, we would agree with the argument that newspaper coverage is an indicator more sensitive to detect friction in the socio-political environment, while it might be less sensitive for subtle changes in industry-internal dynamics. The main reason for that we see in the audience of newspapers. Issues addressed in newspapers must attract the attention of a large array of citizens, and socio-political issues are more likely to do so. Another source that may support the study of socio-political issues of legitimacy is social media such as Twitter or Reddit. We see the study of social media as a complementary source of legitimacy as very promising as it can include the variety of citizen's judgments of the focal technology while studying media more accounts for judgments of institutional evaluators (Etter et al., 2018). To gain more insights into legitimation strategies within the industry, one could include other sources, such as professional industry journals or stakeholder interviews. However, this was not the central goal of this study.

Second, the way we delineated context structures did not always divide the context along clear-cut system bounds, as, for example, it divided topics referring to politics into the socio-political environment and energy supply. The structures we have identified may well be described by Geels' (2014) triple embeddedness framework (TEF) as *industry regime, economic (task)*, and *socio-political environment*. However, a formal combination of TEF and technology legitimacy in a common framework was beyond this article's scope, mainly due to the partially different theoretical foundations of both concepts. We have to leave this potentially fruitful path of development for future research. On the other hand, the divide of context elements into the three environments proved highly informative, particularly regarding the separation of regional and federal political levels to different environments. The separation nicely shows which issues are focused on by different levels of policymaking.

Third, a shortcoming of our approach to measuring topic sentiment is that it is inherently independent of time and does not allow for changes in topic sentiment over time. While in the literature on product review sentiment, several approaches exist that combine sentiment analysis with topic modeling, none of them can also account for temporal changes in topics or sentiment (Alam et al., 2016; García-Pablos et al., 2018). As the temporal dynamics were of fundamental interest to our research endeavor, we decided to use STM that has proven significant performance improvements compared to classical topic modeling approaches when temporal structures are considered (Roberts et al., 2016a). We alleviated the dynamic limitations of our notion of topic sentiment by refining the model by a high topic resolution of 44 topics. The high topic resolution creates topics with a higher semantic coherence; therefore, we expect that changes in sentiment are also reflected in the topic structure changes. Our procedure of weighting topic sentiment with topic prevalence to create a temporal assessment of sentiment over time gives a good approximation of sentiment change.

5. Conclusions

The legitimacy of wind power is fundamental for policymakers to pursue ambitious climate and renewable energy targets. For stakeholders in the wind industry, legitimacy is a prerequisite to maintain stable relations with its environment and to ensure enduring resource flows. First and foremost, our study contributes to a detailed assessment of the legitimacy of wind power in Germany and may illustrate future developments in other national contexts.

To achieve that, we developed an approach combining natural language processing and statistics that incorporate the basic building blocks of technology legitimacy. Our approach was able to identify the contexts of wind power and quantify factors such as sentiment and salience for different topics or issues of wind power, and, equally important, allows us to analyze legitimacy's processual character. In investigating long-term processes of socio-technical change, scholars of technology legitimacy and sustainability transitions alike face the challenges of assessing large amounts of textual data over time and identifying changes of institutional arrangements within the data. Exploiting the advantages of STM to include covariates in estimating topic proportions, the set of methods we propose can account for both: large amounts of text and shifts of discursive patterns over time. Weighted sentiment serves as an indicator to identify arising controversies along the time axis. Another advantage of our approach is that we can assess the complete set of available articles from four newspapers. We can therefore reduce potential bias from single sources and include information that otherwise might be missed. We hold that our approach is very suitable to complement other methods in the pursuit of understanding technological and social change.

