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Original research article

Exploring the role of phase-out policies for low-carbon energy transitions: The case of the German *Energiewende*

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ABSTRACT

The energy sector plays a significant role in reaching the ambitious climate policy target of limiting the global temperature increase to well below 2 °C. To this end, technological change has to be redirected and accelerated in the direction of zero-carbon solutions. Given the urgency and magnitude of the climate change challenge it has been argued that this calls for a policy mix which simultaneously supports low-carbon solutions and also deliberately drives the discontinuation of the established technological regime. Yet, the effect of such phase-out policies on the development and diffusion of low-carbon technologies has received little attention in empirical research so far. This paper addresses this gap by taking the case of the transition of the German electricity system towards renewable energies – the so-called *Energiewende*. Based on a survey of innovation activities of German manufacturers of renewable power generation technologies conducted in 2014 it explores the impact such destabilization policies – most prominently Germany's nuclear phase-out policy – may have on technological change in renewable energies. By drawing on descriptive statistics and combining insights from earlier regression analyses we find evidence that Germany's nuclear phase-out policy had a positive influence on manufacturers' innovation expenditures for renewable energies and was seen as the by far most influential policy instrument for the further expansion of renewable energies in Germany. The insights resulting from our explorative analysis have important implications for the literature on policy mixes and sustainability transitions regarding the 'flip sides' to innovation and the crucial importance of destabilization policies for unleashing 'destructive creation'. We close by discussing policy repercussions for ongoing debates on policies for accelerating the phase-out of coal to meet climate change targets.

1. Introduction

The energy sector plays a significant role in reaching the ambitious climate policy target of limiting the global temperature increase to well below 2 °C, as agreed at COP21 in Paris [1]. To this end, technological change has to be redirected and accelerated in the direction of zero-carbon solutions for which policies play a key role [2–5]. More precisely, the existence of various market and system failures calls for policy mixes including demand pull, technology push and systemic instruments [6–9]. In addition, it has increasingly been pointed out that policy mixes should not only include instruments promoting green niche innovations, such as renewable energies, but that in addition such mixes should also target the destabilization of established regimes [10,11].

The literature on sustainability transitions [12] has considered this 'flip side' to innovation in the form of 'destabilization' of technological regimes [13,14]. More recently, attention has also been given to the 'discontinuation' processes aiming at the phase-out of certain technological trajectories [15–17]. In addition, literatures related to overcoming 'lock in' and incumbency in socio-technical transitions have addressed this phenomenon [18–20]. These contributions are typically based on historical case studies analyzing the different influencing factors that lead up to a particular 'window of opportunity' where a discontinuation policy is realised, offering preliminary insights into the understudied areas of deliberate destabilization and technological discontinuation. Yet, the effect of such destabilization policies on the development and diffusion of green alternatives has received limited attention in empirical research so far.

Research on discontinuation is timely, with discontinuation policies emerging across the energy policy landscape. In the wake of the Fukushima accident and significant long-standing problems regarding cost overruns and financing in the nuclear sector, several countries besides the famous case of Germany are also implementing nuclear phase out policies including Belgium, Scotland, Switzerland, Taiwan, and South Korea [21,22]. In the context of the perceived need to 'accelerate' transitions [23], the phase out of coal is also becoming a prominent policy objective, for example with the UK, the Netherlands, and Quebec among countries and regions proposing such policies [24–26]. Phase out policies are also taking place in the transport

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sector, e.g. with Norway proposing to phase out petrol and diesel cars by 2025 [27]. Yet, despite the relevance of phase out policies in sustainability transitions, so-called 'flip sides' to innovation [14], including destabilization and discontinuation, remain under-studied.

In this paper we address this knowledge gap using the case of the transition of the German electricity generation system towards renewable energies – the so-called *Energiewende* [28–30]. We have chosen this example because it represents a sustainability transition governed by a policy mix which not only includes policies supporting renewable energies but also destabilization policies – most prominently the nuclear phase-out policy set for completion in 2022 [31–33]. Our explorative analysis adds to existing empirical studies which have focused on the economic and technical assessments of the impacts of the nuclear phase out for energy systems [34–40]. Given that the power sector has traditionally been a supplier dominated sector [41] we draw on findings of a survey of innovation activities of German manufacturers in renewable power generation technologies. By combining descriptive statistics and insights of earlier regression analysis [42,43] we explore the impact of the nuclear phase-out policy – as an example of a decisive discontinuation policy with a history of more than ten years – on the development and diffusion of renewable energies. Understanding the effects of the nuclear phase out in Germany on technological change has international policy relevance in terms of providing insights for the increasing number of countries considering phase out policies to accelerate the decarbonization of their energy system.

In the remainder of the paper, we briefly summarize the literature on destabilization / discontinuation policies (Section 2), and then describe the research case (Section 3) and methodology (Section 4). In the main part of the paper we present the results of our exploration of the impact of the German nuclear phase-out policy on technological change in renewable energies (Section 5). We close with a discussion of the theoretical, methodological and policy implications for the governance of the decarbonisation of energy systems (Section 6).

