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CASE STUDIES FROM THE ENERGY SECTOR

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presented by

NICOLAS SCHMID

MA Political Science, University of Stuttgart
MA Political Science, Sciences Po Bordeaux

born on 11.12.1991

citizen of Germany

accepted on the recommendation of

Examiner: Prof. Tobias S. Schmidt

Co-examiner: Prof. Benjamin Cashore

Co-examiner: Prof. Karin Ingold

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Abstract

Technological change, i.e. the invention, innovation and diffusion of new technologies, is a key driver of economic development and societal progress. There is widespread agreement that, historically, *energy technologies* have been at the core of most technological revolutions. Yet, the transition to and diffusion of fossil fuel-based energy technologies has come at high societal and ecological costs, most notably climate change. A fast and deep transition to low-carbon technologies – particularly renewable energy and efficiency technologies – is the main lever to address climate change. While deployment of these technologies has grown significantly over the last decades – largely policy-induced – this transition needs to be further accelerated and deepened through public policies. In light of various trade-offs and competing policy goals, implementing and designing these policies is an intrinsically *political* endeavor. A growing body of literature at the intersection of public policy, political science, and innovation studies covers these aspects of *energy politics*.

Yet, energy politics not only influence technological change through public policy – technological change can also, in turn, influence politics. A better understanding of this *inverse effect of technological change on politics* is necessary to formulate politically feasible and effective energy policy. While a nascent body of literature deals with these aspects in the context of the transition to renewable energy and efficiency technologies, *how exactly* such low-carbon technological change affects *what aspects* of politics still remains a black box. In an exploratory approach, this dissertation attempts to address this research gap with the following overarching question: *How does low-carbon technological change affect energy politics?* To answer this question, this cumulative dissertation is built on a heuristic framework: On an abstract level, it argues that technological change can affect politics through both its *expanding and (re)distributional capacity*. It further proposes that politics can be disaggregated into the categories of *interests, ideas, and institutions*, on the level of both *elite and mass politics*. The individual papers in this dissertation cover various elements of this heuristic framework and leverage a plurality of qualitative and quantitative methods, and individual case studies.

Focusing on how technological change affects the interests and ideas of elite politics, *Paper 1* examines how the transition to renewable energy technologies influenced the composition and strength of advocacy coalitions in the German energy sector. The main contribution of this paper is to substantiate the mechanisms through which policy-induced technological change affects coalitions, and to link these mechanisms to patterns of actor

movements underlying coalition change. *Paper 2* also focuses on aspects of ideas in elite politics and touches upon institutions as moderating factor. It examines how technological change drives regulators' perceived feasibility of more stringent public and private regulation of energy efficiency technologies in the Swiss building sector. The contribution of this paper is to highlight that the interaction among public and private regulation can run through the mechanism of technological change. Also focusing on ideas and institutions in elite politics, *paper 3* examines how technological change affects the positions of political parties on energy technologies in Germany, France, and the United Kingdom. The paper shows that technological change is a driver of party positions and their salience, and that this effect is mediated by party and party system characteristics. Finally, *paper 4* examines interests in mass politics by focusing on how the decline in coal mining affects voting behavior in presidential elections in the United States. The paper shows that also *decline* in technologies can result in political effects, in this case resistance in form of voting in favor of pro-coal candidates.

Based on a mixed methods approach and systematic data collection, these four papers give novel empirical insights into how technological change affects interests, ideas, and institutions in elite and mass energy politics. Based on these insights, the papers engage in theory-building. Notably, the dissertation provides a framework in which energy politics is described as a dynamic *feedback loop* of public policy, technological change, and politics. Further, the dissertation substantiates various *mechanisms* that link technological change to politics, and analyzes the effects of technological change on a variety of relevant political actors. Doing so, it contributes to current academic debates in public policy, political science, and innovation studies on energy politics. Further, this dissertation also has policy implications: Policymakers' focus should be on the expanding and (re)distributional effects of technological change on energy and climate politics. More sensibility to the locus and nature of these political struggles could enable effective forward-looking policy strategies that sow the seeds today for broader political support tomorrow. Finally, future research should aim at testing the theory built in this dissertation with more quantitative research methods. Future research should also build on this exploratory dissertation by expanding the empirical scope to other low-carbon technologies, and expand the policy feedback logic to other policy outcomes such as nature-based solutions and behavioral change.

Zusammenfassung

Technologischer Wandel, d.h. die Erfindung, Verbesserung, und Verbreitung von neuen Technologien, ist ein Haupttreiber von wirtschaftlicher und gesellschaftlicher Entwicklung. Historisch bilden *Energietechnologien* den Kern der meisten technologischen Revolutionen. Die Verbreitung von Energietechnologien auf Basis fossiler Brennstoffe ist jedoch mit hohen gesellschaftlichen und ökologischen Kosten verbunden, insbesondere mit dem Klimawandel. Daher ist eine schnelle und tiefgreifende Transition zu kohlenstoffarmen Technologien – insbesondere zu erneuerbaren Energie- und Effizienztechnologien – der Haupthebel zur Bekämpfung des Klimawandels. Während die Verbreitung dieser Technologien in den letzten Jahrzehnten aufgrund politischer Massnahmen erheblich zugenommen hat, muss diese Transition durch die Politik weiter beschleunigt und vertieft werden. Angesichts konkurrierender politischer Ziele und Abwägungen ist die Umsetzung und Gestaltung dieser Politiken ein intrinsisch *politisches* Unterfangen. Eine wachsende Literatur an der Schnittstelle von Public Policy, Politikwissenschaft und Innovationsforschung deckt diese Aspekte der *Energiepolitik* ab.

Energiepolitik beeinflusst jedoch nicht nur den technologischen Wandel durch politische Massnahmen, sondern *technologischer Wandel kann umgekehrt auch die Politik beeinflussen*. Ein besseres Verständnis der Auswirkungen von technologischem Wandel auf Politik ist notwendig, um eine politisch machbare und wirksame Energiepolitik zu formulieren. Zwar befasst sich eine aufkeimende Literatur mit diesen Aspekten im Zusammenhang mit der Transition zu erneuerbaren Energie- und Effizienztechnologien, allerdings bleibt noch unklar, durch *welche Mechanismen* sich ein solcher technologischer Wandel auf *welche Aspekte* der Politik auswirkt. Diese Dissertation versucht diese Forschungslücke in einem explorativen Ansatz und mit der folgenden übergreifenden Forschungsfrage zu schliessen: *Wie wirkt sich kohlenstoffarmer technologischer Wandel auf die Energiepolitik aus?* Um diese Frage zu beantworten, baut diese kumulative Dissertation auf einem heuristischen Rahmenkonzept auf: Auf abstrakter Ebene wird vorgeschlagen, dass technologischer Wandel die Politik sowohl durch seine *Erweiterungs- als auch durch seine Umverteilungskapazität* beeinflussen kann. Ferner wird argumentiert, dass die Politik in die Kategorien von *Interessen, Ideen und Institutionen*, sowohl auf der Ebene von *Eliten* als auch der *allgemeinen Bevölkerung*, unterteilt werden kann. Die einzelnen Artikel dieser Dissertation decken verschiedene Elemente dieses

heuristischen Rahmens ab und nutzen dabei eine Vielzahl qualitativer und quantitativer Methode, sowie einzelne Fallstudien.

Artikel 1 der Dissertation untersucht, wie sich technologischer Wandel auf Interessen und Ideen von Eliten auswirkt. Konkret analysiert der Artikel, wie sich die Transition zu erneuerbaren Energien auf die Zusammensetzung und Stärke von politischen Koalitionen im deutschen Energiesektor auswirkt. Der Hauptbeitrag besteht darin, die Mechanismen zu begründen, durch welche induzierter technologischer Wandel diese Koalitionen beeinflusst, und diese Mechanismen mit Mustern von Akteursbewegungen zu verknüpfen, die dem Koalitionswandel zugrunde liegen. *Artikel 2* konzentriert sich auf Aspekte von Ideen von Eliten und berührt auch Institutionen als moderierende Faktoren. Es wird untersucht, wie technologischer Wandel die wahrgenommene Machbarkeit einer strengeren öffentlichen und privaten Regulierung von Energieeffizienztechnologien im Schweizer Bausektor vorantreibt. Der Hauptbeitrag dieses Artikel ist es, zu zeigen, dass die Interaktion zwischen öffentlicher und privater Regulation durch den Mechanismus des technologischen Wandels erfolgen kann. Auch *Artikel 3* untersucht Ideen der Elitenpolitik und berührt institutionelle Aspekte. Der Artikel analysiert wie sich technologischer Wandel auf die Positionen politischer Parteien zu Energietechnologien in Deutschland, Frankreich und Großbritannien auswirkt. Der Artikel zeigt, dass technologischer Wandel ein Treiber von Parteipositionen und deren Salienz ist, und, dass dieser Effekt durch Partei- und Parteiensystemmerkmale moderiert wird. Schließlich untersucht *Artikel 4* die Auswirkungen von technologischem Wandel auf Interessen in der allgemeinen Bevölkerung. Der Artikel analysiert, wie sich der Rückgang des Kohlebergbaus in den USA und einhergehende Jobverluste auf das Wahlverhalten bei US-Präsidentschaftswahlen auswirken. Der Artikel zeigt, dass auch der *Niedergang* von Technologien zu politischen Auswirkungen führen kann, in diesem Fall zu geändertem Wahlverhalten zugunsten von Pro-Kohle-Kandidaten.

Basierend auf verschiedenen Methoden und systematischer Datenerfassung geben diese Artikel neue empirische Einblicke in die Auswirkungen technologischen Wandels auf Interessen, Ideen, und Institutionen in der Energiepolitik. Aufbauend auf dieser Empirie ist Theoriebildung das Ziel der Artikel. Allgemein wird Energiepolitik als Element eines *Feedbackloops*, bestehend aus politischen Massnahmen, technologischem Wandel und Politik, konzeptualisiert. Des Weiteren entwickeln die Artikel eine Anzahl von *Mechanismen*, die technologischen Wandel mit Politik verbinden, und untersuchen diese Mechanismen in Bezug auf eine Vielzahl relevanter politischer Akteure. Hierbei trägt diese Dissertation zu aktuellen akademischen Debatten in Public Policy, Politikwissenschaft und Innovationsforschung bei. Die gewonnenen Erkenntnisse haben auch Implikationen für politische Entscheidungsträger: Ihr Fokus sollte verstärkt auf den Umverteilungseffekten technologischen Wandels und den damit verbundenen Auswirkungen auf die Energie- und Klimapolitik liegen. Mehr Sensibilität für diese Aspekte könnte zukunftsgerichtete Strategien stärken, die vorrauschauend den Grundstein für eine breitere, zukünftige Unterstützung ambitionierter Energie- und Klimapolitik legen. Schliesslich sollte weitere Forschung auf dieser explorativen Dissertation aufbauen und die hier gebildete Theorie mit quantitativen Forschungsmethoden testen. Der empirische Fokus sollte ausserdem auf weitere klimarelevante Technologien ausgeweitet werden, und die Logik des Feedbackloops über Technologie hinaus auf naturbasierte Lösungen und Verhaltensänderung angewandt werden.

Every bit of warming matters, every year matters, every choice matters.

Intergovernmental Panel on Climate Change

Global Warming of 1.5 °C report (2018)

Choice manifests itself in society in small increments and moment-to-moment decisions as well as in loud dramatic struggles.

Lewis Mumford

Technics and Civilization (1934)

Der Wechsel zu erneuerbaren Energien hat eine zivilisationsgeschichtliche Bedeutung. Deshalb müssen wir wissen, wie wir ihn beschleunigen können. Knapp sind nicht die erneuerbaren Energien, knapp ist die Zeit.

Hermann Scheer

Der Energethische Imperativ (2010)

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I) Synopsis

1. Introduction

1.1. Technological change as a double-edged sword

Technological change is an endogenous part of economic development and growth (Acemoglu et al. 2012; Romer 1990; Schumpeter 1942) and, ultimately, at the heart of societal and political change (Acemoglu and Robinson 2005; Rosenberg and Birdzell 1985; Rosenberg, Landau, and Mowery 1992)[1]. The pace and scope of technological change have increased dramatically since the 18th century. Economic historian Carlota Perez (2009) identified five technological revolutions or "surges" from 1771 to today: the industrial revolution, the age of steam and railways, the age of steel, the age of oil, and the age of information and telecommunications (see also Freeman and Perez 1988). These revolutions are distinguishable from other innovations because they were "[...] opening a vast innovation opportunity space and providing a new set of associated generic technologies, infrastructures and organizational principles that can significantly increase the efficiency and effectiveness of all industries and activities" (Perez 2009). Such profound economic transformations often come at the cost of pre-existing technologies and infrastructure in what Joseph Schumpeter famously coined *creative destruction* or a "process of industrial mutation [that] incessantly revolutionized the economic structure from within, incessantly destroying the old one, incessantly creating a new one" (Schumpeter 1942, 83).

While not every new technology has the potential to trigger such profound economic transformation and creative destruction, there is widespread agreement that *energy technologies* have been at the core of most technological revolutions and subsequent societal

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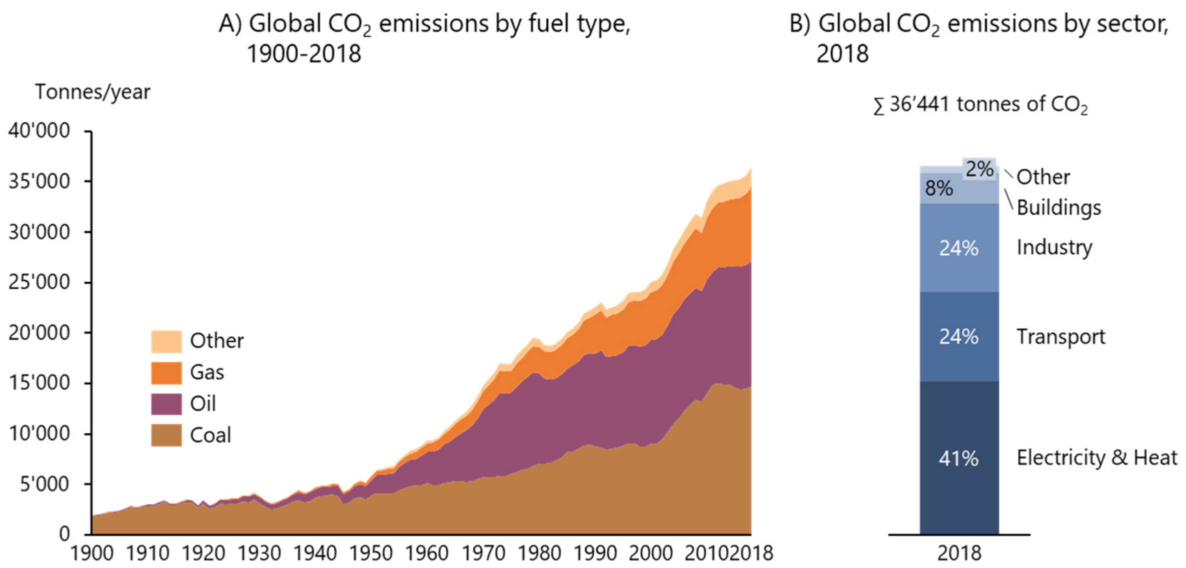
[1] In this dissertation, I define technological change as the invention, innovation and diffusion of new technologies (Abernathy and Utterback 1978; Utterback 1974). *Invention* refers to the introduction or discovery of new technology. *Innovation* is the process by which an invention is developed from prototype to dominant design. *Diffusion* is the process by which a new technology is propagated over time among markets.

and political change (David 1990; Smil 2017; Wilson and Grubler 2015). Waves of economic development have historically been accompanied by transitions to new energy sources and corresponding technologies (Fouquet 2010, 2016; Grübler, Nakićenović, and Victor 1999; Smil 2017; Wilson and Grubler 2015). The industrial revolution is a classic example for the importance of energy technologies because it was inseparable from the emergence of coal-based steam technology (Kalkuhl et al. 2019). The displacement of steam technology by petroleum and electricity-based technologies provided the fundament from which subsequent technological revolutions evolved (Bresnahan and Trajtenberg 1995; David 1990; Rifkin 2011). These advances in energy technologies have enormously *expanded the scope of possible human action* by increasing humankind's capacity to manipulate the natural environment, access new energy services (Fouquet 2016), and move billions out of poverty (Deaton 2014).

However, technological change and associated economic development and growth also come at social and ecological costs, so-called *negative externalities*. One of the largest negative externalities is anthropogenic climate change, which is primarily driven by advances in energy technologies. The transition toward fossil fuel-based energy technologies over the past technological revolutions has resulted in a global energy system that is highly carbon-intensive. Coal, oil, and natural gas met around 85% of all energy needs in 2018 (IEA 2019). Accompanied by an increase in energy demand, this transition has resulted in continually rising greenhouse gas emissions, especially of carbon dioxide (CO_2) (IPCC 2018). Figure 1 below illustrates the global annual CO_2 emissions by energy source from 1900 to 2018 (A), as well as the emissions differentiated by sector in 2018 (B). Over the 20th century, annual CO_2 emissions have increased by more than 1000%, and approximately another 50% from 2000 to 2018. In 2018, the generation of electricity and heat accounted for most emissions with around 40%.



A) Global CO_2 emissions by fuel type, 1900-2018

B) Global CO_2 emissions by sector, 2018

Figure 1: Global CO_2 emissions A) by fuel type 1900-2018 'Other' includes emissions from cement and flaring. Sources: Global Carbon Project (GCP) and Carbon Dioxide Information Analysis Center (CDIAC); **B) by sector in 2018** 'Other' includes fugitive emissions. Source: Climate Analysis Indicators Tool (CAIT) Data Explorer.

These annual emissions have cumulated to the highest levels of CO_2 concentrations in the Earth's atmosphere in over 800,000 years. The rise in global average temperature is attributed to these high concentrations. In absence of climate mitigation, rising temperatures will lead to sea level rise, heavy precipitation, and drought, as well as ecosystems degradation, including species loss and extinction (IPCC 2018), with innumerable consequences for humankind. Fast and deep mitigation is especially crucial in light of self-reinforcing feedbacks and cascading effects that could destabilize the climate on earth and cause continued rising temperatures (Steffen et al. 2018).