Legitimacy has been described as a social process in which legitimation first arises on a local level, diffuses to new situations, and finally becomes validated on a general level (Johnson et al., 2006). Our results indicate that a similar process may also be at play in the delegitimation of technology, a finding that contributes to the legitimacy literature and the socio-technical transitions literature that has increasingly become concerned with the politics of ongoing transitions (e.g., Markard, 2018). While wind power had a generally high level of legitimacy over the past decades, its legitimacy is increasingly challenged locally, where individual projects conflict with societal values and regional planning law. The case study showed that these conflicts increasingly diffuse into the general perception of wind power and enforce regulatory action on a general, federal level. Also, local protest groups started to collaborate on a federal level and become more involved in federal politics. While wind power still is a legitimate source of electricity mainly due to its role in reducing carbon emissions, these results point to the need for continued political action, particularly on the regional level, where recent scholarship revealed that particularly pragmatic and normative legitimacy might be highly location-specific (Rohe and Chlebna, 2021).

Our results point to an increasing misalignment between the energy supply system institutions and the socio-political environment context. More specifically, the energy supply goals aim to increase the number of wind turbines to decrease greenhouse gas emissions of energy supply. The support scheme employed to pursue these goals is inclined to favor large-scale wind turbines and wind parks. The introduction of renewable energy tenders in 2017 to foster competition and further price declines even contributes to that. However, when space for turbines increasingly gets scarce, the expansion of wind power leads to increased friction with environmental values, health concerns, and perceptions of landscapes.

Such misalignment has severe consequences for the engagement of actors in the wind industry. Since 2018, the installations of onshore wind turbines have reduced, and the participation in renewable energy tenders is below the advertised capacities. Within the federal wind power policy, a debate on minimum distances of wind turbines to dwellings broke loose, threatening to reduce areas available for installing wind turbines even further.

Our results show that regional issues with health, environment, and landscapes have increased in prevalence over the past years, challenging wind power's legitimacy on normative grounds. Additionally, the risks of financial participation have come to the fore, along with regulations that may have adverse effects on the participation of civic groups, such as the introduction of tenders for wind power. This participation has long been said to be a cornerstone of the success of the German 'Energiewende' (Morris and Jungjohann, 2016), and participation is an essential ingredient of pragmatic legitimacy. Policymakers, therefore, could more actively engage with issues of participation and pragmatic legitimacy to make the benefits of wind power more visible to residents and balance the perceived adverse effects of wind power.

While wind power may be a particular case in some instances, it is important to note that wind power is a technology of high importance in transitions towards electricity systems with low emissions. Local conflicts and acceptance issues are, in fact, not a German particularity but have been observed in various countries (Ellis and Ferraro, 2016; Rand and Hoen, 2017). Therefore, the case study is informative beyond national borders and points to the challenges of legitimacy that wind power might also face in other national contexts. Additionally, we think that the continuous reproduction of legitimacy is an issue that might also be encountered by other technologies in the context of maturing long-term sustainability transitions.

From our case study, additional promising directions for future research can be delineated. As our sample was restricted to national newspapers, future research could delve into local newspapers to identify local specifics of different conflicts. While acceptance research has arguably contributed to an understanding of local conflicts (Reusswig et al., 2016; Wolsink, 2007), analysis of local media framing issues can yield insights into how such conflicts are communicated and reproduced (Hindmarsh, 2014). Our study focused on one primary data source to study legitimacy. Future research could include different perspectives, such as expert interviews or sector-specific journals and online media outlets or social media. Apart from research on the specific case, future research can show whether our proposition to conceptualize technology context with Geels' triple embeddedness is fruitful to understand technology legitimacy better.

6. Author statement

JDH: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - Original Draft, Visualization; MO: Software, Validation, Investigation, Data Curation, Writing - Review & Editing; DK: Writing - Review & Editing.

Declaration of interest

None.

Appendix

Table A. 1: Topic labels and topic descriptions after close-reading a sub-sample of the most representative articles per topic.