2. Literature review

"Discontinuous change" is a core concept in innovation studies [44,45], where technological change occurs in waves of 'creative destruction' in which old technologies are replaced by the new [46]. While the end stage of a technology's life is recognized within this framing this is usually encapsulated as a consequence of the disruptive force of new technologies and business models rather than discontinuation being driven by policy. Typically, this literature has been limited to discontinuity in terms of specific firms or actors [47]. In contrast, there has been some work in policy studies focused on 'policy termination' and 'policy dismantling' [48,49], but this literature tends to look at termination in relation to the withdrawal of funding for certain policy initiatives, rather than from the perspective of broader technological systems. That is, little has been written concerning broader policy processes related to the ending of certain technological trajectories [16,50].

While the broader literature on sustainability transitions includes 'destabilization' of dominant (and unsustainable) 'socio-technical regimes' as a key concept, this has usually been encapsulated as resulting from the emergence, protection and diffusion of new niche-based sustainable technologies or innovations [51,52]. However, there has been increasing attention to the ways in which the dynamics and stability of the regime level curtail sustainability transitions from developing at adequate rates to meet ambitious technological and environmental targets [53–55]. Revisiting key notions of 'path dependency' [56] and 'lock in' [20], attention has turned towards understanding the dynamics of the regime level in terms of strategies of incumbent actors [57–60] (also see Johnstone et al. in this issue) and active 'regime resistance' preventing or delaying transitions [18]. Given the observed stability at the regime level the destabilization of the regime through endogenous and exogenous economic and political pressures has become a recent focus in the transitions literature. An early example is the historical analysis outlining the evolution of the destabilization of the coal regime in the UK [13,14].

Within this context, Kivimaa and Kern argued that policy mixes for transitions ideally "include elements of 'creative destruction', involving both policies aiming for the 'creation' of new and for 'destabilizing' the old." [10]. They have identified four entry points for such destabilization policies impacting the 'motors of creative destruction': control policies (such as carbon trading), significant changes in regime rules (such as electricity market reform), reduced support for dominant regime technologies (such as reduced public funding for research and development on coal (R&D)), and changes in social networks as well as the replacement of key actors (such as the substitution of incumbents with new entrants in policy advisory councils). The EU emission trading system (EU ETS) is one example for such a control policy, as it establishes a carbon price signal which can help leveling the playing field between carbon-intensive and low-carbon alternatives. However, it has been increasingly argued that these market-based approaches have not been sufficient in promoting energy transitions at the rates necessary to meet ambitious climate change targets [61–63]. Given various barriers, lock-ins, path dependencies and resistance to low-carbon energy transitions further government intervention in steering them is required [4,20,64–71] (see also Bergek et al. in this issue).

'Discontinuation' has also been a recent interest in the governance literature which focuses on the governance processes involved in the active disengagement "from an on-going policy or governance commitment" [16:112]. This research draws on a conceptual governance heuristic looking at the constellations of actors, issues, and 'windows of opportunity' which can lead to the rare policy moments when it becomes feasible for governance to enact a ban or phase out policy. The analysis of multiple historic case studies of differing technological areas enabled a better understanding of the economic, technical, political, and cultural drivers that enable discontinuation to be realised in particular contexts.[1] Yet, while these cases are concerned with the discursive and material factors through which discontinuation policy is realised and managed as an interactive governance process, they generally end once a policy decision has been reached.

Yet, despite being generally rare and politically challenging to enact [15] phase out policies are becoming a growing political reality in the context of greater urgency in reducing greenhouse gas emissions. For example, increasingly policy makers at national and the EU level are suggesting that a more rapid coal phase out through more proactive governmental intervention will be necessary if ambitious climate goals are to be met [72]. Indeed, there is an emerging consensus that the use of unabated coal generation must rapidly decline over the next decade if temperature rises shall be stabilized at 2 °C [73]. In addition, a number of countries are now phasing out or making plans to phase out nuclear energy, such as Belgium, Germany, Scotland, South Korea, Switzerland, and Taiwan [21,22]. Therefore, given the contemporary relevance of destabilization policies for energy transitions it is a question of high policy relevance to better understand the impacts of such dedicated phase-out policies.

Yet, while there is ample evidence on the so far limited impact of the EU ETS as a market-based control policy on low-carbon innovation [62], there is little empirical evidence on the impact of other destabilization policies, such as phasing out nuclear or coal, on technological change in competing low-carbon technologies. To close this research gap, in this paper we examine the case of the German *Energiewende* [28–30,74], with a focus on the impact of its dedicated nuclear phase-out policy on the development and diffusion of renewable energies. We have chosen this research case because it provides one of the few examples of dedicated phase-out policies which has been in place for over a decade and has been embedded in the context of a broader policy mix aiming at the decarbonization of the energy system [6,75,76]. This empirical case is relevant to emerging literatures on policy mixes particularly in relation to the effects of understudied 'flip sides' to innovation, and to broader European policy contexts where whether or

[1] The case studies included bans on DDT [50], the phase-out of incandescent light bulbs [105], the internal combustion engine [15] and nuclear policy in the UK and Germany [17].

not nuclear phase out is being implemented is becoming a crucial point of difference between countries [77,78], yet the effects such a policy has on the development of renewable energies is under-examined.

3. Research case

For exploring the impact of phase-out policies on technological change we use the case of the transition of the German electricity generation system towards renewable energies – the so-called *Energiewende* – with its target of reaching at least a level of 80% electricity generation by renewable energies by 2050 [29,32]. This long-term target is supported through a rich instrument mix [33], with the core instrument being the Renewable Energy Sources Act (EEG).