The main lever to prevent such dangerous levels of climate change is the reduction of CO_2 and other greenhouse gas emissions. However, while governments have agreed to reduce emissions in line with the "well below 2°C" target of the 2015 Paris Agreement, the so-called *emissions gap* between this target and reality remains large (UNEP 2019). To realistically achieve the Paris climate target, scientists argue that emissions will need to peak no later than 2020 and then be halved every decade thereafter through 2050 (Figueres et al. 2017; Rockström et al. 2017). These required reduction rates surpass even those experienced during periods of massive socioeconomic crisis such as the Great Depression (Otto et al. 2020), and match the emission reductions associated with the Covid-19 pandemic (Le Quéré et al. 2020). These comparisons indicate the historic and unprecedented challenge of climate change mitigation and the need for a fundamental transformation of our energy and economic systems "comparable with those of previous industrial revolutions" (Pearson and Foxon 2012).

While nature-based solutions and behavioral change also matter (Bastin et al. 2019; W. Steffen et al. 2018; Wiedmann et al. 2020), the key lever for such deep and rapid transformation is the transition from fossil fuel-based to low-carbon technologies (Anadon et al. 2016; IEA 2019; IPCC 2018; Wilson et al. 2020). Given their large share in CO_2 emissions, electricity and heat generation are particularly important for climate change mitigation (Figure 1B above; Anadon et al. 2016; Gallagher, Holdren, and Sagar 2006). Lowering emissions in electricity and heat generation necessitates a transition to renewable energy technologies and energy efficiency (Bogdanov et al. 2019; Jewell et al. 2019; McCollum et al. 2018; Rogelj et al. 2018; UNEP 2019)[2].

Recent developments indicate progress in this direction, primarily thanks to public policy (see 1.2.). As depicted in Figure 2A, renewable energy technologies, such as solar photovoltaic (PV) and on- and offshore wind, have experienced exponential growth rates since the early 2010s (see also IRENA 2020). At the same time, solar PV and wind have become the cheapest source of electricity in many markets (UNEP 2019). Figure 2B depicts the cost

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[2] This dissertation focuses on such technological change in the energy sector, and specifically the transition from fossil fuel-based and nuclear technologies to renewable energy technologies, coined the "energy transition". I follow Grübler et al. (2016) who define an energy transition "as a change in the state of an energy system as opposed to a change in individual energy technology or fuel source". Hence, aggregate changes in the energy sector can be understood as combinations of changes in the use of individual energy technologies (Fouquet and Pearson 2012), including supply side, energy efficiency and demand-side technologies.

decreases per cumulative installed capacity of solar PV modules. Between 2000 and 2016 costs have fallen by approximately 83%.

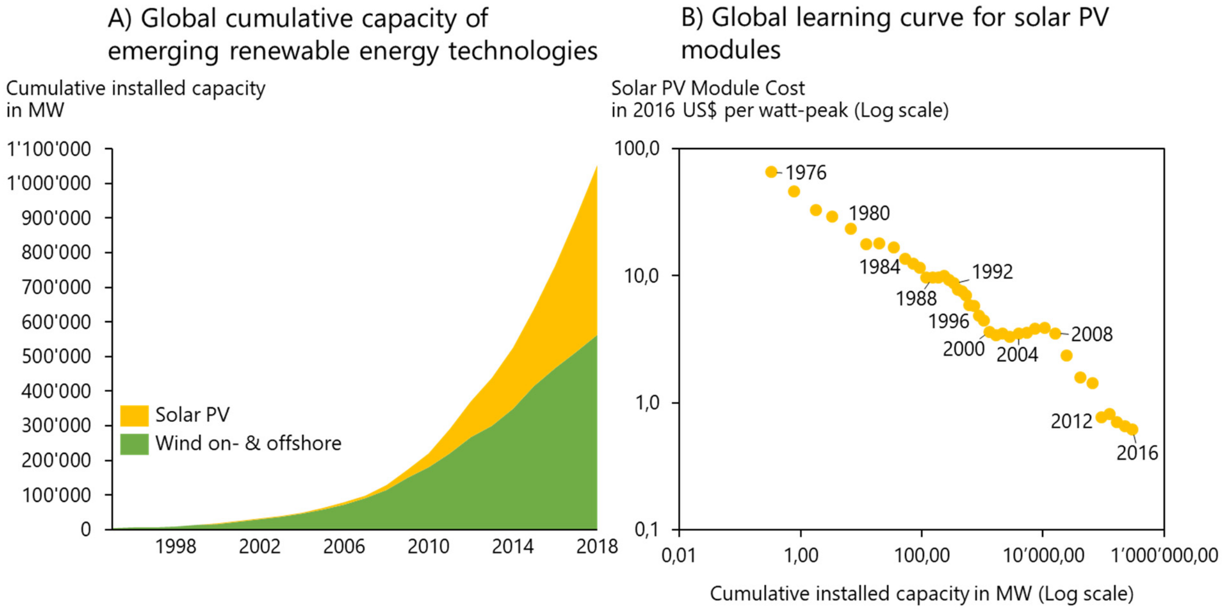

Figure 2: Technological change in emerging renewable energy technologies A) Global cumulative capacity of geothermal, solar photovoltaic (PV), and wind on- and offshore. Sources: BP Statistical Review of World Energy 2019, IRENA. **B) Global learning curve for solar PV modules**. Sources: IRENA, SolarServer.

However, the transition to renewable energy technologies is not fast, deep, or wide enough to meet the Paris climate targets. Deployment must grow approximately six times faster and the phase-out of fossil-fuel based electricity and heat generation must be accelerated to realistically achieve the "well below 2°C" target (IRENA 2020; Jewell et al. 2019; UNEP 2019).

1.2. The role of public policy in steering and accelerating technological change

Public policy provided the basis for the exponential growth of renewable energy technologies described above (van den Bergh 2013; Jacobsson and Lauber 2006; del Río González 2009; Rogge and Reichardt 2016; Schmidt et al. 2012). Policy is also crucial to further accelerate and deepen the transition to renewable energy technologies (Grubler, Wilson, and Nemet 2016; Schmidt and Sewerin 2019), and low-carbon technologies more generally (Acemoglu et al. 2012; Geels et al. 2017). It is necessary because renewable energy technologies do not provide fundamentally new services or do not necessarily perform better than their fossil fuel-based competitors (Fouquet 2010; Pearson and Foxon 2012; Wilson and Grubler 2015). Renewables also do not benefit from the decade-old co-evolution with incumbent institutions and societal habits that benefit fossil fuel-based technologies and that have effectively led to a so-called *carbon lock-in* (Seto et al. 2016; Unruh 2000).

Consequently, markets alone are unlikely to provide low-carbon technologies due to several market and system failures (Gillingham and Sweeney 2012; Mealy and Teytelboym 2020). These failures suggest that governments need not only to internalize negative externalities through instruments such as carbon pricing but to also pro-actively engage in industrial policy (Rodrik 2014) and create new markets for low-carbon technologies (Mazzucato 2018; Mazzucato and Penna 2016). Governments can foster technological change through technology push and demand pull policies (Nemet 2009), by removing existent support for incumbent technologies (Kivimaa and Kern 2016), or by tackling system failures (Foxon et al. 2005). Recent innovation literature highlights the need for mixing these different approaches (Del Río 2014; Schmidt and Sewerin 2019), and emphasizes the need to take into account technology characteristics in the design of individual policies in these mixes (Haelg, Waelchli, and Schmidt 2018; Huenteler et al. 2016; Schmidt and Huenteler 2016). Further, to address climate change a wide-ranging portfolio of energy technologies is necessary (Wilson and Grubler 2015) which implies that public policy needs to weigh technology diversity and deployment of individual technologies (van den Bergh 2013; Sandén and Azar 2005). A basic question hence is how governments can identify technologies that fit their policy goals (Schmidt, Schmid, and Sewerin 2019), and how technology policy can be most effectively and efficiently designed to reach these goals (Haelg, Waelchli, and Schmidt 2018; Matsuo and Schmidt 2019). These trade-offs and policy design choices point to the intrinsically *political* character of energy policy (Meadowcroft 2011). Given the dependence on public policy, relevance for other economic sectors, and large negative externalities, the energy sector, and associated technologies are likely to be unique and prime examples for these *politics of technological change* (Compston 2009; Finnegan 2019; Hughes and Lipscy 2013).

1.3. The politics of technological change

Given the prevalence of public policy in steering and accelerating the transition to low-carbon technologies, underlying *politics* largely define the feasibility of climate change mitigation[3]. This link between politics and subsequent policy output is a key concern of political science and public policy literature. Central debates in these bodies of literature revolve around how to conceptualize and measure *elite politics*, such as interest groups and political parties, and *mass politics*, such as citizens' voting behavior or public opinion, and how these politics, in turn, are translated into subsequent policy output. While it is difficult to synthesize general laws from this literature – given the contingent and dynamic nature of political affairs – three abstract types of political forces driving public policy can be distinguished (Béland 2019; Hall 1997; Hay 2004; Heclo 1994; Palier and Surel 2005): *interests*, *ideas*, and *institutions*.

Interests can generally be defined as the "distribution of power and resources across social groups" (Hall 1997). Interests-based studies are concerned with politics as a struggle over scarce resources among elite and mass politics (Campbell 2002; Downs 1957). Ideas can be defined as "claims about descriptions of the world, causal relationships, or the normative legitimacy of certain actions" (Parsons 2002, 48). Research in this vein is concerned with the origin of ideational change and its influence on policy (Haas 1992; Hajer 1995). Finally, institutions can be defined as formal political institutions or informal norms which guide the

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[3] In this dissertation, I use a broad definition of politics, encompassing all of the decision-making structures and procedures that have to do with the allocation and distribution of wealth and power in society, in line with Lasswell's (1936) definition of politics as "who gets what, when, how".

behavior of actors and can create constraints on policy options (Béland 2019; North 1990). Here, research is concerned with how institutions shape and moderate political outputs and outcomes (Scharpf 1991; Schmitter and Lehmbruch 1979; Streeck and Thelen 2005).

A growing literature deals with how interests, ideas, and institutions – in both elite and mass politics – are driving public policy targeted at technological change in the energy sector (Drews and van den Bergh 2016; Van de Graaf, Haesebrouck, and Debaere 2018; Green 2015; Kern 2011). For instance, energy politics scholars examine themes such as the balance of power between various organized groups (Cheon and Urpelainen 2013; Cory, Lerner, and Osgood 2020; Hughes and Urpelainen 2015; Meckling 2011; Mildenberger 2020; Rennkamp et al. 2017; Stokes 2020), the role of political parties (Dumas, Rising, and Urpelainen 2016; Geddes et al. 2020), electoral politics and public opinion (Ingold, Stadelmann-Steffen, and Kammermann 2019; Stokes 2016), formal and informal institutions (Meckling and Nahm 2018; Wood et al. 2020), or path dependency (Lockwood et al. 2017a; Rosenbloom, Meadowcroft, and Cashore 2019). What these studies have in common is that they highlight the relevance of political factors as drivers of energy and climate policy.

Yet, the relation between politics, policy, and technological change is not unidirectional. Politics not only influence technological change through public policy, *technological change, in turn, can also shape subsequent politics* (Taylor 2016; Winner 1980). Economic history provides plenty of examples of how technological change – policy-induced or not – triggered sweeping societal, and ultimately political change (Landes 1969; White 1962). One example is the rise of a new working class and associated political emancipation during the industrial revolution. On an abstract level, technological change may affect politics in two ways. First, technological change *increases the scope of possible human action*, and hence the possibilities of public policy in an *expanding capacity*. Technological change brings some previously unattainable societal or political goals within the realm of choice or makes some public policy options more attractive by changing their cost (Mesthene 1969; Scharff and Dusek 2014). Second, technological change imposes losses and gains on actors in a process of *creative destruction* in a *(re)distributional capacity* (Schumpeter 1942). Costs and losses involved with technological change are powerful interest-based motives to politically oppose technological change (Acemoglu and Robinson 2006; Mokyr 1992, 1994). A nascent literature deals with these effects of technological change on energy politics (Aklin and Urpelainen 2013; Breetz, Mildenberger, and Stokes 2018; Geels 2002; Hale 2018; Lachapelle, MacNeil, and Paterson 2017; Lockwood 2015; Markard, Raven, and Truffer 2012; Markard, Suter, and Ingold 2016; Meckling, Sterner, and Wagner 2017; Rosenbloom, Meadowcroft, and Cashore 2019; Schmidt and Sewerin 2017). For example, scholars have examined how the phase-out of coal affects public opinion (Rinscheid and Wüstenhagen 2019), or how the phase-in of renewable energy technologies influenced electoral behavior (Stokes 2016) and international political cooperation (Meckling 2019b).

Despite these recent advances, the *mechanisms* through which the transition to low-carbon technologies affect *various aspects* of energy politics still largely remain a *black box*. The political effects of technological change are often ignored by the discipline of economics, and political science literature has so far only tangentially touched upon the politics of the recent transition to renewable energy technologies. In other words, while one may expect that the current energy transition affects politics – based on experiences from earlier technological change in the energy sector and beyond – there is no systematic research on the mechanisms behind this link, nor on the disaggregated political effects. Such knowledge would not only enrich extant literature on energy politics, but also inform strategic efforts to design and implement politically feasible and effective energy and climate policy.

1.4. Research question and framework of this dissertation

The goal of this dissertation is to open this black box by exploring whether and how technological change affects interests, ideas, and institutions in both elite and mass energy politics. To do so, I draw on established political science and public policy approaches and turn the conventional focus of these approaches upside down: Rather than explaining public policy as a function of politics, this dissertation focuses on how the outcomes of public policy – in this case technological change – influence subsequent politics. Hence, this dissertation attempts to forge a more explicit link between technological change and politics, with the following overarching research question:

How does low-carbon technological change affect energy politics?

To answer this research question, this dissertation leverages insights from four individual papers. Collectively, these papers use a plurality of theoretical approaches, qualitative and quantitative methods, as well as empirical cases. Figure 3 situates the individual papers in an overall conceptual framework. In line with the discussions above, the framework breaks the relationship between technological change and politics down into separate elements. *The general argument put forward is that technological change affects interests, ideas, and institutions of elite and mass energy politics through its expanding and (re)distributive capacity*[4]. Paper 1 covers aspects pertaining to how technological change drives interests and ideas in elite politics, operationalized as advocacy coalitions. Paper 2 and 3 are primarily concerned with ideas in elite politics, understood as regulatory governance and party politics, respectively, yet also touch upon the topic of institutions as moderating factors[5]. Finally, paper 4 focuses on

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[4] Of course, interests, ideas, and institutions, as well as elite and mass politics are not mutually exclusive categories and partly overlap and interact with each other (Béland 2019). However, these categories provide a useful heuristic to abstract from the individual papers of this dissertation.

[5] In light of the urgency to address climate change, timing is a central dimension of policy choice (Jacobs 2016). Hence, this dissertation primarily focuses on interests and ideas because they are more malleable and prone to fast changes compared to the more rigid political and societal institutions.

the effect of technological change on interests in mass politics, operationalized as citizens' voting behavior.

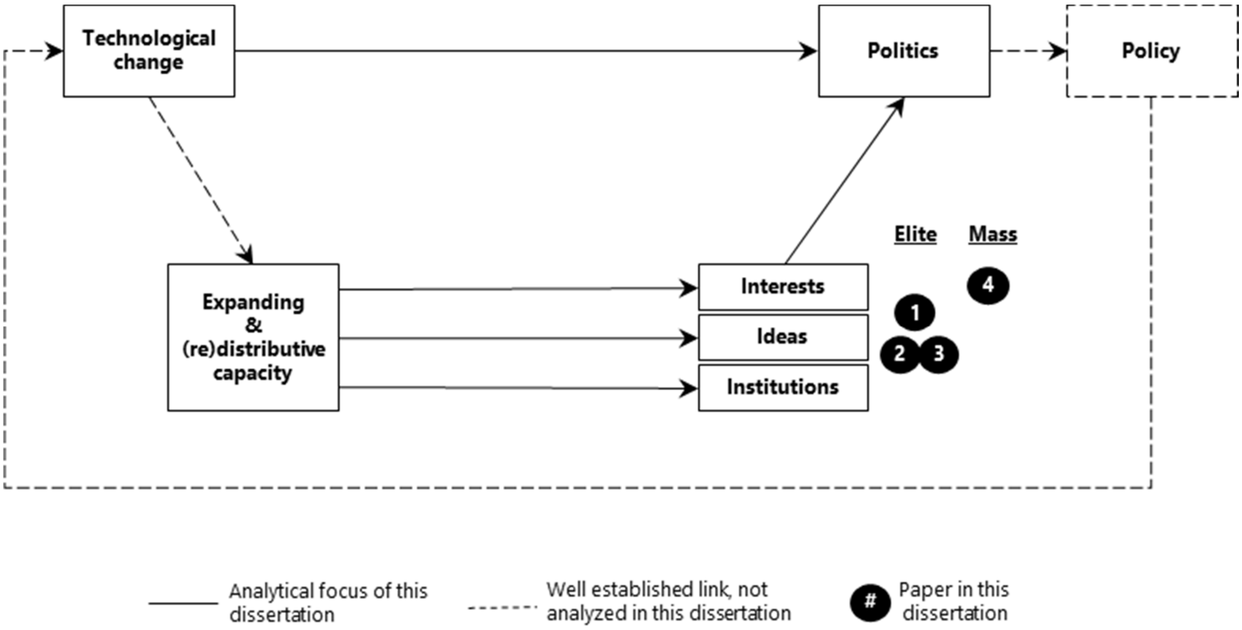

Figure 3: Framework of this dissertation.
Based on Schmidt and Sewerin (2017) and inspired by Coleman (1990).

Collectively, these papers cover a variety of relevant actor types in politics, including advocacy coalitions, regulators, political parties, and voters. All four papers develop specific mechanisms through which technological change affects the interests and ideas of these actors.