#T	Topic	Summary	Mean Prevalence [%]	Rank
10	Offshore wind parks	Articles comprise news on offshore wind projects, on the start of projects, on the start of feed-in of power, or investment decisions and the repair of turbines.	4.71	1
19	Profit reports	Wind energy is mentioned in regular profit reports where different companies are presented along with key performance indicators.	4.10	2
34	Federal energy politics	The articles cover federal energy policy decisions: nuclear phase-out, the renewable energy act (EEG), offshore wind grid connections, and energy summits with the federal states. Some states are particularly interested in the EEG remuneration for wind and biogas.	3.95	3
9	Share of energy carriers in energy demand	The articles present the shares of energy sources in electricity and energy demand. They often emphasize the increasing shares of renewables in the electricity sector.	3.80	4
12	Electricity prices and EEG surcharge	The EEG surcharge is seen as a significant driver of the German electricity prices. While the surcharge decreases in 2017, household prices increase due to higher grid costs. Industry customers are exempted in parts. Wind power is associated with higher electricity prices.	3.36	5
21	Regional elections and coalitions	The articles discuss the politics of the federal states. Wind energy is a conflict topic between parties in the formation of governments and coalitions.	3.21	6
38	Transition of the energy system	The articles cover prospects and issues of an energy system transition holistically. The articles discuss the whole energy system, grids, demand, production, flexibility, storage, and heating and acceptance.	3.01	7
31	Concepts of societal progress	High probability articles comprise interviews or long comments of scientists or politicians on their visions of societal progress aligned with environmental values and climate change mitigation.	3.00	8
13	Wind power capacity development	The articles discuss the expansion of wind power capacities. From 2015 onwards, the new support regime is discussed along with its pull-forward effect and declining capacity installations in 2018.	2.86	9
17	Wind power in culture and everyday life	Several movies and books are discussed that include wind power plants in some form. Besides, descriptions of everyday life contain references to wind power plants.	2.84	10
25	Grid expansion between north and south Germany	Articles discuss the prospects of the planned grid expansion projects between north and south Germany. Most wind capacities are installed in the north, while electricity demand is also high in the south. There are bottlenecks in the transmission grid. Due to protests, the projects should install underground cables as opposed to overhead lines. The grid development plan (Netzentwicklungsplan) caused a peak in prevalence in 2012.	2.72	11
32	Stock market developments	The German stock market index (DAX) is reported regularly. The German turbine manufacturer Nordex is denoted in the TecDax. Over time, their stock price fluctuates with incoming orders and political developments. In 2018, Nordex was the weakest title in the TecDax (losing 57%).	2.72	12
42	Restructuring technology engineering companies	Articles discuss technology company developments. E.g., Siemens and General Electric restructure their companies by splitting up different fields. Siemens fusions its wind power company with Gamesa. Unions fear the loss of jobs.	2.69	13
22	International politics and cooperation	Articles discuss world politics and relations between countries, particularly China and the USA. The Desertec initiative forms a consortium of European companies to produce renewable power in northern Africa.	2.52	14