Introduced in 2000 the EEG established, among others, technology specific feed-in tariffs guaranteed over a period of 20 years [66]. Based on extensive monitoring and evaluation the EEG has been regularly amended since then, leading to a number of policy changes, including the increase of expansion targets for renewable energies and updates of feed-in tariffs based on techno-economic improvements and deployment success. In addition, unexpectedly positive developments in solar PV between 2009 and 12 led to exceptional adjustments in the EEG, which combined with global competition caused some turmoil and consolidation of the Germany PV industry [79,80]. The EEG reform of 2014–also dubbed as EEG 2.0–continued to implement the government's increased focus on cost-effectiveness [81]. For example, technology specific expansion corridors were introduced, and pilots testing a system change from feed-in tariffs to auctions were initiated, using open space PV as the first example.[2]

Aside from the EEG also many complementary policies have been in place for a long time, such as public R&D support, funding programs by the German development bank KfW (Kreditanstalt für Wiederaufbau), or grid expansion measures [33]. Together with the long-term targets and the EEG, this rich policy mix has stimulated rapid technological change in renewable power generation technologies [80,82,83]. This includes the emergence of a strong renewable energy industry which has created jobs and exports its products and services abroad [84,85]. Also, the renewable energy sector has been highly innovative, as measured by patent applications, scientific publications or new products and processes [83,86]. Finally, the share of renewable based electricity generation has increased from 3.4% in 1990–31.6% in 2016, with faster diffusion rates than originally foreseen [87].

Yet, what makes the German *Energiewende* an ideal research case to study the impact of destabilization policies is that the German policy mix also includes destabilization policies. The most prominent one is Germany's nuclear phase-out policy until 2022 which was initially negotiated with incumbents by the Red-Green Schroeder government and adopted in 2002. After a short interlude in 2010/11 it was by and large reinstated by Merkel's conservative-liberal government in 2011 as a reaction to the Fukushima incident. Since then, the nuclear phase-out policy has enjoyed cross-party support, thereby sealing the fate of nuclear energy in Germany [17,31]. In addition, the EU Emission Trading System (EU ETS) represents another destabilization policy by putting a price tag on greenhouse gas (GHG) emissions of regulated sectors, including energy. However, given the large accumulated surplus of EU allowances this EU control policy and its innovation impact has remained rather weak [62]. Finally, the introduction of policies for phasing out coal and lignite has only started to be put on the political agenda prior to the COP21 negotiations at Paris in 2015. Yet, their implementation has been faced with significant resistance by industry, unions and regional policy makers, despite Germany's gap in achieving its 2020 GHG reduction target [88]. This political deadlock in overcoming the 'Climate Paradox' of rising CO_2 emissions from high load factors of existing coal and lignite plants puts into question the political will of the German government for achieving its ambitions GHG reduction target of 40% by 2020 and 80% by 2050 [89].

4. Methodology

4.1. Data collection

In order to explore the impact of destabilization policies on the development and diffusion of renewable energies we draw on the results of a survey of innovation activities of German manufacturers and suppliers in renewable power generation technologies conducted within the GRETCHEN project. While the details of the survey implementation are described elsewhere [42], here we summarize some of the key points. First, a dataset of all German companies active in the supply chain for manufacturing renewable power generation technologies was compiled based on different data sources (e.g. business directories, industry association memberships, business fair catalogues), resulting in the identification of 1092 manufacturers active in producing components, equipment and final products for on- and offshore wind, solar PV, hydropower, bioenergy, wave and tidal energy, geothermal energy and concentrated solar power (as of 2013/2014).[3] Second, building on the Community Innovation Survey (CIS) conducted within the EU a questionnaire was developed which specifically included novel questions on the policy mix, in line with a broader understanding of the term [6] and drawing on qualitative insights on offshore wind [65]. Specifically, the survey attempted to capture policy mix characteristics, such as credibility, consistency, coherence and comprehensiveness, but also included questions on the design features of the EEG and on the targets for the expansion of renewable energies. Third, the innovation survey was conducted by a specialized service provider in the summer of 2014 as a computer assisted telephone interview (CATI) with top level management representatives. It achieved a response rate of 35.7% of all German manufactures of renewable power generation technologies (n = 390), including both new entrants but also incumbent players that have redirected their activities towards emerging green niche markets.

4.2. Data analysis

In this paper, we draw on insights from descriptive statistics [90] and combine findings from regression analyses [42,43] to explore the impact of the nuclear phase-out policy on technological change – differentiated in innovation and diffusion – in renewable energies in Germany, as is depicted in Fig. 1. In the following, we provide a summary on these three building blocks of our explorative analysis.

First, the descriptive analysis served as basis for generating an overview showing the composition of the sample, in terms of firm size, location and technology portfolio, the perceptions of respondents regarding the policy mix, their innovation activities and expenditures, and further information [90]. As a third of the respondents were active in more than one renewable power generation technology, respondents were asked to answer the survey for their main technology only, which led to half of the responses referring to solar PV (37.2%), biogas (22.3%) and onshore wind (17.4%). As is typical for the German manufacturing sector, there is a large share of small and medium sized enterprises (ca 70% SME) and many of them sell their products at home and abroad (on average ca 39.7% of sales in 2013 were exports). Also in line with trends in manufacturing the large majority of the companies had performed innovation activities in 2011–13 (ca 82%), leading to product innovations (ca for 75% of the respondents) as well as process innovations (ca 66%).