The dissertation is structured as follows: The remainder of part I provides a theoretical background to and synopsis of the individual papers. Part I Chapter 2 discusses the role of technological change in seminal debates in political science, as well as in literature on climate and energy politics. It also discusses the theories of public policy and political science used in the individual papers of this dissertation. Chapter 3 outlines the methods used in this dissertation and the case selection rationale. Chapter 4 summarizes the individual papers. Chapter 5 discusses the findings of the individual papers in light of the overarching research question, and outlines contributions to existing literature, avenues for future research, and policy implications. Part II contains the four individual papers of this dissertation as published in or submitted to academic journals. Papers 1-2 are first-authored together with colleagues from the Energy Politics Group. Paper 3 is single-authored. Paper 4 is co-authored with colleagues from the Energy Politics Group. For more details on author contributions and paper status see Table 4 in chapter 6.

2. Theory

To situate my dissertation, chapter 2.1. briefly outlines the role of technological change in two seminal debates in the discipline. Chapter 2.2. discusses whether and how technological change has been analyzed in the more specific energy and climate politics literature. Finally, chapters 2.3. and 2.4. summarize the public policy and political science approaches used in this dissertation. More detailed discussions can be found in the theory sections of the individual papers in part II.

2.1. The role of technological change in seminal debates of political science

Technological change is seldom referred to explicitly in political science and public literature, and is mostly treated as an exogenous factor to the policy process. If examined at all, technology is rather analyzed as an outcome of public policy, i.e. as a dependent variable, than as a driver of the politics underlying public policy. Two debates within the discipline are an exception to this rule and deal rather explicitly with technological change as the driver of politics: modernization and democratization theory, and literature on social policy and the welfare state.

Modernization and democratization theory has argued that technological change influences the regime type of states through economic development. For scholars in this vein, technological change is seen as the precondition for the creation and mobilization of new classes, such as labor and bourgeoisie in the industrial revolution. The growth of these new classes, in turn, provided the basis for an emancipation from traditional political structures and increasing demand for labor and property rights, as well as the creation of more inclusive institutions and political parties (Acemoglu and Robinson 2005; Diamond 1992; Huber, Rueschemeyer, and Stephens 1993; Lipset 1959). Although the mechanisms linking technological change to democratization are intuitive, empirical findings about this complex relationship remain inconclusive (Przeworski et al. 2000; Treisman 2020). More recently, scholars also call into question whether technological change in the fields of automation and artificial intelligence may undermine this "golden age of democratic capitalism" (Boix 2019, 13).

Political science literature on the politics of social policy and the welfare state examines these questions in more detail (Beramendi et al. 2015). Studies in this vein analyze the effects of technological change on different job types, sectors, and skill-sets and their impact on the elite and mass politics of social policy and the welfare state (Gingrich 2019; Häusermann, Kemmerling, and Rueda 2020; Kurer et al. 2019). For instance, scholars are concerned with how automation and globalization may increase vote shares for right and left-wing populist parties as citizens experience "status anxiety" or job loss (Frey, Berger, and Chen 2018; Inglehart and Norris 2016). In a sense, these debates revolve around the social externalities of technological change, such as changing class structures, or labor markets, and their impact on regime type and political institutions. Comparatively little political science research deals with the environmental externalities of technological change. Next, we turn to the small but growing research body on energy and climate politics that deals with such questions.

2.2. The role of technological change in literature on climate and energy politics

For a long time, political science literature on energy and climate politics was dominated by the subfield of International Relations[6], and therefore has primarily dealt with questions pertaining to global institutions (Bättig and Bernauer 2009; Bernauer 2013) and the geopolitics of energy resources (Bjorvatn, Farzanegan, and Schneider 2012; for an overview: Hughes and Lipscy 2013; Watts 2004) rather than explicitly focusing on technological change. Much of this literature was influenced by the concept of the "tragedy of the commons" introduced first by

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[6] For example, International Organization, one of the flagship journals of this subfield, contains 443 articles that use the exact words "climate change". Comparative Political Studies, on the other hand, only generates 22 hits using these terms (Aklin and Mildenberger 2018).

Hardin (1968) and later substantiated by Elinor Ostrom (1990). Ostrom argued that maintaining or achieving sustainability for common goods, such as clean air, required the development of collective action institutions to overcome problems of free-riding. This analytical focus dominated debates on climate and energy politics: Scholars have long assumed that individual nation-states are unlikely to engage in stringent energy and climate policy because the costs outweigh the benefits, and hence that free-riding would be a major problem for addressing climate change (Bernauer 2013; Keohane and Victor 2011, 2016; Nordhaus 2015; Ostrom 2014).

Yet, reality has repeatedly proven these assumptions wrong. A number of countries have engaged in unilateral energy and climate policies without guarantees that other countries would follow (Hale 2018). In addition, with the 2015 Paris Agreement, the decade-long international climate negotiations have seen a major shift away from a universally binding agreement toward a bottom-up and dynamic ratcheting-up logic (Schmidt and Sewerin 2017). Accordingly, in more recent energy and climate politics literature, the dominant Ostromian view is challenged by a growing community of scholars (Aklin and Mildenberger 2018; Hale 2018; Hochstetler and Viola 2012)[7]. For instance, Cashore and Bernstein (2018) argue that the diffusion of the commons metaphor to all problem types regardless of their structural properties represents a tragedy in itself, because it leads to wrong solutions to problems like climate change which are different in their structural features than those Ostrom originally targeted (see also Aklin and Mildenberger 2018; Hale 2018). For Cashore et al., climate change represents a "super wicked" problem type, which demands a focus on path-dependent

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[7] Elinor Ostrom herself has critically examined the assumptions of her framework and came to the conclusion that "polycentric governance systems" may be better adapted than a single unit of authority in governing climate change (A. J. Jordan et al. 2015; Ostrom 1999).

processes and lock-in rather than free-riding (Benjamin Cashore and Bernstein 2018; see also Levin et al. 2012)[8].

Consequently, this criticism was accompanied by a shift in focus away from global institutions toward energy and climate politics on a national or subnational level (Bernstein and Hoffmann 2018; Cao et al. 2014; Purdon 2015), and an emphasis on the distributional consequences linked to technological change (Breetz, Mildenberger, and Stokes 2018; Green 2015; Meadowcroft 2009, 2011). Literature on these themes is small but burgeoning. It ranges from analyses of the balance of power between various organized groups (Cheon and Urpelainen 2013; Hughes and Urpelainen 2015; Meckling 2011; Rennkamp et al. 2017), to the role of political parties (Dumas, Rising, and Urpelainen 2016), electoral politics (Stokes 2016), formal or informal institutions (Meckling and Nahm 2018; Wood et al. 2020), or state-business relations (Hochstetler and Kostka 2015). Scholars are also examining "experimental" governance by subnational and private actors on various levels of governance (Abbott 2012; Bernstein and Hoffmann 2018; Dorsch and Flachsland 2017; Green 2013; Hale 2016). What these studies have in common is that they highlight the relevance of political factors in the transition from fossil fuel-based to renewable energy technologies, or low-carbon technologies generally. They also call into question the political feasibility of economically "first best" solutions such as carbon taxes, supported by many economists, which are politically difficult to implement as they impose costs on powerful incumbent actors.

A subset of these studies, situated at the intersection between political science, public policy, and innovation studies, has also engaged in more explicit analyses of how technological

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[8] According to Levin et al. (2012), climate change is a super wicked problem because i) time is running out, ii) those seeking to solve the problem are also causing it, iii) no central authority exists, and iv) policies are discounting environmental futures irrationally. Based on these problem characteristics, they argue that, in contrast to reducing collective action problems, path dependency and sequencing approaches are most appropriate to address such problems.

change, in turn, is driving changes in energy and climate politics (Aklin and Urpelainen 2013; Jordan and Matt 2014; Lockwood 2015; Meckling 2019a; Meckling et al. 2015; Rosenbloom, Meadowcroft, and Cashore 2019; Schmidt and Sewerin 2017). For example, scholars have examined how technological change in the energy sector enabled more democratic processes (Mitchell 2011; Szulecki 2018; Yildiz et al. 2015), how the phase-in of renewable energy technologies influenced electoral behavior (Stokes 2016), how the phase-out of coal affects public opinion (Rinscheid and Wüstenhagen 2019), or how the transition to renewable energy technologies affects geopolitics (Overland 2019). In this view, the political effects of technological change are key to understanding the political feasibility of ambitious energy and climate policy. In this dissertation, I add to this body of literature by substantiating the mechanisms linking technological change to politics and by differentiating between various aspects and actors of politics. To do so, I draw on established public policy and political science approaches to describe changes in energy politics. These approaches are described in the next chapter.

2.3. Conceptualizing politics with public policy and regulatory governance literature

In this chapter, I discuss the public policy and regulatory governance literature that provided the theoretical basis for papers 1 and 2, respectively. Chapter 2.4. then turns to political science literature on party politics and voting behavior which are used in papers 3 and 4.

Paper 1 draws on the Advocacy Coalition Framework (ACF) to describe changes in interests and ideas in elite politics. The ACF explains policy change as a function of evolving, underlying politics, conceptualized as advocacy coalition structures within a policy subsystem (Fischer 2014; Ingold 2011; Jenkins-Smith et al. 2014; Weible et al. 2019). Such coalition change occurs because of individual actors' belief changes (Sabatier 1988). Beliefs are structured into three hierarchical belief levels, and actors seek to translate these beliefs into policies through coordinated action within advocacy coalitions (Weible et al. 2011). The ACF identifies exogenous factors as important drivers for belief change. As Sabatier (1988, 134) argued, "changes in relevant socioeconomic conditions (…) can dramatically alter the composition and the resources of various coalitions and, in turn, public policy within the subsystem." Despite the prominence of exogenous factors in the ACF, explicit hypotheses on linking such factors to coalition change have mostly remained unclear (Leifeld 2013; Schlager 1995). To conceptualize technological change as a policy outcome rather than an exogenous factor and to explore the mechanisms linking it to the policy process, in paper 1, we complement ACF with policy feedback theory (discussed below).

Paper 2 draws on regulatory governance literature that is concerned with how societies govern increasingly complex regulatory problems (Levi-Faur 2012). Historically, much of this research has described and explained the shift "from government to governance", i.e., from sole state-authority to the involvement of non-state stakeholders (Cashore 2002; Fukuyama 2016; Potoski and Prakash 2005; Steurer 2013). Many studies investigate the nature, legitimacy, and effectiveness of private regulatory instruments (Auld, Renckens, and Cashore 2015; Bernstein and Cashore 2007; van der Heijden 2020). More recently, the focus has shifted to the interactions between public and private regulatory instruments (Gulbrandsen 2014; Renckens 2020; Trencher and van der Heijden 2019). Whether or not combining public and private regulation increases overall governance performance remains unclear because it may both increase or undermine overall governance stringency and scope (Héritier and Eckert 2008; Malhotra, Monin, and Tomz 2019; Matschoss and Repo 2018). Regulation scholarship has been mostly concerned with how disruptive technological change, such as biotechnology or information and communication technologies can be effectively governed (Culpepper and Thelen 2020). Much of this literature is pointing to the reactive character of regulation and the exogeneity of technological change. To better capture the effect of policy-induced technological change on regulatory instruments and their interaction, paper 2 therefore complements governance with policy feedback literature.

To describe the mechanisms through which technological change affects advocacy coalitions and regulatory governance, papers 1 and 2 draw on policy feedback theory. The need to include an additional theory is the result of a conceptual gap in these literature streams. To reiterate, while the ACF alludes to the idea that technological change may interact with the policy process, it predominantly conceptualizes technological change as an "exogenous factor" outside of the policy subsystem. A variety of scholars criticize that ACF and other policy process theories often rely on untheorized external shocks to explain policy change without explicitly conceptualizing the mechanisms linking the two (Fischer 2003; Hay 2002; van der Heijden et al. 2019; John 2003; Peters 2005). Similarly, possibly resulting from the empirical focus on disruptive technologies, extant governance literature has conceptualized technology primarily as an exogenous factor (Culpepper and Thelen 2020), largely ignoring its potential dynamic co-evolution with regulatory instruments.

Policy feedback theory provides a suitable framework to conceptualize the *endogenous* relationship between technological change as a policy outcome and the policy process or regulatory governance. In other words, based on this theory, I develop mechanisms on how technological change affects interests and ideas in energy politics. The core argument of feedback literature is that previous policy change may feed back into subsequent politics (Béland 2010; Hacker and Pierson 2019; Pierson 1993, 2000; Skocpol 1992), which, in turn, affects subsequent policy output. Policy feedback theory hence conceptualizes the policy process as a path dependent feedback loop (Jordan and Matt 2014). While extant feedback studies have focused on this direct feedback of policies on politics, newer studies explicitly integrate feedback effects through policy outcomes such as technological change (Breetz, Mildenberger, and Stokes 2018; Lockwood 2015; Meckling 2019b; Sewerin, Béland, and Cashore 2020).

Policy feedback literature provides the conceptual basis to substantiate mechanisms linking technological change to politics. In paper 1, in line with classical policy feedback literature (Patashnik and Zelizer 2013; Pierson 1993), I distinguish between interpretive and resource mechanisms that link such policy outcomes to advocacy coalitions, i.e. elite politics. The effects of these mechanisms on coalitions depend on the directionality of these mechanisms. Based on the distinction between positive and negative feedback mechanisms, Jacobs and Weaver (2015) describe policy feedback as self-reinforcing when it stabilizes or expands policy support, and self-undermining when it undermines a policy's political viability over time. In paper 2, I use policy feedback theory to conceptualize the mechanisms behind the interaction between public and private regulatory instruments through technological change.

2.4. Conceptualizing politics with party politics and economic voting literature

Besides these public policy and regulatory governance approaches, this dissertation builds on political science literature to examine how technological change affects two particularly important actors in politics: political parties and voters.

Paper 3 focuses on ideas and institutions in elite politics, and examines the role of political parties in sociotechnical transitions by drawing on party politics literature to describe and explain changes in party positions and their salience (Abou-Chadi, Green-Pedersen, and Mortensen 2020; Adams and Somer-Topcu 2009; Walgrave and Nuytemans 2009). Thus, it complements literature on the politics and agency in sociotechnical transitions (Ingold, Stadelmann-Steffen, and Kammermann 2019; Markard, Suter, and Ingold 2016; Meadowcroft

2011; Rosenbloom, Meadowcroft, and Cashore 2019). Several explanations for party position change have accumulated over the last few decades (for a review see Fagerholm 2016). For the purpose of this paper, I focus on three explanations deemed particularly useful for shedding light on party politics in the context of technological change: issue characteristics and related incentives for political parties, party characteristics, and party systems characteristics. The insights from the party politics literature provide the theoretical background for analyzing changes in party positions on energy technologies, as well as how technological change, in turn, affects these positions.

While papers 1-3 are concerned with aspects of elite politics, paper 4 turns to interests in mass politics. To do so, it draws on political science literature on economic voting to discuss how technological change affects voting behavior (Lewis-Beck and Paldam 2000; Lewis-Beck and Nadeau 2011). This literature argues that voters retroactively punish or reward incumbent governments depending on their economic performance, either because the economic situation affects voters' own "pocketbook", or their community (Anderson 2007; Healy, Persson, and Snowberg 2017; Margalit 2011; Stokes 2016). The nature of electoral punishment or reward depends on the type of the economic shock. Economic shocks are more likely to influence voting behavior if they are directly relevant and salient for citizens and their communities. In addition to salience, economic hardship is often geographically confined because economic activities are spatially concentrated and sectors are affected differently by shocks. More recent economic voting research investigates the impact of local economic performance, and the performance of specific economic sectors, on economic voting (Rogers 2014).

In sum, this dissertation combines policy-related research (Herrera and Post 2019) with more classic political science themes such as voting and parties (Hacker and Pierson 2014) to describe various aspects of energy politics.

Table 1 provides an overview on the theoretical basis of the four individual papers, as well as their role in the research framework introduced in chapter 1.4. The next chapter discusses the research designs of this dissertation.

Table 1: Overview on the individual papers and their theoretical approach and role in the overarching research framework of this dissertation.

#	Title	Role in research framework	Theory	Research question(s)
1	Explaining advocacy coalition change with policy feedback	Focus on elite politics & interests and ideas.	Advocacy Coalition Framework to conceptualize politics. Combined with policy feedback theory to conceptualize how the policy outcome technological change affects coalitions through different feedback mechanisms.	How are politics affected by feedback from policy outcomes?
2	Governing complex societal problems: The impact of private on public regulation through technological change	Focus on elite politics & ideas and institutions.	Regulatory governance approach to conceptualize the interaction between public and private regulatory instruments. Combined with policy feedback theory to conceptualize the role of technological change in shaping instrument interaction.	How does private regulation influence public regulation, and how does technological change affect this relationship?
3	A comparative and dynamic analysis of political party positions on energy technologies	Focus on elite politics & ideas and institutions.	Literature on the politics of sociotechnical transitions. Combined with political science literature on party politics to conceptualize party position change and the role of technological change therein.	How do political parties change their positions on energy technologies, and how does technological change affect these positions?
4	Electoral response to the decline of coal mining in the United States	Focus on mass politics & interests.	Economic voting literature to conceptualize how coal-mining decline can affect voting behavior and electoral outcomes.	How does the decline in coal mining jobs affect voting behavior?

3. Research design

In this chapter, the methods (3.1., 3.2.) and case selection rationales (3.3.) of papers 1-4 are briefly summarized. For a more detailed description, please refer to the methods sections of the individual papers (part II). The methods employed in this dissertation, both qualitative and quantitative, are used with the "dual goal of describing and explaining" (King, Keohane, and Verba 1994). As this dissertation is of exploratory nature into an emerging field of research, systematic description is needed first, and only in a second step can explanation be attempted. As King et al. (2019) emphasize "[e]ven if explanation – connecting causes and effects – is the ultimate goal, description has a central role in all explanation, and it is fundamentally important in and of itself. It is not description versus explanation that distinguishes scientific research from other research; it is whether systematic inference is conducted according to valid procedures". The exploratory nature of this dissertation also requires methodological eclecticism. As Vivien Schmidt has put it (2008, 322), "[p]olitical reality is vast and complicated. No one methodological approach is able to explain it sufficiently. Each gets at a different piece of reality, at different levels of abstraction, with different kinds of generalizations, and different objects and logics of explanation." Given that the topic of this dissertation can be characterized as a "super-wicked" policy problem (Levin et al. 2012), a specific set of methods are required that enable the researcher to account for historical trajectories and path dependencies (Cashore and Bernstein 2018). In light of these considerations, this dissertation uses a mix of qualitative and quantitative methods to answer the research question (Collier and Elman 2008; Lieberman 2005)[9]. In addition, given that randomization is almost impossible in political science

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[9] Collier and Elman (2008) disaggregate the qualitative—quantitative distinction in terms of four criteria: i) level of measurement; ii) large versus small N; iii) use of statistical and mathematical tools; and iv) whether the analysis builds on a dense knowledge of one or a few cases or a large-N study that would routinely be seen as quantitative.

and public policy research, a theoretically guided case selection is central for rigorous research design (Rohlfing 2012; Seawright and Gerring 2008).