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#T	Topic	Summary	Mean Prevalence [%]	Rank
14	Wind turbine world market	Articles follow the wind turbine world market's development: A low number of orders after the financial crisis 2009 and corresponding overcapacities are observed. Large competition from 2012 leads to low prices, which relaxed in 2014 when companies have gotten more efficient. In 2017 the market became more insecure again: world trade issues, low prices, and the new support regime in Germany increase uncertainty, in which German companies focus more on the international market.	2.51	15
5	Prokon insolvency	The wind park operator and investor files bankruptcy in 2014, more than 75,000 persons held profit participation rights. Investors press fraud charges and delayed filing of insolvency.	2.42	16
33	Legal conflicts and law-making	Wind power is the subject of legal proceedings of different legal issues and is a conflict topic between the federal assembly and parliament. This includes proceedings due to siting decisions, species protection, or property rights.	2.36	17
39	Transformation of large electricity companies	The articles discuss the large transformations that German utilities and PNE (a wind power planner) go through. The companies' restructuring with the ongoing energy transition is discussed and goes in hand with personnel changes. Wind energy is part of their portfolios.	2.33	18
41	Security of supply	The articles discuss the conventional power plant fleet and its importance for maintaining the security of supply. Particularly in the south of Germany, there is not enough capacity, and the grid connections to the north are not strong enough. On weekends, electricity in wholesale markets is cheap or has negative prices. The intermittency of wind is related to all issues.	2.23	19
4	Innovation in energy generation	Articles cover the technology development of wind power plants and related technologies. For example, wooden towers or damage detection by robots are discussed, as well as kites for power production. Also, other innovative technologies, such as wave energy, are mentioned.	2.18	20
3	Regional conflicts with wind projects	Municipalities, federal states, and local courts influence the installation process. Some block the process; some try to steer. There are many conflicts within local councils/governments and with residents. Many articles focus on the southwest of Germany: Communities in Baden Württemberg or Rheinland-Pfalz.	2.17	21
6	Climate change and climate policy	Articles discuss climate change and different climate policy approaches, from the R&D expenditure to CO_2 markets and subsidies for technologies. The Paris climate agreement is discussed. Wind power should play a role in low-CO_2 electricity production.	2.16	22
2	Investment in wind projects and the wind industry	The articles discuss the many options of sustainable investment, including wind power. A variety of fonds exist, but the market is relatively small. Investors are increasingly interested in sustainable investment. Also, risks and opportunities are revealed.	2.15	23
23	Wind energy exhibition location	Schleswig-Holstein (SH) and Hamburg fight for years over the right to organize the world's largest wind exhibition/fair (2011–2013). The conflict concerns the federal state governments as well as fair organizers and wind turbine manufacturers and affects the relations between Hamburg and SH. Other policies of regional importance are mentioned.	2.13	24
30	Marketing of sustainable energy	The articles discuss different concepts of the provision of renewable energy to end-users. Different actors play a role: cooperatives, municipal utilities, companies offering renewable tariffs. Both heat and electricity are a topic, also coupled in regional energy concepts.	2.13	25
29	Acquisition of company shares	Companies buy shares or merge with other companies. Wind energy plays some role in all of the acquisitions.	2.11	26
43	Nuclear energy	The decisions on the phase-out of nuclear energy are discussed. Several countries decide to phase-out after the Fukushima nuclear accidents. Wind power is discussed as an alternative for power production, whose expansion should be enforced.	2.11	27
40	Shipyards demise	Shipyards in Germany struggle with the financial crisis in 2009; many shipyards search for new investors or go bankrupt. A wind manufacturer buys Nordseewerke to produce offshore wind components. The Nordseewerke file for bankruptcy in 2012.	1.92	28
8	Electro-chemical energy production and storage	Articles report innovation and research findings on fuel cells, electrolysis, methanation, osmosis power, redox-flow batteries. (Excess) wind energy can be stored with such technologies.	1.86	29
26	Education	The articles discuss study or education programs with a focus on renewable energies.	1.79	30
28	Wind turbine effects on humans and animals	Articles report that wind turbines endanger whales in the Baltic and northern sea by acoustic noise, (subsonic) noise is unhealthy for humans, or that wind turbines kill birds and bats.	1.71	31
44	Innovation in industry	The importance of innovation and progress in the industry for the German economy are emphasized. Different branches of the industry also contribute to the production of wind turbines by producing innovative materials.	1.67	32
37	Wind turbines' interaction with physical environment: landscape, weather, infrastructure	Articles describe landscapes and the positioning of wind turbines therein. Some wind turbines are in conflict with air traffic control. Also, storm damage is reported, or flashing lights on top of the turbines that have visual effects at night.	1.66	33
27	Miscellaneous international news	The articles discuss different countries and domestic issues, e.g., corruption or mafia structures, economic struggles, or remaining in the European Union (Brexit, UK). Wind power is a minor topic in most articles.	1.64	34
7	EU energy policy	The European Union implements the internal energy market, controls renewable support schemes, organizes summits for new energy efficiency measures, and adopts renewable targets.	1.57	35
15	Offshore-Cluster North Sea	Bremerhaven wants to build an offshore wind terminal and struggles over siting decisions and competition from Cuxhaven, where Siemens decided to build a plant for turbines in 2015, and Lower Saxony (Niedersachsen) plans an offshore wind cluster.	1.56	36
35	Sustainable urban development	Several projects are discussed that include renewable energies to urban development pursuing the creation of sustainable quarters in cities. Many projects convert existing infrastructure and include wind energy.	1.54	37
16	Wind park impact on shipping and coast	Articles discuss collision risks of ships and wind farms, new challenges for installers of offshore wind and wind parks on islands, as well as threats to the environment.	1.39	38