[2] The most recent changes of the EEG in 2016 have continued this policy paradigm change in German renewable energy policy by rolling out auctions as standard allocation mechanism across all technologies – with exceptions being in place for small players, such as households – and by putting a greater emphasis on remaining within the envisaged, rather conservative expansion corridors. Consequently, it has been argued that the government is now favoring investments by incumbents and slowing down the *Energiewende* [104], despite the large majority of Germans demanding a faster transition towards renewables [106].

[3] This number is in line with Doblinger et al. who identified 1,208 manufacturers and project developers active in renewable energies in Germany in 2012 [107].

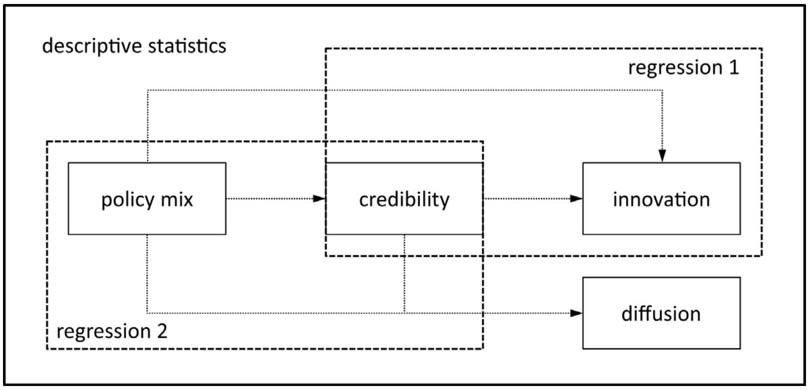

Fig. 1. Schematic illustration of combination of descriptive and regression analysis.
Note: Sources of analysis: descriptive statistics [90], regression 1 [42], regression 2 [43]; the 'policy mix box' includes, among others, the nuclear phase-out, policy mix characteristics other than policy mix credibility (which is highlighted in its own box), the EEG and its design features.

Second, regression 1 aimed at answering the research question regarding whether policy mix characteristics matter for innovation, namely consistency, credibility, coherence and comprehensiveness [42]. Taking manufacturers innovation expenditures for 2014 and 2015 as a dependent variable, and firm-external and firm-internal factors as explanatory variables, a "corner solution" bivariate Tobit model was employed to specify the regression equation for innovation expenditures in 2014 and 2015 (using STATA). Firm-external factors focused on the effects of market demand (measured by global sales), public support for technology push (measured by German and European subsidies received in 2011–2013) and the effects of policy mix characteristics (as perceived by manufactures at the time of the survey, i.e. 2014). Regarding the latter, the study differentiates between the consistency of the policy strategy, of the instrument mix and of the overarching policy mix; national and sub-national policy mix credibility; the informational and procedural coherence of policy processes; and the comprehensiveness of the instrument mix. In terms of firm-internal factors the study includes firm size (measured by total global sales in 2013), experience (measured by number of years the manufacturer has been active in the main renewable power generation technology) and technology portfolio (controlling for wind power). The study finds evidence that the consistency of the overarching policy mix and the credibility of the policy mix at the national level have a positive impact on innovation expenditures, and suggests a strong interaction effect between the two. As could have been expected from other studies, both demand pull as well as technology push instruments are positively correlated with innovation expenditures, as are firm size, experience and technology portfolio.

Third, inspired by the findings of earlier qualitative work and regression 1 regarding the relevance of policy mix credibility – i.e. the reliability and believability of the policy mix – regression 2 sets out to investigate the determinants of this credibility [43], thereby also aiming to shed more light on the links with other policy mix characteristics, in particular consistency. The dependent variable 'credibility' was created through conducting an exploratory factor analysis with varimax rotation for seven credibility items which ultimately enabled the construction of an internally consistent scale aggregating four of these items.[4] The explanatory variables for the linear regression (performed with SPSS) included other characteristics and elements of the policy mix. Regarding the former, and similarly to regression 1, the study differentiates between the consistency of the policy strategy, of the instrument mix and of the overarching policy mix; the informational and procedural coherence of policy processes; and the comprehensiveness of the instrument mix. Regarding the latter, the study distinguishes between the policy strategy (focusing on (the reduction of) the ambitiousness of the target for renewable energies), eight policy instruments (including two destabilization policies, namely the nuclear phase-out and the EU ETS, see Fig. 5), and the design features of the Renewable Energy Sources Act (EEG). The study finds that manufacturers' perceptions on the nuclear phase out add significantly to explaining the variance in perceived policy mix credibility. In addition, there is also strong evidence that the adopted changes in the EEG design features had a negative impact on credibility. Furthermore, the study confirms a positive correlation between credibility and consistency as well as with the coherence of policy processes– both regarding informational and procedural coherence of policy processes.

4.3. Combination of analysis

In this paper, we are combining the insights from these three analyses to explore the link between destabilization policies and technological change. In a first step we explore the innovation impact by combining insights from the assessments of companies regarding the impact of various aspects of the policy mix [90] with insights from both regression analyses 1 [42] and 2 [43]. In a second step, we explore the impact of destabilization policies on the diffusion of renewable energies by drawing on the direct assessments of companies regarding the expected impact of various policy instruments – including the nuclear phase-out – on the future expansion of renewable energies [90]. Clearly, this analysis is not free from limitations and results should thus be interpreted with caution. Aside from the limitations outlined in the separate papers for regression analyses 1 [42] and 2 [43], we want to particularly emphasize that our explorative analysis cannot reveal causal explanations but at best only provides correlations. Also, while both regressions are sufficiently distinct and can be logically combined, some overlaps regarding policy mix characteristics remain. We argue, however, that this first empirical exploration into the link between destabilization policies, and in particular the findings regarding the relevance of the nuclear phase-out, provide some important insights for policy makers interested in creative destruction as well as directions for future research.