3.1. Qualitative methods

Papers 1, 2, and 3 use qualitative case study methods with the goal to explore mechanisms linking technological change to politics. These methods are particularly well suited for exploratory research designs and theory building (Eisenhardt 1989; Seawright and Gerring 2008).

Paper 1 analyzes how technological change affects advocacy coalition change in the German energy sector from 1983-2013. While the analysis of advocacy coalition change relies on a more quantitative approach, network analysis (see 3.2.), the role of technological change for coalition change is analyzed with process tracing. The goal of process tracing is to identify the intervening causal process between variables through an analysis of change and sequence of events (Beach and Pedersen 2013; Collier 2011). The goal of process tracing in Paper 1 is to affirm the relevance of technological change as an important but overlooked factor of coalition change.

Paper 2 examines the interactions between Swiss public and private regulation of energy efficiency in buildings and the role of technological change therein. While the analysis of regulatory stringency of public and private regulatory instruments relies on the quantitative assessment of stringency values (see 3.2.), the role of technological change for instrument interaction was explored with semi-structured expert interviews and desktop research. The semi-structured interviewees were identified following a snowballing sampling method with a combination of positional, decisional, and reputational approaches balancing different viewpoints of key stakeholders (Hoffmann-Lange 2009).

Paper 3 analyzes how technological change affects political party agendas in Germany, France, and the United Kingdom (UK) from 1980 until 2017. While the analysis of party agendas is based on a systematic mapping of party positions on energy technologies based on frequency data, the impact of technological change on these party positions is analyzed with a qualitative assessment of the party manifestos. To do so, relevant manifesto text was manually identified and analyzed. The methodology of paper 3 builds on the vast literature on party politics and manifestos that uses similar research designs (e.g., Abou-Chadi 2016; Adams and Somer-Topcu 2009).

3.2. Quantitative methods

All papers use quantitative methods to different degrees – from basic descriptive analyses to map changes in politics (Papers 2, and 3), to more sophisticated social network analyses based on quantitative data (Paper 1), and advanced quantitative methods to provide explanations for why politics change (Paper 4).

Paper 1 identifies coalition change with discourse network analysis (DNA). DNA is a combination of content analysis and social network analysis (Leifeld 2013, 2016). Based on the systematic coding of text, the method creates two-mode affiliation networks by linking actors (such as firms, NGOs, political parties) to concepts (such as positions on energy technologies). Such an actor–technology network can visualize the changes in politics as changes in networks of political actors and underlying shared ideas or interests.

Paper 2 uncovers changes in public and private regulation with quantitative descriptive analysis of the changes in regulatory stringency values. Based on a novel cross-sectional and longitudinal dataset, this method allows for new insights into the interaction between public and private regulation.

Paper 3 examines party position change on energy technologies using quantitative descriptive analysis, similar to paper 2. Based on a novel dataset and building on the party manifesto project, this empirical assessment enables a comparative and longitudinal analysis of how parties position themselves towards energy technologies.

Paper 4 analyzes whether local decline in coal mining jobs has led to changing voting behavior in US presidential elections from 2000 to 2016. The paper exploits the quasi-experimental setting of local variation in the strong and fast decline in coal mining jobs between 2011 and 2016. Using a difference-in-differences method (Wing, Simon, and Bello-Gomez 2018), the paper examines whether strongly affected counties voted more for the Republican pro-coal presidential candidates than less affected counties.

3.3. Case selection rationale

Besides method selection, an important aspect of both qualitative and quantitative research design is a case selection that fits the research question (Rohlfing 2012; Seawright and Gerring 2008). In the following, I shortly outline my selection rationales of the individual papers.

Paper 1 analyzes technological change in the German energy sector for three reasons. First, as one of the frontrunners of transitions to low-carbon energy systems, Germany is a particularly relevant case. Second, the German energy sector has undergone major changes in previous decades, transitioning toward renewable energy technologies (Lauber and Jacobsson 2016), which allows for analyses on coalition change. Third, in the German case these technological changes are predominantly a result of public policy (Renn and Marshall 2016), which means that changes in politics caused by technological change should be reflected in subsequent policy output. Collectively, these reasons make the German energy transition an "extreme case" that is suitable for an inductive research design with the goal to build theory (Seawright and Gerring 2008).

Paper 2 analyzes the regulation of energy efficiency in the Swiss building sector for three reasons. First, the building sector accounts for 19% of direct and indirect global greenhouse gas emissions, and it is the regulatory field with the highest potential for energy efficiency improvements (IPCC 2018). Second, energy efficiency improvements are dependent on regulation, as multiple barriers hamper the diffusion of energy efficient technologies (Gillingham, Rapson, and Wagner 2016; Rosenow, Kern, and Rogge 2017). Third, the Swiss case offers a high level of data variance regarding public and private regulatory instruments due to substantial and long-lasting regulatory activity in this field. Switzerland can indeed be considered as a leader in energy efficiency regulation (Kemmler, Spillmann, and Koziel 2018).

Paper 3 examines party position changes on energy technologies in Germany, France, and the United Kingdom, for two reasons. First, Germany, France, and the United Kingdom have distinct energy systems and dynamics with different market shares and diffusion rates in renewable, fossil fuel-based and nuclear energy technologies. Second, all three countries have different political systems and electoral institutions, ranging from a two-and-a-half party system to a full multi-party system with strong niche parties (Guinaudeau and Persico 2013). Such diverse case selection strategy (Seawright and Gerring 2008) is suitable for exploratory research into the party politics of technological change in the energy sector.

Finally, Paper 4 analyzes the effects of coal mining decline on electoral outcomes in the United States presidential elections, for three reasons. First, the United States was the third-largest coal producer worldwide in 2016, which makes it a highly relevant case. Second, US coal politics is not only a domestic matter, but – due to the centrality of the United States in international politics and global energy markets – has consequences for the global response to climate change. Finally, there are no systematic and quantitative analyses on the electoral consequences of decline, despite the urgent need to phase-out coal for mitigating climate change. The strong coal decline between 2011 and 2016, and local variation therein, as well as the salience of coal in the 2012 and 2016 election campaigns provide a unique empirical case to examine whether and to what extent coal decline affects electoral outcomes.

3.4. Overview

Table 2 provides an overview on the methods, research cases and data used for the four papers of this dissertation.

Table 2: Overview on research designs used in the individual papers.

#	Title	Method	Research case	Data
1	Explaining advocacy coalition change with policy feedback	Mixed methods: Discourse network analysis and process tracing	Technological change in the German energy sector, 1983-2013	Newspaper data, transcripts of parliamentary debates, protocols of committee meetings
2	Governing complex societal problems: The impact of private on public regulation through technological change	Mixed methods: Descriptive quantitative analysis and explanatory qualitative analysis	Public and private regulation of energy efficiency in buildings in Switzerland, 1975-2018	Quantitative data: Stringency of public and private regulatory instruments; Qualitative data: Semi-structured interviews, reports, technology data
3	A comparative and dynamic analysis of political party positions on energy technologies	Mixed methods: Systematic text coding for quantitative mapping, qualitative analysis	Political parties' positions on energy technologies in Germany, France, and the UK, 1980-2017	Party manifestos, policy documents
4	Electoral response to the decline of coal mining in the United States	Quantitative methods: Difference-in-differences analysis	Coal mining decline in the US and presidential elections, 2000-2016	Coal data, voting data, socio-economic and demographic data

4. Summary of papers

This section provides a summary of each of the papers. For more details, please refer to the individual papers in part II). A discussion of the general theoretical and policy implications can be found in chapter 5.

4.1. Paper 1: Explaining advocacy coalition change with policy feedback

Paper 1 focuses on aspects pertaining to interests and ideas in elite politics. It inductively develops a typology of actor movements underlying coalition change, and feedback mechanisms linking policy outcomes, in this case technological change, to coalition change. The goal of the paper is to build theory on how technological change affects politics, and to draw broader conclusions for theories of policy change.

The paper is based on the premise that despite the prominence of exogenous factors for explaining policy change in public policy theories (Baumgartner et al. 2009; Cashore and Howlett 2007; Hall 1993; Kingdon 1995; Sabatier 1988), the precise mechanisms that link such factors to policy change remain elusive (Schlager 1995). Based on a case study on technological change in the German energy sector, this paper reassesses the nature of exogenous factors. The key argument is that in many cases conceptualizing empirical phenomena as *policy outcomes* instead of *truly exogenous shocks* provides a sound theoretical framework to explain the politics underlying policy change. Importantly, policy outcomes are conceptualized not as "shock" but rather as an integral part of long-term feedback *loops* among policy, policy outcomes, and subsequent politics. In line with the Advocacy Coalition Framework (ACF), politics are understood as the relative strength and structure of different advocacy coalitions in a given policy subsystem (Ingold 2011; Jenkins-Smith et al. 2014; Sabatier 1988; Weible et al. 2019). To substantiate the mechanisms through which policy outcomes drive advocacy coalition change, the paper draws on policy feedback literature (Béland 2010; Béland and

Schlager 2019; Jacobs and Weaver 2015; Pierson 1993; Sewerin, Béland, and Cashore 2020). The paper differs from extant public policy research which largely analyzes the politics of policy change as a driver – rather than a result – of policy outcomes. The main point of the paper is to provide this novel and complementary perspective, with the following guiding research question: *How are politics affected by feedback from policy outcomes?*

Empirically, the paper focuses on policy-induced technological change as a distinct form of policy outcomes (Schmidt and Sewerin 2017). It examines advocacy coalition change in the German energy policy subsystem during the period 1983 to 2013, and proceeds in two steps: First, Discourse Network Analysis (DNA) is used to assess coalition change in the German energy subsystem (Leifeld 2016) based on text analysis of over 3000 newspaper articles. Second, through theory-building process tracing the paper establishes both the mechanisms and the effects that link policy-induced technological change to coalition change (Beach and Pedersen 2013). With DNA, the paper shows that the advocacy coalitions that support fossil fuel-based technologies (FFT) and nuclear technologies (NT) become less powerful in the subsystem, while the advocacy coalition for renewable energy technologies (RET) increases in terms of size and actor diversity. The analysis identifies coalition decline and growth and detect four actor movements that underlie these coalition changes: actor disappearance, appearance, dissociation, and association. Figure 4 below shows these coalition changes for three periods from 1983 to 2013.

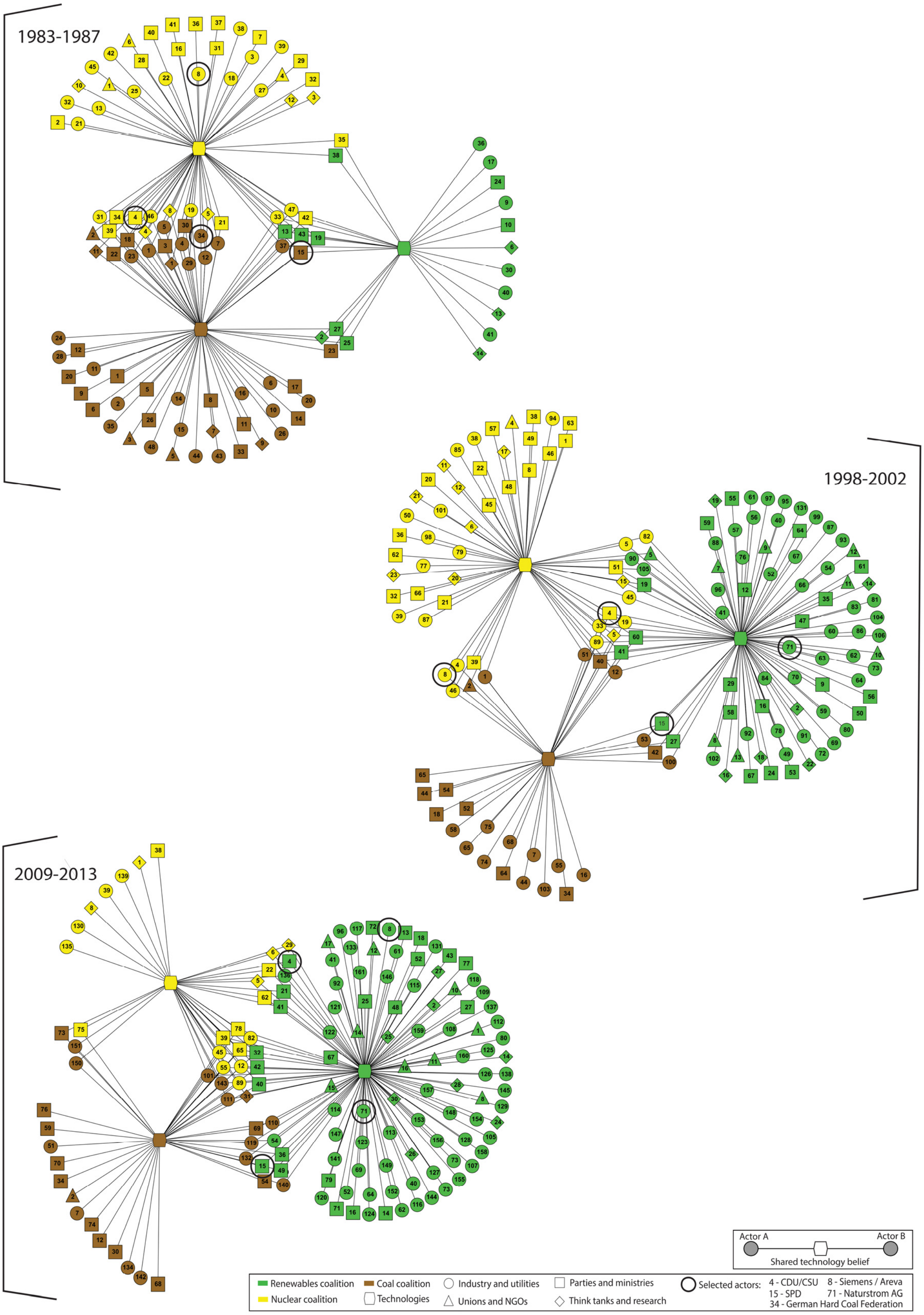

Figure 4: Change in advocacy coalitions in the German energy subsystem from 1983-2013. The two-mode support affiliation networks represent the German energy subsystem in three periods: 1983-1987, 1998-2002, and 2009-2013. Nodes are actors that coalesce around the aggregates of positive statements on energy technologies (FFT, NT, RET). Networks are based on coding of 3387 newspaper articles, yielding 3900 coded statements of 288 actors. Actor nodes are colored according to each node's most frequently supported energy technology. The graph layout is based on stress minimization.

To explain these actor movements underlying coalition change, process tracing is used to qualitatively establish the mechanisms by which policy outcomes affect advocacy coalitions. Policy outcomes, in this case policy-induced technological change, are found to drive coalition change through four feedback mechanisms: negative resource, positive resource, negative interpretive, and positive interpretive mechanisms. Based on these findings, the paper develops propositions on how coalition change and feedback mechanisms are linked to four policy trajectories: policy stability, expansion, contraction, and transformation. Figure 5 illustrates the relation between these actor movements (quadrants), feedback mechanisms (axes), and their link to the policy trajectories (colors).

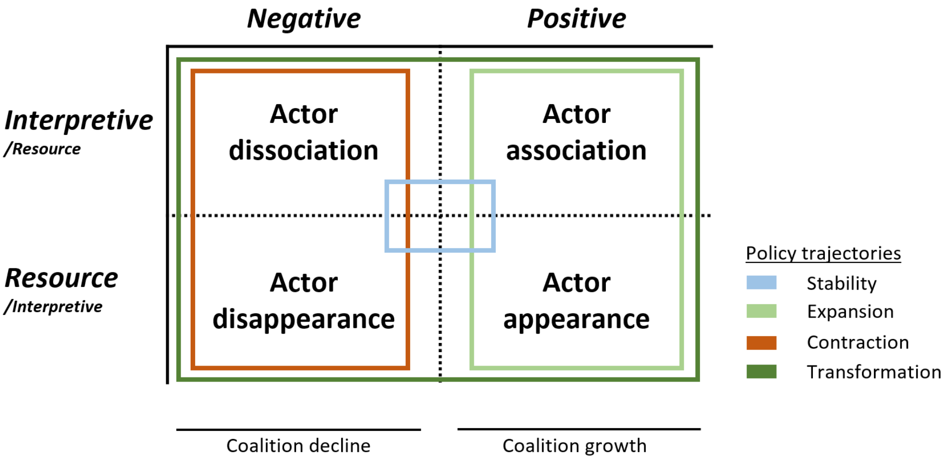

Figure 5: Feedback mechanisms (axes), their effects on actor movements (quadrants) and coalition change, and the link to policy trajectories (colors).

Hence, this paper shows that patterns of coalition change are the effect rather than the cause of policy outcomes, offering an alternative perspective to the ACF and other general policy theories. By explicitly discussing how policy outcomes are dynamically linked to actor movements, and thus coalition change, the paper speaks to the ongoing discussion within the ACF community regarding the drivers of coalition and policy change (Nohrstedt and Weible 2010; Weible and Ingold 2018; Weible and Jenkins-Smith 2016). The use of policy feedback concepts within the ACF shows how the integration of different approaches can help the framework to gain more descriptive and explanatory leverage (Pierce et al. 2017). With a focus on policy-induced technological change, the paper contributes to applying feedback concepts beyond well-trodden policy fields, such as social policy (Béland, Rocco, and Waddan 2018). Through the empirical focus on the energy policy subsystem, it also contributes to the emerging literature on the importance of politics in energy transitions (Aklin and Urpelainen 2013; Köhler et al. 2019; Meckling 2019a; Rosenbloom, Meadowcroft, and Cashore 2019; Schmidt, Schmid, and Sewerin 2019; Sovacool and Brisbois 2019; Stokes 2016).