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#T	Topic	Summary	Mean Prevalence [%]	Rank
18	Digitalization of industry	Reports discuss the different aspects of the digitalization and usage of data analytics in the industry, including energy. Predictive maintenance and forecasting of weather conditions for wind turbines are an application.	1.36	39
11	SMEs in the German industry	The German industry is comprised of many SMEs. Those are presented here. Some also produce parts for wind turbines and plants.	1.26	40
36	Bavarian politics	The conflict between Aigner and Seehofer is a common topic in Bavarian energy politics. Also, election outcomes are discussed, and the Bavarian "energy dialog" within which Bavaria discussed the energy transition with stakeholders. Seehofer blocks the wind expansion by regulations that ensure a minimal distance to dwellings.	1.22	41
1	Alternative fuels for transport	Articles discuss electric vehicles, but also hydrogen fuel cell vehicles for personal transport. (Excess) Wind energy could be used to charge cars and produce hydrogen.	1.20	42
20	Natural resources utilization	Articles report on rare earth elements, agriculture, and bioenergy. Wind energy is regularly mentioned as an application field of rare earth materials and compared to bioenergy generation. From 2016 onwards, reports on environmental issues with insects or birds due to herbicide and insecticide usage and wind energy.	1.18	43
24	Private wealth building and taxation	Analysis of private investments profitability and tax advantages.	1.00	44

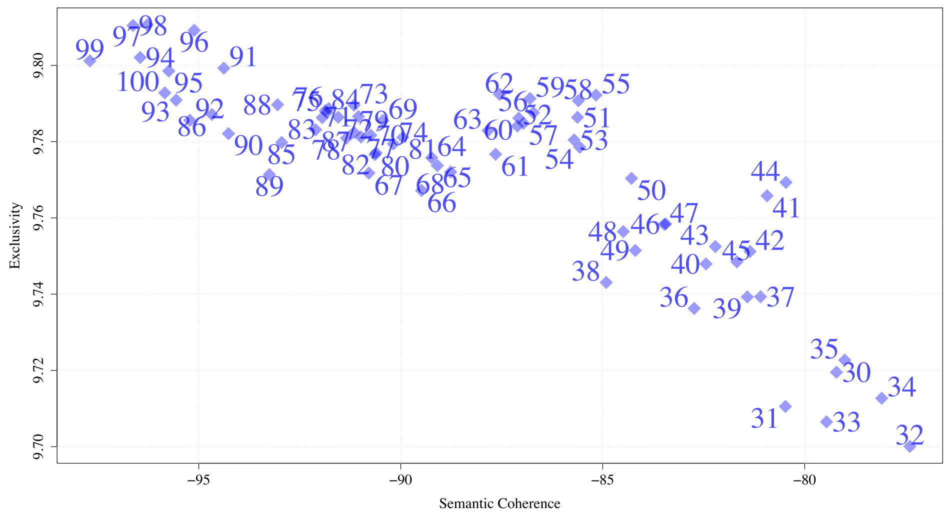

Figure A. 1: Semantic coherence and Exclusivity of topic models from 20 to 100 topics, given a spectral initialization.

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