5. Results

In this section we investigate the link between destabilization policies and technological change by first exploring the impact of the German nuclear phase-out and other destabilization policies on innovation in renewable energies, and then turn to their impact on diffusion.

5.1. Impact on innovation

Exploring the innovation impact of the German nuclear phase-out policy is not straightforward, as this policy has not been included in a direct question on the link between policy and innovation, but only the EU ETS as another destabilization policy. More precisely, innovating manufactures were asked to assess the influence of different aspects of the policy mix for their innovation activities in the period 2011–13 (see Fig. 2). The results show that domestic and foreign demand pull instruments are seen as most influential elements of the policy mix – both today‘s and expected future demand pull

[4] These four items included: Concerning the increase of electricity generation from renewable energies in Germany, there is (1) a clear political vision, (2) a firm political will, (3) unambiguous political signals and (4) strong support from the German government.

instruments – which is in line with findings of the eco-innovation literature [91–94]. However, the findings also show that the renewable expansion targets for the year 2025 and a credible commitment to the *Energiewende* is seen as almost equally important aspects of the policy mix. Interestingly, these demand pull instruments and the policy strategy with its long-term target were viewed as more important than German and EU R&D support for renewable energies – which had been received by roughly a quarter of respondents [90]. As could have been expected from earlier studies [62], the EU ETS was deemed as the least relevant political factor for determining companies' innovation activities. Finally, to contrast the importance of political factors with the importance assigned to market factors companies were also asked about the influence of the demand for innovations from their customers, which was seen as the most influential factor, thereby highlighting that in the supplier driven electricity sector the policy mix drives innovation by influencing demand.

customers and unfavorable foreign support were seen as the lowest obstacles to innovation, while the lack of incentives from the EU ETS ranged in the middle field.

Given that a credible political commitment to the *Energiewende* (or perceived lack thereof) was among the top 2 most influential political factors in determining companies' innovation activities, in the following we take a closer look at the development of this perceived policy mix credibility, and then turn to its determinants – which will eventually lead us to destabilization policies, and in particular to the nuclear phase-out. As can be seen in Fig. 4, manufacturers were most aware of the political will to promote power generation from renewable energies at the time of the nuclear phase-out reinstitution after Fukushima (2011/12). However, companies think this credibility of the policy mix supporting renewable energies has ebbed

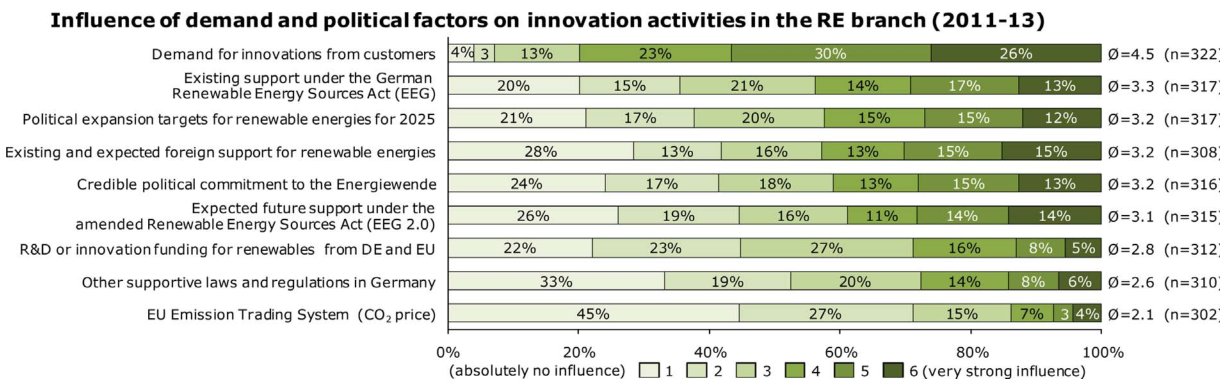

Fig. 2. Company assessment of influence of policy mix on innovation (ranked by strength).
Source: [90]

Manufactures who had no innovation activities in the period 2011–13 were asked a similar question about the influence of the above mentioned political factors on their decision not to pursue any innovation activities in renewable energies in that period. As can be seen in Fig. 3, what non-innovators missed most was a credible political

away since then and expect it to stabilize at a fairly low level with the 2014 amendment of the EEG .[5]