4.2. Paper 2: Governing complex societal problems: The impact of private on public regulation through technological change

While paper 1 examines how technological change affects the politics underlying general patterns of policy change, paper 2 differentiates between public and private regulatory instruments and analyzes how technological change affects their interplay. Notably, it examines how technological change affects regulators' cognitive perception of the technical and economic feasibility of efficiency technologies and hence drives regulatory stringency.

The paper starts with the premise that complex governance structures, comprised of both public and private regulatory instruments, are needed to address "super-wicked" problems such as climate change (Hsu et al. 2019; Jordan et al. 2015; Levi-Faur 2006; Levin et al. 2012; Meadowcroft 2007). Besides questions of legitimacy and potential pitfalls of private regulatory instruments (Bernstein and Cashore 2007; Cashore 2002), assessing the effectiveness and stringency of these complex governance structures requires an understanding of the interaction between public and private instruments (Eberlein et al. 2014; Gulbrandsen 2014; Judge-Lord, McDermott, and Cashore 2020; Renckens 2020). Research on instrument interaction has shown that public regulation plays a crucial role in facilitating the emergence, implementation, and enforcement of private regulation (Héritier and Eckert 2008). However, the reverse effect, i.e., the *impact of private regulation on public regulation,* remains understudied (Malhotra, Monin, and Tomz 2019). This paper argues that in order to fully comprehend the effectiveness of private regulation, an improved understanding of its impact on public regulation is required. While several mechanisms may exist, the focus is on the role of technological change and its feedback on regulation. In extant regulation literature, technology is predominantly seen as an exogenous factor (Porter 2014; Snir and Ravid 2016) or a tool to improve the performance of regulatory instruments (Auld et al. 2010) rather than a target of regulation itself. In contrast to this conception, and in line with innovation studies

(Hoppmann, Huenteler, and Girod 2014; Kivimaa and Kern 2016; Schmidt and Sewerin 2019), this paper understands technology as the *target outcome* of a policy, meaning that the goal of the policy is to induce technological change. The paper draws on policy feedback literature (Béland and Schlager 2019; Pierson 1993; Sewerin, Béland, and Cashore 2020) to discuss how private regulation can, over time, feed back into public regulation through technological change. In this context, technological change may constitute one of several important *mechanisms* that explains the impact of private regulation on public regulation. The paper asks the following research question: *How does private regulation influence public regulation, and how does technological change affect this relationship*?

To address this question, empirically, the paper focuses on the case of energy efficiency in the Swiss building sector, which provides a suitable case for an exploratory theory-building study. To understand the impact of private regulation on public regulation, it employs a mixed-methods approach to analyze changes in the *regulatory stringency* of two Swiss regulatory instruments over time—namely, public building standards and a private building label. First, a novel and extensive dataset is constructed on both public regulation across 23 Swiss Cantons (i.e., subnational jurisdictions) and private regulation over more than 30 and 20 years, respectively. The analysis shows that the stringency of both public and private regulatory instruments increases over time, with the latter being more stringent. Figure 6 (A-E) below depicts these changes in regulatory governance.

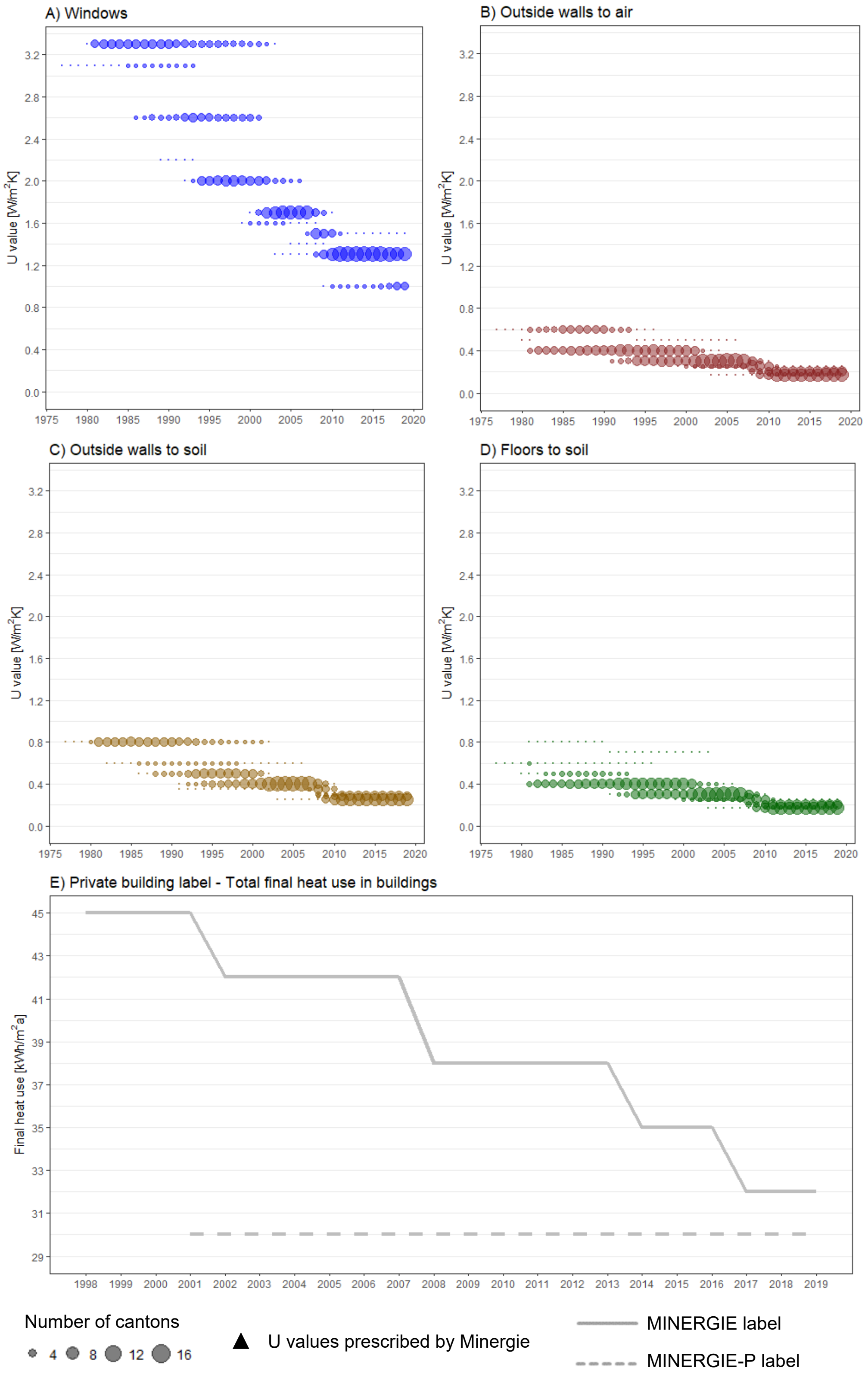

Figure 6: Public building standards for (A) windows (blue); (B) outside walls to air (red); (C) outside walls to soil; and (D) floors to soil (green) for each year. Decreasing values correspond to increasing stringency of the standard and label. The bubble size corresponds to the number of cantons with the same value (ntotal = 23). The black triangles correspond to the U values prescribed by the private building label. **(E) Private building label's prescribed total final heat use in new residential buildings for standard buildings (solid line) and for buildings meeting specific requirements regarding the building shell (dashed line).** The final heat use includes the weighted energy use for heating, ventilation, air conditioning, and hot water.

Second, 27 semi-structured expert interviews are conducted to understand the drivers behind public and private regulatory stringency and their interaction. The analysis shows that private regulation can drive higher stringency in public regulation at a subsequent time by fostering technological innovation in niches. These niche markets enabled innovation in and diffusion of new energy-efficient technologies, such as three-glazed windows and improved wall insulation. These technologies became cheaper due to increased market diffusion and resulted in economies of scale and learning effects for the technology manufacturers, installers, and users. This wider range of technically feasible options and economically affordable technologies, in turn, constituted positive feedback effects for subsequent regulatory change. This effect is subject to moderating factors such as cantonal differences in bureaucratic capabilities or political majorities, and technology differences such as variation in innovation dynamics between windows and walls. Figure 7 below summarizes the argument of the paper.

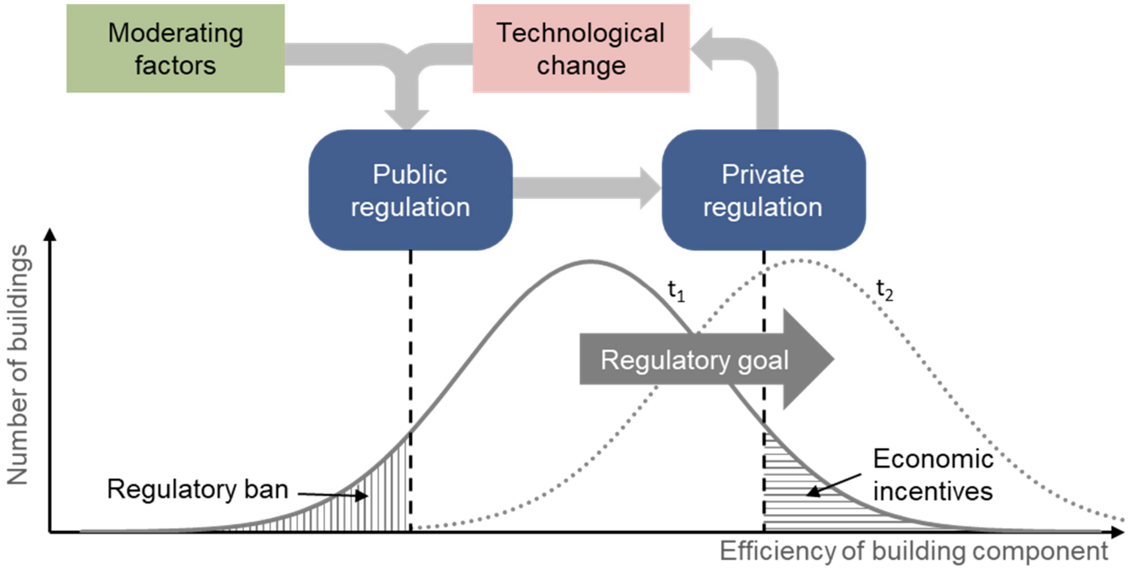

Figure 7: Interaction between public and private regulation through the mechanism of technological change. The regulatory goal to increase overall efficiency of building components over time (time 1 to time 2) is driven, on the one hand, by the private building label, which increases the economic incentives and feasibility of more efficient building components, and on the other hand, by public building standards, which ban inefficient building components (adapted from Interviewee 2).

Hence, this paper shows that, under certain conditions, combining public and private regulation can increase overall governance performance through a mutual ratcheting-up process. The longitudinal analysis provides substantial evidence for a symbiotic interaction between public and private regulatory instruments through the mechanism of technological change. While the public instrument ensures a broad scope of the governance structure, the private instrument set the benchmark for the direction of changes in instrument stringency. Technological change induced by private regulation increased the political feasibility of more stringent public regulation by expanding the availability of technically feasible and economically affordable efficiency technologies, which constituted positive feedback effects in the regulatory process. The analysis reveals a successful case of a ratcheting-up process between both public and private regulation and hence informs ongoing debates about such ratcheting-up in climate and environmental policy (Cashore et al. 2007; Judge-Lord, McDermott, and Cashore 2020; Meckling et al. 2015; Pahle et al. 2018).

4.3. Paper 3: A comparative and dynamic analysis of political party positions on energy technologies

Paper 3 zooms into a particular actor type of energy politics, namely political parties. It examines how the ideas of political parties on energy technologies change as a result of technological change, and whether institutional settings such as party systems moderate this effect.

The paper starts with the premise that there is a lack of systematic research on the role of political parties in sociotechnical transitions: Parties are not or only tangentially mentioned in recent review articles and research agendas (Fischer and Newig 2016; Köhler et al. 2019; Lockwood et al. 2017a; Roberts et al. 2018; Sovacool and Brisbois 2019). More specifically, it is unclear how political parties position themselves toward energy technologies, how these positions change over time, and how transitions, in turn, affect party positions. This is problematic for two reasons. First, as highlighted by innovation and transitions literature, accounting for such sector and technology-sensitive differences is necessary for meaningful analyses and effective policy recommendations (Azar and Sandén 2011; Huenteler et al. 2016; Zeppini and van den Bergh 2011). Second, as shown by political science literature relating to party politics, in democracies, political parties are not only key designers of public policy but they also mediate and navigate political conflict (Abou-Chadi, Green-Pedersen, and Mortensen 2020; Adams and Somer-Topcu 2009; Benoit and Laver 2006; Ware 1996). Crucially, party positions have been found to be reflected in subsequent policy change (Borghetto and Belchior 2020; Brouard et al. 2018). A systematic and dynamic assessment of political party positions on technologies is hence necessary for improving our understanding of the politics of sociotechnical transitions. Given the urgent need to accelerate policy change to address time-sensitive sustainability challenges (Kivimaa et al. 2020; Roberts et al. 2018), the rate and directionality of party position change is particularly relevant. Paper 3 addresses this gap with the following research question: *How do political parties change their positions on energy technologies, and how does technological change affect these positions?*

To answer this question, empirically, the paper takes an exploratory approach and examines party position changes related to energy technologies in a longitudinal and comparative case study of Germany, France, and the United Kingdom (UK) from 1980 to 2017. Methodologically, the paper proceeded in two steps. First, it mapped party position changes related to energy technologies based on a novel dataset that included all major parties in the three countries over a period of four decades. This dataset complements the established Party Manifesto Project (Krause et al. 2018) with technology-specific codes on both the niche and regime levels, including renewable energy technologies (RET), nuclear technology (NT), and fossil fuel-based technologies (FFT). Besides offering pro- and contra-positions on energy technologies, this dataset also allowed to capture the salience of positions in party manifestos. The analysis revealed differences relevant to individual energy technologies, party families, time, and countries. Figure 8 shows the different salience levels allocated to energy technologies by country and party family. The analysis shows that the energy sector is a less salient issue compared to more generic policy issues such as environmental protection or social welfare, yet that there are differences between countries and party families.

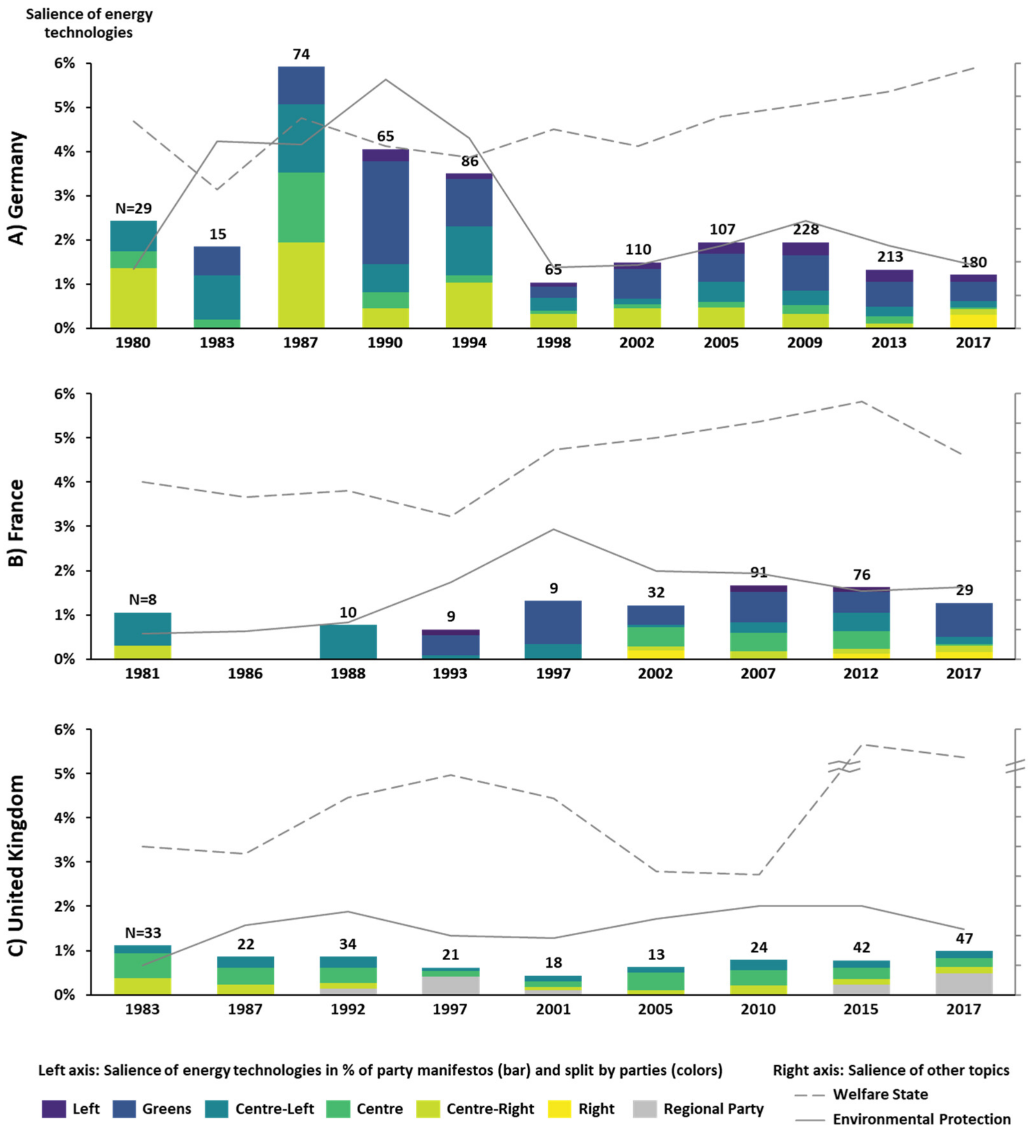

Figure 8: Salience of energy technologies in party manifestos by party family in Germany (A), France (B), and the United Kingdom (C) from 1980 to 2017 and in comparison to other topics. Salience measured as the share of quasi-sentences in a party manifesto (number (N) of coded sentences on energy technologies indicated above bars). Data on salience of Welfare State [variable ID: welfare] and Environmental Protection [variable ID: 501] taken from the Manifesto Project (Krause et al. 2018), and depicted on a secondary axis (right) at a different scale.