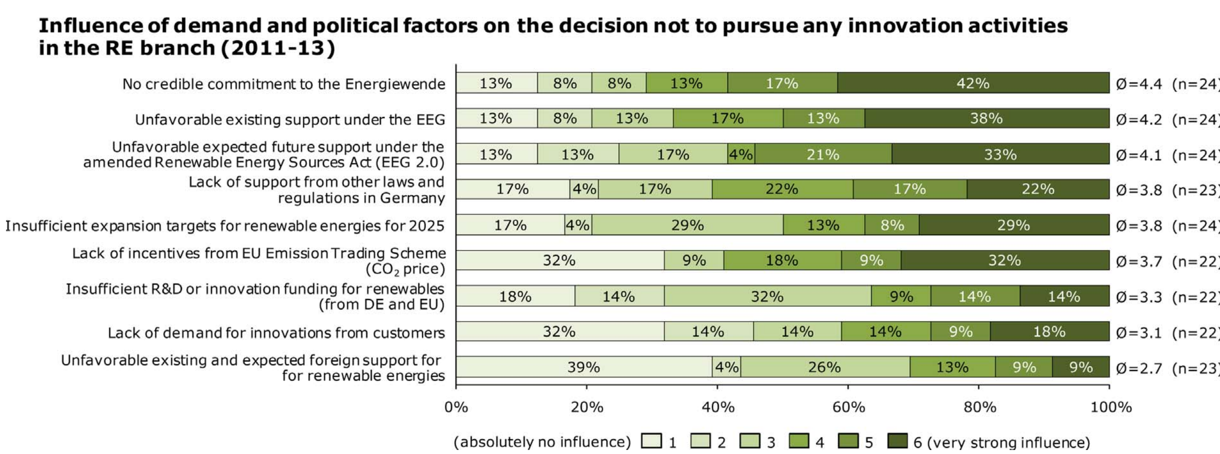

Fig. 3. Company assessment of influence of policy mix on decision not to innovate.
Source: [90]

commitment to the *Energiewende*, further underlining the relevance of policy mix credibility for stimulating innovation. They also criticized the insufficient support under the German Renewable Energy Sources Act (EEG). In contrast, the lack of demand for innovations from

[5] Because it may be quite difficult to accurately remember the perceived strength of the political will, with the situation today potentially blurring past perceptions, this concern was alleviated by asking respondents about perceptions at key points in time (events or issues which had been heavily debated and covered in the media back then, such as the nuclear phase-out after Fukushima or discussions initiated by the former ministers for the environment and the economy on an electricity price brake).

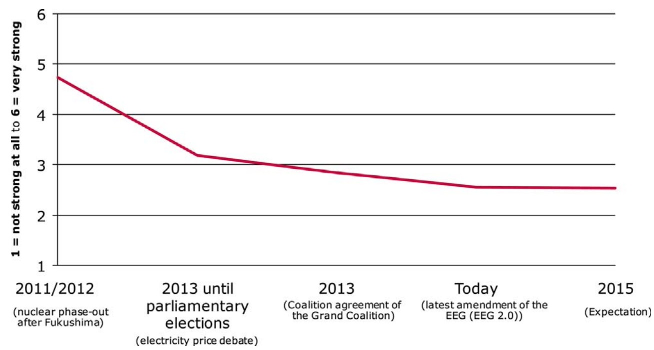

Fig. 4. Perceived political will of the German government regarding expansion of renewable energies (n = 368).
Source: [90]

Given the indicated relevance of credibility for companies' innovation activities Rogge and Schleich included a variable measuring the perceived credibility of the policy mix in 2014 in their regression analysis [42]. This credibility variable distinguishes between the national and sub-national levels, and draws on companies' assessments of different items at the time of the survey (2014). The regression analysis, which also includes variables for technology push and demand pull instruments (both significant) as well as other characteristics of the policy mix (only its consistency is significant), indicates that those companies which view the policy mix at a national level as more credible invest more in R&D in renewable energies. However, the analysis also shows a strong interaction effect between the overarching consistency of the policy mix and credibility at the national level.[6]

Given that policy mix credibility seems to be a potentially important determinant for companies' innovation activities and expenditures, Rogge and Duetschke investigated the reasons why companies belief (or not) in the policy mix, i.e. what determines the different perceptions about the strength of the political will of the German government in promoting the expansion of renewable energies [43]. They find that, among others, the changes in the design of the German EEG negatively impact on the perceived credibility of the policy mix. Regarding other policy instruments they find strong evidence that the perception of the nuclear phase-out policy (on which almost all manufacturers had an opinion) matters for explaining perceived policy mix credibility. They also find, albeit weak evidence that the EU Emission Trading System may potentially be positively correlated with credibility. This shows that the implementation of destabilization policies positively contributes to companies' perceptions of the credibility of the policy mix, but depends on their stringency. This in turn leads to higher investments in corporate R&D in renewable energies, thereby suggesting an indirect link between destabilization policies – at least in the form of the nuclear phase-out in Germany – and low-carbon innovation. However, this link is not a direct one but seems to operate through its influence on the credibility of the policy mix, which in turn seems to matter for innovation.

5.2. Impact on diffusion

After establishing that destabilization policies – at least in the case of the German nuclear phase-out policy – may positively impact on low-carbon innovation, we now turn to the question whether such policies might also have an impact on the diffusion of renewable power generation technologies. To answer this question, we draw on the assessments of the surveyed manufacturers regarding their support for the expansion of renewable electricity generation (see Fig. 5).[7] Interestingly, German-based manufacturers believe the nuclear phase-out offers the strongest support for the diffusion of renewable energies – with the EEG, R&D support and training programs coming in second place. In contrast, the EU Emission Trading System hardly seems to have any effect. The same holds for the framework conditions for fossil power generation technologies, where no specific phase-out policy was in place at the time of the survey .