Figure 9 zooms into these differences. It shows that compared to FFT and NT, party positions on RET are relatively homogenous and increasingly supportive over time. With exceptions, Left to Center parties allocated more salience to energy technologies and were more opposed to FFT and NT than their Center-Right to Right counterparts. Generally, niche parties changed their positions on technologies faster than incumbent parties. Finally, while energy technologies were found to be a rather salient issue in Germany, they were seen as less salient

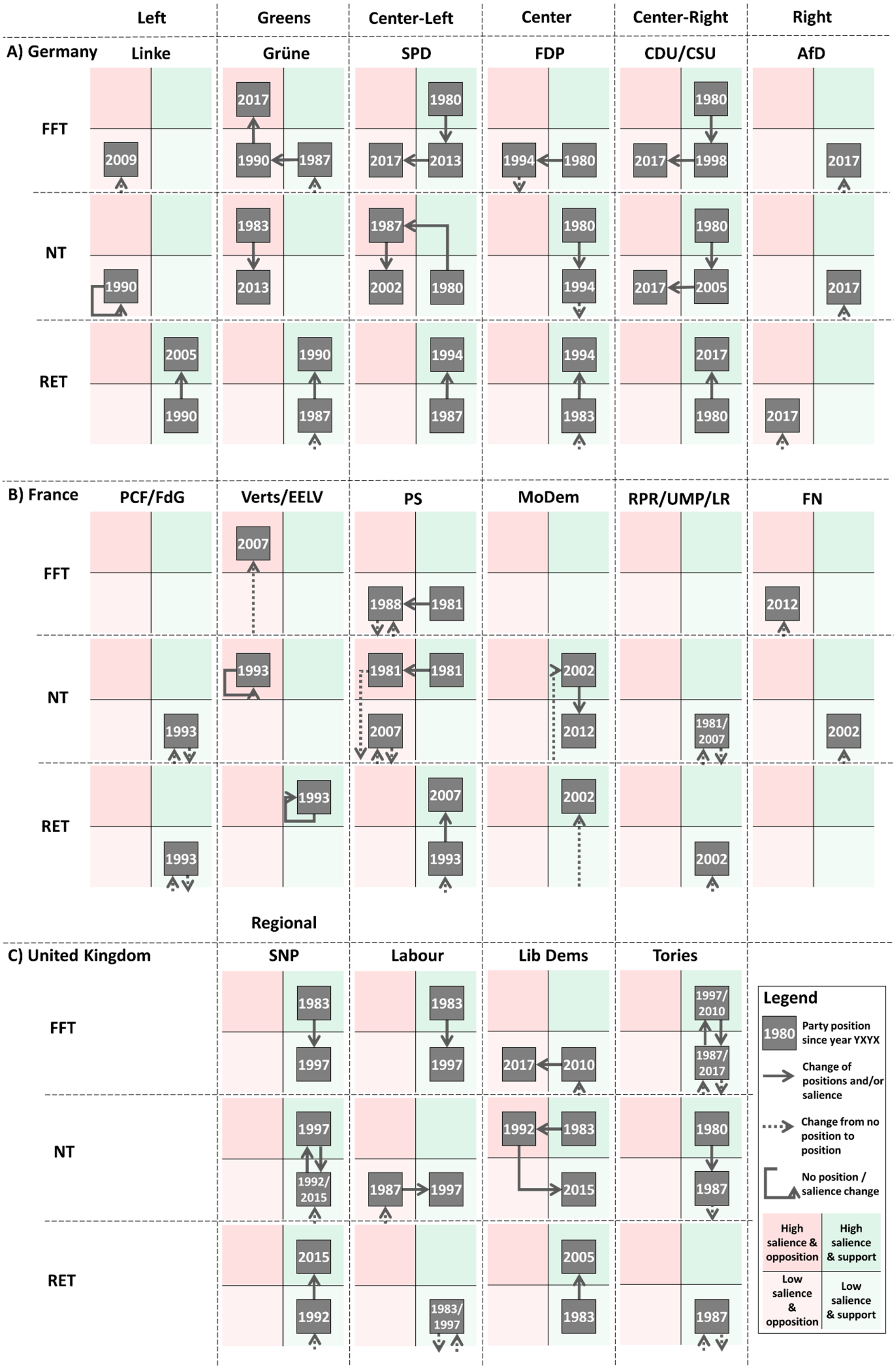

Figure 9: Positions of political parties on energy technologies and their salience in Germany, France and the United Kingdom from 1980 to 2017. Stylized visualization of collected data (see Table A.2 in the annex). Threshold value for low and high salience: 50th percentile of salience distribution per party (based on the share of quasi-sentences allocated to the individual technology group divided by the total quasi-sentences per manifesto).

in French and British party agendas. In addition, technology-specific patterns varied across countries. For example, NT was increasingly opposed in Germany while it remained relatively unchallenged in France, and was the subject of a renaissance in the UK.

In a next step, the paper qualitatively analyzed the collected data to examine the role of technological change in party position changes. The analysis shows that technological change – moderated by party characteristics and the type of party system – is one factor that drives party positions as well as the salience of these positions. The analysis also identified three related mechanisms through which technological change affected the issue characteristics of energy technologies: perceived co-benefits or costs of a given technology; changes in the menu of policy options; and path dependence associated with existing technology and infrastructure. Here, issue characteristics are defined as features of energy technologies, such as their relative costs, deployment, and localization, in terms of value chain and associated jobs and economic activity. The analysis shows that political parties refer to changes in these issue characteristics as an argumentative underpinning for their changes in positions on technologies.

On a more abstract level, this paper makes three important contributions. First, this is the first study that systematically maps political party positions on energy technologies. Second, this paper contributes to the growing literature on politics, actors, and agency in sociotechnical transitions as it represents a response to the calls for more research in this vein (Köhler et al. 2019; Lockwood et al. 2017b; Rosenbloom, Meadowcroft, and Cashore 2019; Sovacool and Brisbois 2019). With the focus on party politics, this study complements previous research on the role of political actors such as those involved with social movements (Hess 2018), intermediary actors (Kivimaa et al. 2019), or advocacy coalitions (Markard, Suter, and Ingold 2016). Third, the paper shed light on how technological change drives party positions.

The findings indicate that, to varying degrees, political parties are updating their positions on technologies in what can be called a learning process (Goyal and Howlett 2020). Such learning by political parties suggests that policymakers may intentionally foster long-term political party support for renewable energy technologies by improving their underlying issue characteristics, such as costs, through the establishment of protective spaces (Lockwood 2016). In other words, by inducing technological change, policymakers may trigger a virtuous feedback loop in which policy-induced niche technologies are increasingly supported by political parties, which may subsequently lead to more ambitious and stringent types of policy outputs (Levin et al. 2012; Rosenbloom, Meadowcroft, and Cashore 2019).

4.4. Paper 4: Electoral response to the decline of coal mining in the United States

While papers 1 to 3 focus on how technological change affects elite politics, paper 4 examines interests in the mass politics of technological change. Paper 4 also complements the other papers in that it focuses on technology decline rather than innovation and diffusion of new technologies.

More specifically, this paper analyzes whether and how the decline in coal mining in the US has affected voting behavior in US presidential elections. Phasing out coal has a central role in almost all scenarios that are compatible with the Paris Agreement and the Sustainable Development Goals (SDGs) agenda (Edenhofer et al. 2018; Tong et al. 2019). Yet, such transitions from old to new technologies affect value chains and jobs (Burke, Best, and Jotzo 2019; Carley, Evans, and Konisky 2018; Mayfield et al. 2019) and, in turn, can provoke political backlash. Political science literature on economic voting shows that voters punish policymakers in charge for policies that directly impact their economic welfare or the socio-economic situation of their community (Healy and Malhotra 2013; Lewis-Beck and Stegmaier 2000). Such economic voting can slow down the transition to new, cleaner energy carriers, ultimately jeopardizing the SDGs and the Paris climate targets. Quantitative studies on economic voting in the context of coal decline are lacking so far. Only very few – mostly qualitative – studies have investigated the political and societal effects of coal decline (Carley, Evans, and Konisky 2018; Vona 2019) and scholars call for more research on the topic (Jewell and Cherp 2020). The paper addresses this gap and analyse the effects of coal mining decline on local voting outcomes in US presidential elections.

Coal was a highly salient topic during the US presidential campaigns of 2012 and, especially, 2016, with Republican and Democratic candidates holding completely opposing views on the issue (Brown and Sovacool 2017). Republicans supported coal mining and framed the Obama administration's energy and climate policies (e.g. the Clean Power Plan of 2015) as a 'war on coal'. On the other hand, the Democrats promised to accelerate the transition away from coal towards renewable energy carriers. These political debates around coal happened in an increasingly difficult environment for the coal industry: US coal production has fallen massively since 2011, and the US coal mining industry lost 39,650 jobs from 2011 to 2016, a 43% drop, representing a loss of about 100 million annual labour hours. Coal mines were primarily driven out of business by cheaper alternative energy carriers and international coal market prices (Kolstad 2017; Mendelevitch, Hauenstein, and Holz 2019). The incidence of coal mining job losses hence depend primarily on the local characteristics of coal mines and their productivity (Jordan, Lange, and Linn 2018) and was independent of federal and state policy.

The paper uses this quasi-experimental setting of rapid and locally concentrated coal mining decline combined with high political salience. To do so, it employs a matched difference-in-difference (DiD) analysis to test whether the loss of coal mining jobs affected county-level (i.e., local) voting outcomes in the presidential elections from 2000 to 2016. Specifically, the paper investigates the voting outcomes of the counties that lost coal jobs between 2011 and 2016 (*N* = 163 'treated' counties) and compare those with the counterfactual development of most similar control counties identified with a matching technique based on six socio-economic variables. Figure 10 shows treated and matched counties on a map and parallel pre-treatment trends for matched samples for one of the two main setups. Treated counties are those that experienced a loss in coal jobs from 2011 to 2016. A matching algorithm chooses control counties from all US states. The treated and control counties followed identical pre-treatment voting trends over 16 years from 1992 to 2008. These trends changed from 2012 onward, satisfying the pre-treatment parallel trends assumption and indicating a voting outcome difference between treated and control counties in 2012 and 2016.

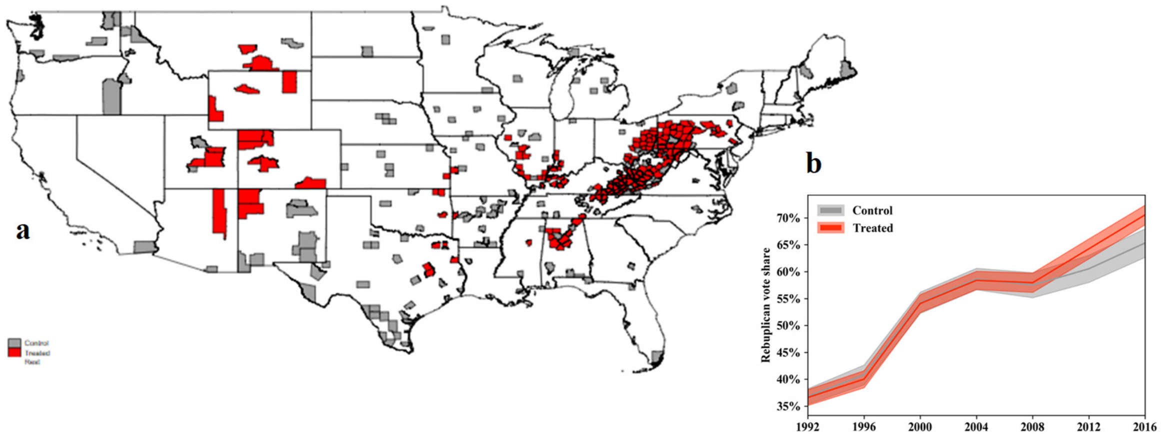

Figure 10: Treated and control counties for the first main setup. (A) Location of treated and control counties and (B) parallel pre-treatment trends since 1992 for all US states. Treated counties in red, *N* = 163, control counties in grey, *N* = 163.

In a first step, for the estimation of the effect size, the paper reports results along seven specifications with additional robustness checks. Here, for space reasons, only findings from the main specification are reported, however, effect sizes were relatively stable across all specifications. As shown in Figure 11, Republican vote shares in counties with coal mining job losses were 3.9 pp higher compared with control counties in 2012. The effect increased to 5.4 pp in 2016. The effect sizes were relatively stable across all specifications ranging from 2.4 to 4.3 pp for 2012 and 2.8 to 5.6 pp for 2016. The size of the effect is substantial when compared with average coal job losses in the treated counties. Job losses ranged from 1 to 3,218 per county, with an average of 265. The loss of 100 coal jobs translates to a 2.0 pp higher vote share for the Republican candidate in 2016 (1.5 pp in 2012). Importantly, these effect sizes suggest that it was not only affected coal miners who voted differently as 5.4 pp represents 273,520 votes which exceeds the 43,123 coal jobs lost by a factor of more than 6.

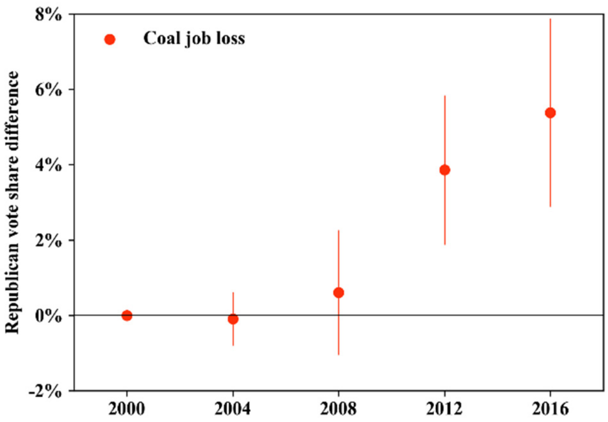

Figure 11: The effect of coal job losses on presidential elections: effect size for presidential elections from 2004 to 2016 for the main specification. The results are robust when using the loss of coal mining labour hours or coal mine closure as treatment and are unaffected by third party vote shares. All treatment samples are matched individually. Displayed coefficients include a 95% confidence interval and are estimated with time and county fixed effects and standard errors clustered at county level.

In the second step, the paper turns to treatment intensity. The intensity of coal job losses was highly uneven amongst counties. To account for this variation, two additional specifications are run. First, the analysis shows that the effect stemmed entirely from the counties with strong coal job losses. There was an increase in Republican vote shares of 5.9 pp in counties with strong coal job losses in 2012 (6.2 pp in 2016). Residents of only weakly affected counties, however, did not vote statistically differently from the control counties. This result points to the importance of the magnitude of coal job losses for an electoral response. Second, the analysis shows that the loss of coal jobs in western counties (*N* = 28) did not affect voting outcomes, whereas eastern counties with coal job losses (*N* = 135) showed an effect similar in magnitude to the estimated effect in the total sample (3.8 pp in 2012 and 5.1 pp in 2016).

Finally, in the third step, the paper investigates geographic spillovers in voting behaviour from coal to surrounding non-coal counties. Whereas there is no spillover effect in the 2012 presidential elections, there were spillovers in 2016 that extended up to 50 km around counties with coal job losses. The size of the spillovers is substantial. There was an increase in

Republican vote shares of 2.2 pp in the 2016 election for counties without coal job losses that are within 50 km of a county with coal job losses. The existence of spillover effects is politically important because, in addition to the disproportionately strong backlash to coal job losses within affected counties, spillovers into neighbouring regions further increase the political cost of transitioning away from coal.

In sum, the findings of this paper indicate that coal phase-outs worldwide required to meet the Sustainable Development Goals may be politically costly. While this paper establishes the existence of an electoral response and its size, future research should shed more light on the underlying mechanisms. For example, a remaining question is whether purely economic or also cultural factors trigger the electoral response and whether they need to be activated with an active political campaign. In case economic factors dominate, lump-sum transfers to and retraining programs of affected workers and communities might be the best option. If, however, the disruption of a cultural identity plays a major role, policy responses are more complicated and may (additionally) require managing the coal mining heritage.

5. Discussion and conclusion

This final chapter first discusses the overall findings and contributions of this dissertation (5.1.). It then outlines avenues for future research that may also address the limitations of this dissertation (5.2.). Chapter 5.3. outlines general policy implications, and chapter 5.4. contains concluding remarks.

5.1. Discussion and contributions to the literature

The goal of this dissertation is to examine whether and how technological change affects interests, ideas, and institutions in both elite and mass energy politics. In an exploratory and inductive approach, I forge a more explicit link between technological change and politics, thereby contributing to the nascent debate on technology and energy politics at the intersection of political science, public policy, and innovation literature. To answer my research question, this dissertation leverages insights from four individual papers. Collectively, these papers use a plurality of theoretical approaches, qualitative and quantitative methods, as well as empirical cases.

Overall, the findings of the papers show that technological change is indeed a driver of energy politics. Technological change has resulted in significant coalition change in favor of renewable energy technologies in the German energy sector (paper 1), facilitated more stringent public and private regulation (paper 2), shaped the way political parties position themselves toward energy technologies (paper 3), and affected electoral behavior (paper 4). The papers of this dissertation also discovered and conceptualized several mechanisms linking technological change to these political effects. On the one hand, actors change their positions on energy technologies because of the cognitive perception of decreasing costs, increasing job provision, or other co-benefits of such technologies. In paper 1, I labeled this an *interpretive* mechanism. These aspects relate to the *expanding capacity* of technological change mentioned in the introduction in that they turn previously unavailable policy options into available and feasible choices. On the other hand, energy politics change because new actors emerge and grow while incumbent actors shrink and disappear as a result of technological change. While renewable energy technologies gain in market shares, economic activity around fossil fuel-based technologies, such as coal mining, declines. This *distributional capacity* of technological change is both induced by public policy (paper 1), and due to broader market forces (paper 4). In paper 1, I label this link between technological change and politics a *resource* mechanism. As indicated, both interpretive and resource mechanisms may work in positive and negative directionality.