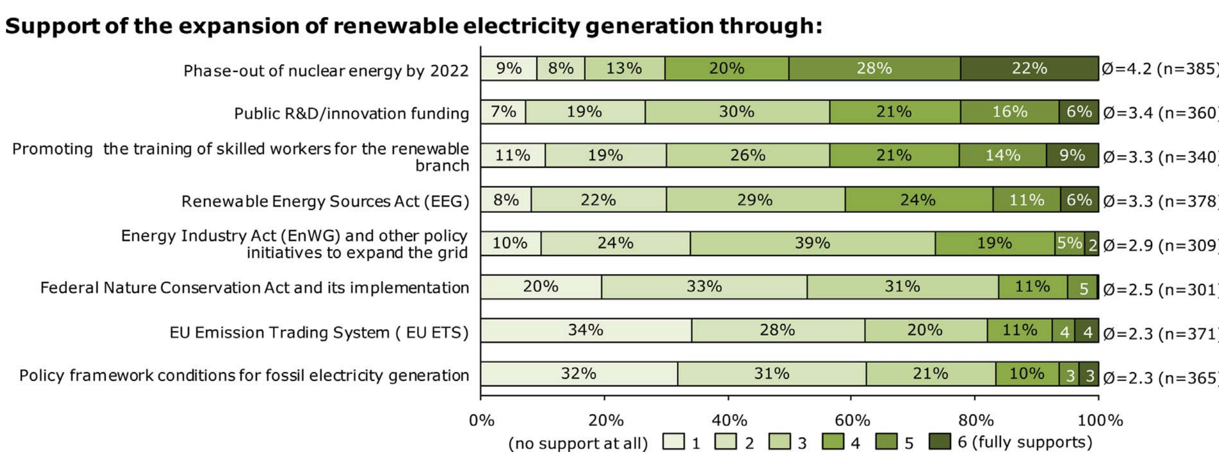

Fig. 5. Company assessment of impact of policy instruments on diffusion of renewable energies.
Note: Respondents were asked to assess the instruments in the following order: EEG, R&D funding, EnWG/grid, training, nature conservation, EU ETS, fossils, nuclear phase out.
Source: [90]

6. Discussion and conclusion

In this paper we have explored whether the German nuclear phase-out policy originally introduced in 2002 and – after a short interlude in

[6] In the full model which combines all policy mix characteristics as well as further firm-external and firm-internal factors, only policy mix consistency and its interaction effect with credibility at the national level remain statistically significant, suggesting the need for larger sample sizes and investigations into the links between consistency and credibility.

[7] Please note that companies could refrain from assessing any instrument – either because they did not want to provide information or because they did not know the answer. For simplicity and clarity, here we have only provided the responses of those who provided an assessment of the impact of an instrument – which is why the number of responses per instrument vaies. For example, while all but five companies had an opinion (and voiced it) on the impact of the nuclear phase-out (which, incidentally, was asked as last instrument in the list of these eight policies), whereas the impact of the Energy Industry Act and the Federal Nature Conservation Act was not answered by 81 and 89 manufacturers, respectively, mainly because they felt they did not know this.

2010/11–reinstated in 2011 has had an impact on the development and diffusion of renewable power generation technologies. To answer this question we have drawn on insights gained from an innovation survey conducted among German manufacturers and suppliers in renewable power generation technologies. We found that in 2014 manufacturers believed the nuclear phase-out offers the strongest support for the future diffusion of renewable energies. That is, while the EEG remains important for future markets, the manufacturers expect that their future sales will be most positively influenced by the nuclear phase-out policy which offers a clear decarbonization trajectory build on renewable energies. In contrast, the EU Emission Trading System – another destabilization policy – hardly seems to have had any effect, which, given its low allowance prices, is hardly surprising and in line with previous studies pointing to the importance of the instrument's stringency. Manufactures also did not think that the framework conditions for fossil power generation technologies would have a positive impact on the future expansion of renewable energies, which may be hardly surprising given that they did not foresee any specific phase-out policy at the time of the survey in 2014.

Regarding the impact of the nuclear phase-out policy on innovation, we find a positive link, which seems to materialize through the effect of the existence of this policy on the overall credibility of the German policy mix for renewable energies. The findings suggest that manufacturers were most keenly aware of the political will to promote power generation from renewable energies at the time of the nuclear phase-out after Fukushima. However, companies think that the credibility of the policy mix has ebbed away since then. This is important given that credibility was regarded by companies as being almost as important a factor for determining their innovation activities as the political expansion targets, the German Renewable Energy Sources Act (EEG) and comparable foreign demand pull instruments. The EU Emission Trading System on the other hand, played hardly any role. This matters because regression analysis indicates that those companies which view the policy mix as more credible invest more in R&D for renewable energies. Importantly, it is not only the changes in the design of the German feed-in tariffs for renewable energies and other EEG design features that determine the perceived credibility of the policy mix, but also the nuclear phase-out as the only other policy instrument which had a strongly significant effect. That is, this destabilization policy is shown to positively contribute to companies' perceptions of the credibility of the overarching policy mix. And this, in turn, seems to lead to higher investments in corporate R&D in renewable energies, therefore highlighting that the nuclear phase-out policy may also have had a positive innovation impact on these competing low-carbon technologies.