While papers 1 and 2 indicate that these mechanisms and the resulting effects on energy politics may break the carbon lock-in, findings of papers 3 and 4 also emphasize that technological change from fossil fuel-based to renewable energy technologies triggers resistance in both elite and mass politics. Such resistance takes the form of lasting political party support for incumbent energy technologies, or voters' support for pro-coal presidential candidates. Hence, while the findings suggest that political momentum for low-carbon technologies is building, especially in elite politics such as advocacy coalitions and regulatory governance, they also show that the realm of electoral politics, both on supply and demand side, remains subject to political inertia in favor of fossil fuel-based technologies. These conclusions should be taken with a grain of salt, because the papers of this dissertation *also* demonstrate that the politics of technological change is a contingent and dynamic phenomenon that depends on country-specific institutions (paper 3), individual technologies and their characteristics (paper 2), and temporal dynamics (all papers). Besides these general considerations regarding my research question, in the following, I want to emphasize three contributions of this dissertation.

First, a key contribution of this dissertation is to conceptualize the policy process as a policy feedback loop, in which previous policy choices affect subsequent politics through the policy outcome of technological change. By explicitly integrating policy outcomes in the feedback loop, this dissertation has contributed to overcoming the traditional dichotomy between exogenous and endogenous drivers of policy change that is prevalent in public and political science literature. Doing so, this dissertation has also explored and developed more detailed mechanisms linking technological change to various aspects and actors of energy politics. For instance, by combining ACF and regulation literature with policy feedback theory, papers 1 and 2 have developed theory on how technological change leads to coalition change and affects the interaction among regulatory instruments. Drawing on party politics literature, paper 3 described how technological change affects party agendas by affecting the issue characteristics underlying energy technologies.

Second, this dissertation contributes to integrating technological change more explicitly as a relevant factor in explanatory approaches of politics. To the best of my knowledge, all four papers give novel, previously unavailable empirical insights on how technological change affects energy politics. These new empirical insights are relevant given the centrality of technological change in creating and solving climate change. The findings of this dissertation support the assertion that energy politics is mostly driven by distributive conflicts resulting from technological change, i.e. the transition from fossil fuel-based to renewable energy technologies. These findings also suggest that the focus on global institutions and the prevention of free-riding in large parts of extant energy and climate politics literature is not addressing the most important dilemma. Rather, the expanding and (re)distributive capacity of technological change and their effects on elite and mass politics are the prime drivers of public policy and hence largely influence the political feasibility of ambitious energy and climate policy.

Third, this dissertation embraces two key developments in the field of political science as described by Goodin (2011): evolutionary thinking and network approaches. With the focus on how technological change affects long-term patterns of changes in politics, this dissertation highlights the evolutionary aspects of politics, which is strongly influenced by innovation scholars and evolutionary economists. In large parts, the dissertation also emphasizes networked governance in that it examined various actor types – such as advocacy coalitions, political parties, and voters – at different governance loci – such as national and subnational levels.

5.2. Avenues for future research

In the following, I wish to highlight avenues for future research, which may also address some of the methodological, empirical, and conceptual limitations of this dissertation.

Methodological limitations and avenues for future research

Methodologically, the case study approach of this dissertation can attract criticism regarding its potential for generalizability and the difficulty to establish causal relationships. Further, the case studies do not assess the relative weight of technological change in explaining energy politics compared to competing explanatory factors. However, the goal of this dissertation was to develop theory and to uncover new empirics in an exploratory approach. Future research should build on these efforts and use more quantitative research designs to test the theory built in this dissertation.

Another more specific methodological limitation of this dissertation is that it often relies on self-reported actor positions on energy technologies, for instance in the form of newspaper articles (Paper 1), interview data (Paper 2), or party manifestos (Paper 3). As Ingold et al. (2020)

have argued, there may be mismatches between policy positions that actors self-report and positions they advocate during a policy process. For instance, Ingold et al. highlight that expert evaluations of party positions may be more accurate compared to analyses of party manifestos (see also Mikhaylov, Laver, and Benoit 2012). While for many political phenomena there are almost no alternatives to assessing self-reported actor positions, future research may cushion this problem by additionally focusing on behavioral data, such as voting behavior on energy policy by members of parliament or monetary contributions to political parties by interest groups.

Empirical limitations and avenues for future research

Empirically, this dissertation necessarily restricted the analysis to some countries, technologies, and political phenomena. I want to highlight additional areas I deem relevant and interesting for future research. First, the empirical scope should be expanded to emerging energy technologies that are projected to be crucial to reach the Paris climate targets. The report on innovation needs for future clean energy systems by the International Energy Agency (2020) may serve as starting points for such an endeavor. Critical technologies include battery storage (Beuse, Schmidt, and Wood 2018), hydrogen for energy demand that is difficult to electrify, or various carbon dioxide removal technologies that may be used to compensate for residual emissions and achieve net negative emissions (IPCC 2018; Minx et al. 2017). Similar to the energy technologies analyzed in this dissertation, these emerging technologies are likely subject to constraints that need to be overcome with public policy, putting energy politics center stage.

Further, the conceptual framework and theory built in this dissertation may also be applied beyond energy technologies. Such an extension may not only provide insights into new empirics but also increase the external validity of the argument. For example, current developments in automation or information and communication technologies may serve as interesting comparative cases. While these technologies are relatively well covered in relation to social policy and welfare states (Autor 2015; Dermont and Weisstanner 2020; Frank et al. 2019; Frey, Berger, and Chen 2018; Frey and Osborne 2017; Kurer and Gallego 2019), they directly and indirectly also affect the transition to low-carbon technologies. For instance, the energy transition creates the need for enhanced digitalization of electricity grids (Judson, Soutar, and Mitchell 2020; UNIDO 2017). Such technological change may come with novel political challenges as it spans previously disconnected regulatory governance fields (digital and energy technologies).

Another climate-relevant sector that is worthwhile investigating through the technology-politics lens is the food sector. Technological change is accelerating in various parts of the food sector and could be significantly enhanced with public policy to lower greenhouse gas emissions and other negative externalities (Fesenfeld, Schmidt, and Schrode 2018; Herrero et al. 2020). Lessons from the energy sector on the political effects of technological change may be applicable to this sector and help accelerate its transition (Fesenfeld et al. 2020).

Besides technological change, two other levers are also relevant for emissions reductions: behavioral change and natural sinks (Steffen et al. 2018; Wiedmann et al. 2020). For instance, recent research highlights the potential of natural carbon sinks and nature-based solutions such as tree restorations for climate change mitigation (Bastin et al. 2019; Fernández-Martínez et al. 2019; van der Jagt et al. 2019; WEF 2020). While the theory built in this dissertation is largely specific to technological change, the general framework of the policy feedback loop may be applicable to such nature-based outcomes. Yona, Cashore, and Schmitz (2019) provide first insights into how a policy feedback loop perspective may be used for such purposes (see also Bodin et al. 2019).

Conceptual limitations and avenues for future research

Finally, this dissertation focused on a select set of political phenomena and hence select concepts from political science and public policy literature. The discipline of political science provides a much larger set of frameworks and theories that may be harnessed to describe how technological change affects interests, ideas, and institutions in elite and mass energy politics. Future research could leverage these frameworks to address an important gap in this dissertation: the *interaction* between interests, ideas, and institutions on both elite and mass level.

First, while this dissertation has touched upon the interaction between institutions and ideas on the elite level (paper 2 and 3), future research should expand on these themes in order to provide a more complete picture of energy and climate politics. To do so, scholars may draw on established concepts such as political opportunity structures (Kitschelt 1986), or the three new institutionalisms (Hall and Taylor 1996): rational choice, historical and sociological institutionalism. These approaches put the interactions between institutions and ideas, as well as between institutions and interests center stage.

Second, while not explicitly covered in any of the papers, the interaction between interests and ideas relates to the old debate between idealist versus materialist explanations of political change (Campbell 2002; Hall 1993). During periods of high uncertainty – which are prevalent in the current energy transition (Grubler, Wilson, and Nemet 2016), and in technological change more generally (Tushman and Rosenkopf 1992) – ideational processes may be prevalent in defining actors' interests (Blyth 2002), and keeping diffuse interests together (Shanahan, Jones, and Mcbeth 2011).

Finally, elite and mass politics may interact. Although paper 4 alludes to the importance of the supply side of politics in shaping electoral outcomes, how exactly political elites may trigger ideational or interest-based change among mass politics in the context of technological change remains unclear. Economic historian Eric Hobsbawm suggested that while the "by-products of technical change produce explosive material", elite politics in the form of "bodies of agitators, propagandists and organizers" are needed to make such explosive material burst into mass protests (1952, 337). Future research should examine this interaction between elite and mass politics and may draw on – among others – insights from social movement theory (Tarrow 1995).

5.3. Policy implications

Besides these contributions to academic literature, this dissertation also contains lessons for policymakers and practitioners. Here, I outline general policy implications spanning all four papers. More specific policy recommendations can be found in the individual papers in part II.

The most important message emerging out of this dissertation is the need to recognize that the transition from fossil fuel-based to renewable energy technologies is intrinsically political. The findings suggest that, in contrast to widespread belief, the main locus of contention of energy and climate politics is found in national and subnational politics rather than in global climate negotiations. Similarly, the main concern of policymakers and practitioners should not be to limit free-riding in emissions reductions but to focus on the expanding and (re)distributional effects of technological change and associated effects on energy and climate politics. More sensibility to the locus and nature of these political struggles could increase the probability not only of "technology smart" policy choices, but also of policy choices that take into account their political feasibility (see also Victor 2015). Given the time constraints linked to climate change, a narrow focus on economically first-best yet politically difficult policies, such as carbon pricing, may be a suboptimal approach. Instead, policymakers and practitioners should embrace the centrality of distributional effects of technological change and engage in forward-looking policy design targeted at increasing political support for ambitious climate action over time (Levin et al. 2012; Meckling et al. 2015; Pahle et al. 2018; Rosenbloom, Meadowcroft, and Cashore 2019). For instance, such forward-looking approaches should be applied to the current stimulus packages that address the economic turmoil associated with the Covid-19 pandemic. Given the increasing political momentum in favor of renewable energy technologies, these stimulus packages may provide a critical juncture to further entrench political support (Schmid 2020; Steffen et al. 2020), and to trigger positive feedback loops for other climate-relevant technologies such as battery storage or hydrogen. In other words, policymakers should actively shape future energy and climate politics by "sowing the seeds" today for political support tomorrow (Grilli et al. 2018). This dissertation informs such approaches by conceptualizing energy politics as a long-term policy feedback loop and by empirically demonstrating that such strategies can be successful.

5.4. Concluding remarks

Steering and accelerating technological change toward low-carbon technologies is one of the key levers to address climate change. This dissertation has examined how low-carbon technological change affects the interests, ideas, and institutions of elite and mass energy politics. To do so, it leveraged political science and public policy approaches. The papers of this dissertation have shown that energy politics are highly dynamic, and that technological change is a key driver of these dynamics. While the dissertation contains evidence of remaining inertia and resistance to low-carbon technological change, the findings also show that political momentum for more ambitious energy and climate policy is building. Now, this momentum needs to broadened and entrenched to deepen and accelerate the transition to low-carbon technologies. As the International Panel on Climate Change (2018) points out, "every bit of warming matters, every year matters, every choice matters."

6. Overview of papers

Table 4 provides an overview on the authorship and status of the four papers of this dissertation.

Table 4: Overview of the papers in this dissertation.

#	Title	Authors	Author contributions	Status
1	Explaining advocacy coalition change with policy feedback	Nicolas Schmid, Sebastian Sewerin, Tobias S. Schmidt	NS, together with TS and SS developed the idea. NS collected and analyzed the data with feedback from TS and SS. NS, together with SS and TS, wrote the paper.	Published in *Policy Studies Journal*
2	Governing complex societal problems: The impact of private on public regulation through technological change	Nicolas Schmid, Leonore Haelg, Sebastian Sewerin, Tobias S. Schmidt, Irina Simmen	NS, together with LH, SS, and TS developed the idea. IS collected the quantitative data, NS, LH and IS conducted the interviews. NS and LH interpreted the results with feedback from TS and SS. NS and LH wrote the paper with inputs from TS and SS.	Published in *Regulation & Governance*
3	A comparative and dynamic analysis of political party positions on energy technologies	Nicolas Schmid		Under review at *Environmental Innovation and Societal Transitions*
4	Electoral response to the decline of coal mining in the United States	Florian Egli, Nicolas Schmid, Tobias S. Schmidt	FE, together with NS and TS developed the research idea and the research design. FE carried out the empirical analysis. FE, NS and TS wrote the paper.	Submitted to *American Political Science Review*

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II) Individual papers

Paper 1: Explaining advocacy coalition change with policy feedback

Authors: Nicolas Schmid*[1], Sebastian Sewerin[1], Tobias S. Schmidt[1]

* Corresponding author: nicolas.schmid@gess.ethz.ch

[1] ETH Zurich, Department of Humanities, Social and Political Sciences, Energy Politics Group, Haldeneggsteig 4, CH-8092 Zurich, Switzerland

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Abstract:

Despite the prominence of exogenous factors in theories of policy change, the precise mechanisms that link such factors to policy change remain elusive: The effects of exogenous factors on the politics underlying policy change are not sufficiently conceptualized and empirically analyzed. To address this gap, we propose to distinguish between truly exogenous factors and policy outcomes to better understand policy change. Specifically, we combine the Advocacy Coalition Framework with policy feedback theory to conceptualize a complete feedback loop among policy, policy outcomes, and subsequent politics. Aiming at theory-building, we use policy feedback mechanisms to explain why advocacy coalitions change over time. Empirically, we conduct a longitudinal single case study on policy-induced technological change in the German energy subsystem, an extreme case of policy outcomes, from 1983 to 2013. First, using discourse network analysis, we identify four patterns of actor movements, explaining coalition decline and growth. Second, using process tracing, we detect four policy feedback mechanisms explaining these four actor movements. With this inductive mixed-methods approach, we build a conceptual framework in which policy outcomes affect subsequent politics through feedback mechanisms. We develop propositions on how coalition change and feedback mechanisms explain four ideal-typical trajectories of policy change.

1. Introduction

The dichotomy between exogenous and endogenous factors of policy change plays a prominent role in influential theoretical accounts of policy change (Cashore and Howlett 2007). While minor policy change is often attributed to endogenous factors, exogenous factors are often considered necessary conditions for *major* policy change (Baumgartner et al. 2009; Hall 1993; Kingdon 1995; Sabatier 1988). For example, in the Advocacy Coalition Framework (ACF), exogenous (or external) factors are considered drivers of change in otherwise stable policy subsystems, thereby enabling policy change (Sabatier 1988). Despite the prominence of external factors in explaining policy change, the precise mechanisms that link exogenous factors to policy change remain elusive. Consequently, empirical applications underline the sudden, unforeseeable character of exogenous factors, which are described as either "crisis", "perturbation", or "shock" (Nohrstedt and Weible 2010). Arguably, this development has somewhat obscured that exogenous factors can also change over a long(er) period and, most importantly, that they can result from previously made policy decisions (Schmidt and Sewerin 2017). To overcome this conceptual gap, we suggest to reassess the nature of exogenous factors and empirically investigate their impact on the politics underlying policy change. Based on the ACF, we conceptualize politics as the relative strength and structure of different advocacy coalitions in a given policy subsystem. In brief, the ACF suggests that policy change is the consequence of changes in advocacy coalition structures within policy subsystems (Fischer 2014; Sabatier 1988). Yet, coalition change and the precise *mechanisms* between such change and exogenous factors are not well understood (Leifeld 2013; Schlager 1995). To further substantiate these mechanisms, we draw on policy feedback literature (Béland 2010; Béland and Schlager 2019; Jacobs and Weaver 2015; Pierson 1993). We argue that our understanding of the politics of policy change can be advanced by conceptualizing the long-term dynamics in policy subsystems as feedback mechanisms and their effects on advocacy coalitions. Such a feedback perspective requires a distinction between *truly exogenous factors* and *policy outcomes*. Importantly, policy outcomes should not be understood as "shock" but rather as an integral part of long-term feedback *loops* among policy, policy outcomes, and subsequent politics. Most current societal challenges, such as environmental degradation or economic crises, are not truly exogenous but are at least partly policy-induced challenges. We therefore propose a conceptual framework for understanding the politics of policy change as a result of policy outcomes and their feedback effects. Our framework differs from extant public policy research which largely analyzes the politics of policy change as a driver – rather than a result – of policy outcomes. The main point of the paper is to provide this novel and complementary perspective. Our guiding research question is: *How are politics affected by feedback from policy outcomes?*

Empirically, we focus on policy-induced technological change as a distinct form of policy outcomes (Schmidt and Sewerin 2017) and its effects on advocacy coalition change, here understood as the relative strength and structure of *technology-specific* advocacy coalitions. More specifically, we analyze advocacy coalition change in the German energy policy subsystem during the period 1983-2013. We proceed in two steps: First, we conduct a Discourse Network Analysis (DNA) to assess coalition change in the German energy subsystem (Leifeld 2016). Second, we use theory-building process tracing to establish both the mechanisms and the effects that link policy-induced technological change to coalition change (Beach and Pedersen 2013). With DNA, we show that the advocacy coalitions that support fossil fuel-based technologies (FFT) and nuclear technologies (NT) become less powerful in the subsystem, while the advocacy coalition for renewable energy technologies (RET) increases in terms of size and actor diversity. In more general terms, we find patterns of *coalition decline* and *growth*, which we explain with four actor movements: *disappearance*, *appearance*, *dissociation*, and *association*. Through process tracing, we identify four ideal-typical feedback mechanisms explaining these actor movements: *negative resource*, *positive resource*, *negative interpretive*, and *positive interpretive*. Then, we develop propositions how these feedback mechanisms and the resulting actor movements relate to four trajectories of policy change: *stability*, *contraction*, *expansion*, and *transformation*. Finally, we discuss the relevance and implications of our findings for the ACF, feedback, energy transition, and policy design literatures.