Our explorative analysis contributes to literatures on destabilization and discontinuation which are furthering work in innovation studies related to the understudied 'flip sides' to innovation [14]. So far, attention towards destabilization has focused on how particular socio technical regimes become weakened through technical, economic and political pressures, as suggested by the historical case study of UK coal [13,14]. In addition, recent research on discontinuation has taken a governance perspective in order to understand how it becomes politically feasible to enact policies directed at the discontinuation of certain technological pathways. Yet, while these approaches have contributed to understanding the policy process around discontinuation and destabilization, what the effects of discontinuation policies are for socio-technical change have not been studied. While it has been noted that "…the deliberate destabilization and decline of fossil fuel based industries may play a productive role in sustainability transitions, because it would create more space for renewables" [14:36], this had not been verified through empirical research. Drawing on empirical data, this paper demonstrates more clearly the effect that the nuclear phase-out policy seems to have in terms of technological change in renewable energies in Germany. These explorative insights contribute to broader understandings of the implications that discontinuation policies have on innovation, thereby addressing a key research gap. In summary, this paper differs from previous research on discontinuation and destabilization in two ways: first, it analyses a current and ongoing discontinuation policy rather than a historical case study, and second, rather than focusing on the policy process and governance has studied discontinuation from the perspective of how such policies influence the broader policy mix and technological change.

Although the role of nuclear in low carbon transitions remains contested in terms of the 'actual sustainability' of nuclear [95], it is clear that following Fukushima, a number of countries are considering phasing out the technology [96]. In Europe for example, the UK's ambitious nuclear new build agenda is actually the exceptional case, with minimal new build taking place elsewhere [97]. It is not just Germany, but also Belgium, Switzerland, and Scotland that are planning to phase out nuclear, while in Sweden, Spain, and the Netherlands, phase out currently looks more likely than nuclear new build [37]. Further afield, Taiwan is also implementing a nuclear phase out policy [98], and most recently South Korea has also signaled the intention to end the use of nuclear power [21]. For countries making such decisions, the positive effect perceived by renewable manufacturers of a phase out policy should be taken note of, but the range of policies that Germany has in place to also support renewables (like the Renewable Energy Sources Act and strong R&D support) is also important, as is the consistency of this policy mix. Germany had implemented significant long-term support mechanisms prior to the final phase out decision after Fukushima, so other countries looking to phase out nuclear should also consider the broader policy mix in terms of whether sufficient instruments are in place to promote the growth of technological alternatives in the form of renewables and energy efficiency.

This research also has relevance for coal phase out policies. A key challenge over the next decade that has been recognized is the need to phase out coal in order to promote more rapid transitions in order to meet climate change targets [73,99]. For example, the UK has announced a coal phase out by 2025 [72], and the Netherlands have also passed initial laws to phase out the five remaining coal plants in operation in the country [26]. The insights generated from this research may be useful in understanding what the impacts of coal phase out may be on renewables industries. Our research suggests that removing coal may also yield positive results for the development and diffusion of low-carbon technologies. However, again, the exceptional nature of the German case must be pointed out in terms of the long-term commitment to a renewables future envisaged in the Energiewende, as well as the nature of German politics to intervene more readily in markets [100]. This implies that countries pursuing coal phase out policies may be well advised to embed these into a broader policy mix with ambitious long-term targets and a supporting instrument mix consisting of both destabilization and creation policies, but also to enhance the procedural and informational coherence of policy making and implementation. Finally, should Germany eventually overcome the strong resistance of incumbents to implement a coal phase-out – as strongly suggested by think tanks and environmental NGOs [88,101] – we would assume that such a coal phase-out would not only reduce CO_2 emissions but could also – similarly to the nuclear phase-out policy – yield a positive impact on the diffusion and innovation of low-carbon solutions for a renewables based energy system. In this sense, by creating space in future markets destabilization policies would perhaps best be seen as 'transformative' demand pull instruments to be added to the policy mix to accelerate transition processes.

In addition, this paper speaks to building understandings of the role of destabilization and discontinuity in sustainability transitions more generally, a hitherto under-researched aspect of transitions studies [18]. It adds to previous research on destabilization and discontinuity in technological systems [15–17,50] by highlighting the impacts that discontinuation policies may have on the broader energy sector once they are implemented. The credibility and importance of the phase out policy for manufacturers in the renewables sector in Germany gives some indication of how policies aimed at the regime level and niche-supporting policies interact within a policy mix. Such niche-regime interactions are an area requiring more attention [19,102]. In particular, research in sustainability transitions has recently tried to understand how processes of niche protection and empowerment can be achieved [11,103]. Despite turbulence in the German energy transition and on-going political debates [81,104], nuclear phase-out appears to play a key role in cementing the credibility to the overall policy mix, enabling certainty in the face of challenging market conditions. As such, the German nuclear phase-out could be encapsulated as a process that assists in protecting, empowering and shielding niche developments through companies' confidence remaining high due in part to the clear overall direction of the German energy transition which the nuclear phase out makes clear.

Our study is not free from limitations. First, it only represents a first empirical exploration of the link between destabilization policies and technological change in renewable energies as low-carbon alternatives. Second, its data is limited by only covering one country, one point in time and only one type of actor. It should therefore be interpreted with caution and rather be seen as a stepping-stone towards future research on discontinuation and destabilization policies.

Future research could look at other phase out policies in terms of the ways in which they strengthen (or hinder) commitments towards niche developments in sustainability transitions, analyzing the relationship more directly and could do so from the perspective of different actors. This requires the explicit consideration of phase out policies in a study's design from the outset – not only regarding their impact on diffusion but also regarding their impact on innovation.

In conclusion, this paper has provided quantitative evidence gathered among German manufacturers of renewable power generation technologies that the German nuclear phase-out policy may positively impact technological change in renewable energies. As such, future policy efforts should pay much greater attention to devising feasible strategies for adopting such destabilization policies despite the likelihood of significant resistance of incumbents.

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