The remainder of the paper is structured in the following manner: Section 2 discusses the limitations of ACF research and how policy feedback literature might help address these limitations. Section 3 outlines the research case and method. Section 4 presents the results of our analysis. Section 5 presents the implications of our findings for policy theories. Section 6 discusses the relevance of our contributions for specific literature streams and concludes the paper.

2. Theory

2.1. Understanding policy change through advocacy coalition change

Understanding how and why policy change comes about is a central issue in policy research. The ACF explains policy change as a function of changes in advocacy coalition structures within a policy subsystem (Fischer 2014; Jenkins-Smith et al. 2014; Sabatier 1988). Such coalition change occurs because of individual actors' belief changes (Sabatier 1988). Beliefs are structured into three hierarchical belief levels, and actors seek to translate these beliefs into policies through coordinated action within advocacy coalitions (Weible et al. 2011). Hence, at its core, the ACF postulates that it is necessary to understand the drivers of changes in actors' beliefs, hence coalition change, to explain policy change (see Figure 1 below). In the ACF framework, exogenous factors are identified as important drivers for belief change. As Sabatier (1988, 134) argued, "changes in relevant socioeconomic conditions (…) can dramatically alter the composition and the resources of various coalitions and, in turn, public policy within the subsystem". Despite the prominence of exogenous factors in the ACF, explicit hypotheses on linking such factors to coalition change have mostly remained unclear (Kübler 2001; Leifeld 2013; Mintrom and Vergari 1996; Nohrstedt 2010; Schlager 1995). This might be because the ACF focuses on defining and describing coalition constellations at a given point in time (Weible et al. 2019), rather than on explaining why coalitions change over time (John 2003; Mintrom and Vergari 1996). Of the few empirical studies that have explored coalitions over time, most have produced evidence of coalition stability, even in the context of significant external shocks (Matti and Sandström 2011; Pierce 2011; Pierce et al. 2017; Weible et al. 2011; Zafonte and Sabatier 2004).

To overcome this impasse, researchers have engaged with the exact *mechanisms* through which exogenous factors affect coalition change, and ultimately policy change (Leifeld 2013; Nohrstedt 2010; Weible et al. 2011; Weible and Heikkila 2016). For example, Nohrstedt and Weible (2010) proposed hypotheses on the interaction between short-term exogenous factors and coalition change. Their discussion and other related contributions suggest three reasons why research efforts are stalling. First, the diversity of exogenous factors and the lack of clear definitions makes it difficult to establish generalizable mechanisms. As Nohrstedt and Weible (2010) argued, the conceptualization of exogenous factors is problematic because the label "crisis" encompasses a large variety of different phenomena, such as technological and macroeconomic change or public opinion. These factors might have different causal links to the policy subsystem, that is, macroeconomic change might relate differently to advocacy coalitions than would public opinion. Second, the vocabulary used by researchers focuses on single events, and employs diverse concepts such as "crises," "external events," or "external shocks". These concepts mostly allude to the sudden character of exogenous factors, and emphasize the impact of single events and crises on policy change (compare Nohrstedt 2008). The importance of long-term dynamics in these exogenous factors is underemphasized. Consequently, dynamic and long-term exogenous factors of coalition change remain understudied, despite their important role in shaping policy processes (Jones and Jenkins-Smith 2009). For example, only a few studies investigated the role of socioeconomic development or technological change (see Markard, Suter, and Ingold 2016). Third, in many policy subsystems, the dichotomy between endogenous and exogenous factors is artificial. The exogeneity of these factors is a matter of degree, ranging from *truly exogenous events*, such as large-scale earthquakes, to dynamics that are clearly policy-induced, such as pensions or health insurance coverage, or the diffusion of RET. Indeed, exogenous factors, as conceptualized in the ACF and in other theories of policy stability and change (Baumgartner et al. 2009; Hall 1993; Kingdon 1995; Sabatier 1988), are often *outcomes* of policy output within a subsystem.

More recently, Weible and Ingold (2018) engaged with these questions regarding the nature of exogenous factors and their temporality. They developed four categories of exogenous factors to explain coalition change or stasis: sudden events and shocks, enduring chronic threats, short term spillovers between policy subsystems, and long-term sporadic changes in societal values. However, the authors neither discussed the mechanisms that link exogenous factors to coalition change, nor did they conduct an empirical analysis. To substantiate such mechanisms, in the following, we draw on policy feedback literature for its established feedback mechanisms and focus on temporal dynamics.

2.2. Understanding coalition change through policy feedback

The central idea of policy feedback literature is to highlight temporality by arguing that policy change, over time, feeds back into the political process (Béland 2010; Béland and Schlager 2019; Jacobs and Weaver 2015; Larsen 2018; Pierson 1993; Skocpol 1995). While classical feedback literature has focused on the specific link between policy and subsequent politics, more recent research has expanded the focus to the feedback *loop* from policy to subsequent politics to subsequent policy (Jordan and Matt 2014). Despite these important contributions, conceptual challenges remain because the individual elements of the feedback loop and their relation to one another are not clearly defined (Campbell 2012). For instance, the role of *policy outcomes* and their relation to and distinction from policy output and politics has not been conceptualized sufficiently. Nevertheless, in contrast to the ACF and other general theories of policy change, policy feedback literature allows to distinguish between *truly exogenous factors* and policy outcomes. We argue that most current societal challenges are not truly exogenous, rather, they are part of a feedback loop and hence contain endogenous components (Pierson 1993; Schmidt and Sewerin 2017). When applied to the ACF, such a distinction implies that, in most policy subsystems, coalition change is affected by policy outcomes rather than being influenced by truly exogenous factors (Nowlin 2016).

To conceptualize policy outcomes, their relation to the other elements of the feedback loop needs to be defined (see Figure 1 below). First, we distinguish between feedback *mechanisms* and their *effects*. While the former describes a process and channel through which policy outcomes influence subsequent politics, the latter describes the impact of these mechanisms on subsequent politics. Second, one of the most central contributions of policy feedback literature is the distinction between *interpretive* and *resource* mechanisms (Patashnik and Zelizer 2013; Pierson 1993). Studies that investigated interpretive mechanisms viewed policies as sources of information and meaning, thereby changing cognitive evaluations (Pierson 1993). Such interpretive feedback mechanisms are related to the ACF's concept of policy-oriented learning (Sabatier 1988). Policy feedback can also affect politics through a resource mechanism. Policies provide means and incentives for actors through resource mechanisms, which influence their relative material power and create both winners and losers (Campbell 2012; Patashnik 2008). ACF scholarship discusses the effects of this resource mechanism as the result of an external shock or event (Nohrstedt 2008). Third, the effects of these mechanisms on coalitions depend on the directionality of the interpretive and resource feedback mechanisms. Based on the distinction between *positive* and *negative* feedback mechanisms, Jacobs and Weaver (2015) described policy feedback as self-reinforcing when it stabilizes or expands policy support, and self-undermining when it undermines a policy's political viability over time.

2.3. Conceptualizing the policy feedback loop with ACF and feedback literature

Bringing together both ACF and policy feedback literature enables us to conceptualize the complete policy feedback loop. Building on the ACF, we conceptualize politics as the relative strength and structure of advocacy coalitions that share common beliefs regarding desirable policy outcomes. By drawing on policy feedback literature with its dynamic conceptualization of the policy process, we explain coalition change with feedback mechanisms and their effects. Figure 1 depicts this feedback loop, which begins with politics, conceptualized as advocacy coalitions, at t_i. In keeping with the ACF, we assume that these coalition structures at t_i determine policy at t_{i+1}. In turn, these policies affect policy outcomes at t_{i+2} [10]. These policy outcomes feed back into subsequent politics through feedback mechanisms, and thereby lead to coalition change at t_{i+3}. In turn, such coalition change shapes subsequent policymaking at t_{i+4}, thereby triggering a new feedback loop, which alters policy outcomes at t_{i+5} and has feedback effects on advocacy coalitions at t_{i+6}.

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[10] By selecting policy-induced technological change in the energy sector as the outcome, we are able to build on existing literature on policy effectiveness, which has demonstrated the policy-induced character of this specific outcome (see section 3.1. for details).

Note that while our *conceptual* framework contains the complete feedback loop, the *analytical* focus of this paper is the feedback from outcomes on advocacy coalitions (colored in black in Figure 1)[11]. Yet, by building on our inductive analysis, we develop theoretical propositions about the link between advocacy coalition change and policy change (see section 5.2.).

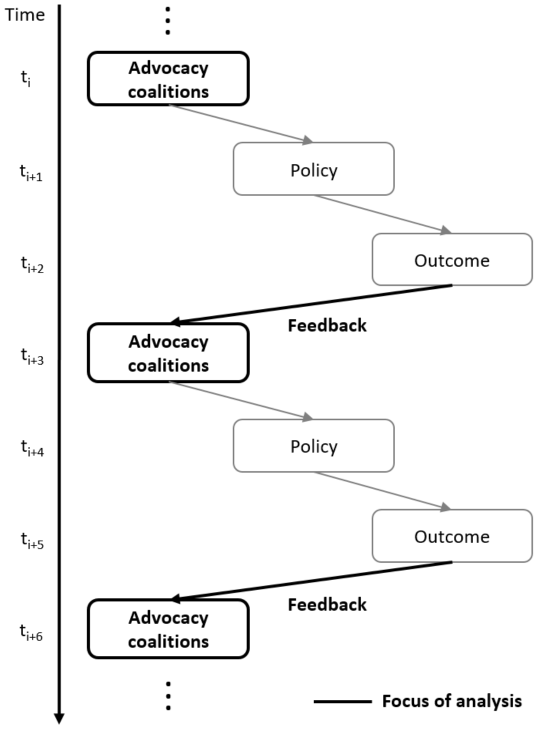

Figure 1. Conceptual Framework and Analytical Focus of the Paper.

3. Research design

3.1. Case selection

To explore the role of policy outcomes and their effects on politics, we analyze technological change - that is, the invention, innovation, and large-scale diffusion of new technologies - for three reasons. First, technological change is a highly relevant phenomenon, as it is the primary driver of economic development (Schumpeter 1942) and fundamentally affects social interaction (Borgmann 1987) and the natural environment. Second, while occasionally

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[11] Note that our empirical analysis focuses on post-enactment feedback of policies while treating both the pre-enactment feedback as well as the link between policy and outcome as a black box.

perceived as fast, technological change is continuous and rather slow, since the process from invention to innovation to broad-scale diffusion of technologies can take significant time (Arthur 2009; Rogers 1962). Thus, technological change differs from exogenous "shocks" with faster impacts. Third, public policy and regulation have a strong influence on technological change (Lundvall 1992; Rodrik 2004; Rosenberg 1982), e.g., through providing incentives to firms to perform research and development (Hall 2002) or through altering relative market sizes and prices, which induce (re-)directed innovation (Acemoglu 2002). Of course, the role of the state in inducing technological change differs by sector, but even in very "entrepreneurial" sectors, such as information and communication technology, the public sector was and is rather central (Mazzucato 2015). Given this important role of the state, technological change is political (Winner 1980) and, importantly, feeds back into the policy process (Edmondson, Kern, and Rogge 2018; Schmidt and Sewerin 2017). New technologies might result in new opportunities or challenges, which require new or adjusted policies (Hoppmann, Huenteler, and Girod 2014).

Technological change in the energy sector is an extreme example of the three characteristics of technological change listed above. First, the energy sector is the largest contributor to anthropogenic greenhouse gas emissions, which are causing global climate change (Mulugetta et al. 2014). Hence, technological change in the energy sector is highly relevant, in that GHG-emitting technologies and practices have to be phased-out and replaced by low- or non-emitting technologies (Geels et al. 2017). Second, despite major shifts towards renewable energy technologies (RET) in the last decade (IEA 2017), energy transitions require a long time (Grubler, Wilson, and Nemet 2016), due to the complexity, scale, uncertainty, and inertia of and within the energy sector (Fouquet 2016). Finally, innovation in the energy sector is largely policy-induced (Johnstone, Haščič, and Popp 2010; Newell, Jaffe, and Stavins 1999).

Hence, the transition of the energy sector to low-carbon energy technologies strongly depends on public policy choices (Nemet 2009; del Río González 2009) and, consequently, the politics underlying these choices (Lockwood et al. 2017; Meadowcroft 2009; Schmidt and Sewerin 2017; Stirling 2014) .

In our study, we focus on the energy transition in Germany as an "extreme case" (Seawright and Gerring 2008) of policy-induced technological change in the energy sector. First, as one of the frontrunners of transitions to low-carbon energy systems, Germany is a very relevant case (Renn and Marshall 2016). Due to early policy activity supporting RET, Germany enabled major advances in these technologies on a global level (Lauber and Jacobsson 2016). Second, the German energy sector has undergone major changes in previous decades, to the benefit of RET and the detriment of fossil-fuel based technologies (FFT) and nuclear technology (NT). Figure 2 illustrates these long-term dynamics in the case of (a) installed capacity of FFT, NT and RET, (b) levelized cost of RET , (c) number of patents for solar PV and wind technologies, and (d) employment in FFT, NT and RET. Third, extensive empirical evidence demonstrates that these developments in the German energy sector are mostly a result of policy intervention (Hoppmann, Huenteler, and Girod 2014; Lauber and Jacobsson 2016; Peters et al. 2012; Polzin et al. 2015). For example, with regard to FFT, German policymakers launched a gradual hard-coal mining phase-out in the 1980s, while protecting the industry in this transition period through subsidies of up to €327 billion between 1983 and 2014 (Renn and Marshall 2016). More recently, German policymakers started negotiations to phase-out of lignite mining and coal power plants (Leipprand and Flachsland 2018). Further, NT was introduced in the 1970s with significant state subsidies, but phased-out by the German government first in 2002 and ultimately in 2011.

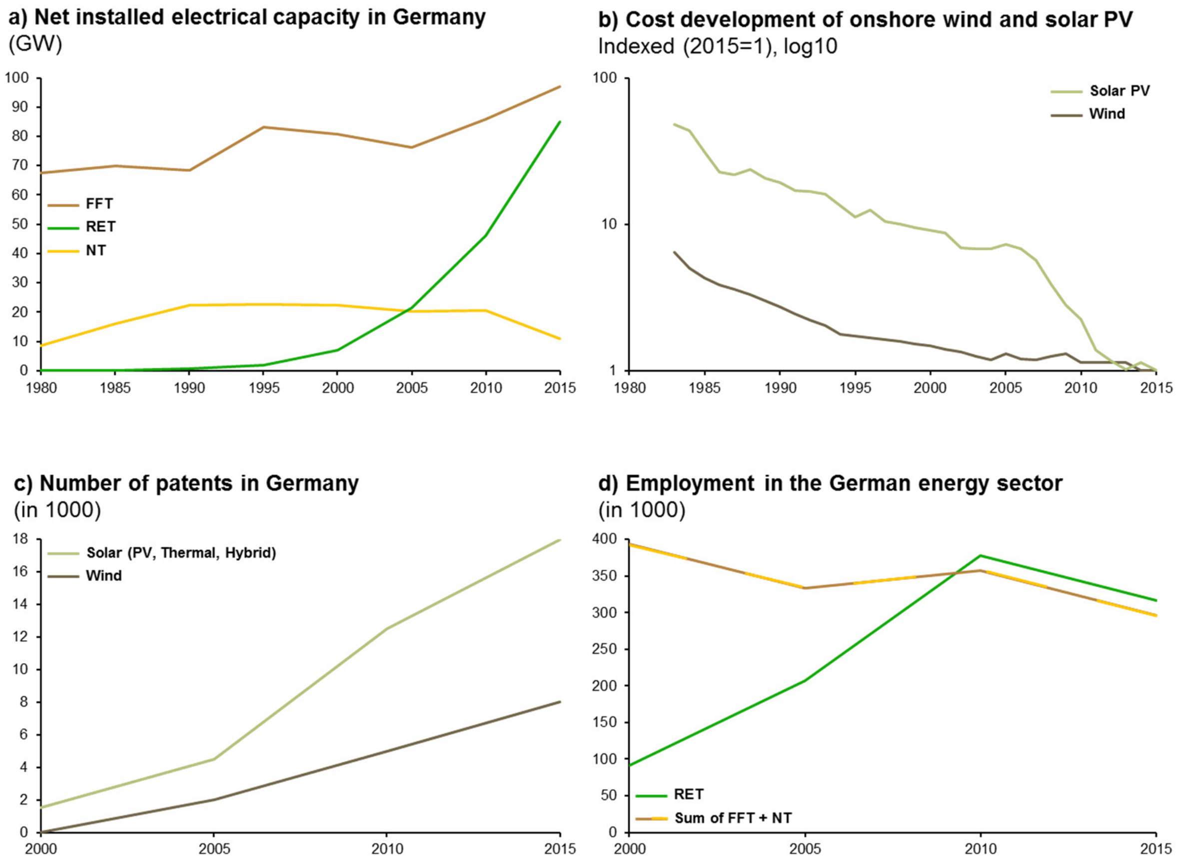

Figure 2: Technological change in the German energy subsystem. a) Net installed electrical capacity in Germany. Based on data from IEA (2018); RET including solar PV, wind on- and offshore, geothermal and hydro; FFT including coal (hard coal and lignite), natural gas and liquid fuel. b) Wind indexed based on levelized cost of electricity; for 2010–2017 data has been taken from IRENA, while that for earlier years is based on data from BNEF and Lawrence Berkeley National Laboratory; solar PV index is based on the module cost, and data is taken from Fraunhofer ISE. c) Number of patents in Germany; based on data from IRENA (2018). d) Employment in the German energy sector. Based on O'Sullivan et al. (2018), estimated from employment through investment in energy technologies and employment in energy generation, distribution, and transmission.

With regard to RET, the German government began subsidizing solar panels with research and development programs in the early 1980s (Jacobsson and Lauber 2006). In 2000, the feed-in law introduced fixed and subsidized feed-in tariffs for electricity from RET compared to the previous feed-in law from 1990, which were decoupled from electricity prices (Lauber and Jacobsson 2016). In our empirical analysis, to address the politics underlying these policies, we focus on three periods within the German energy transition: the 10th (1983-1987), 14th (1998-2002), and 17th (2009-2013) legislative periods. They represent crucial periods of the fundamental (re-)orientation of the German energy sector, during which competition between FFT, NT, and RET was particularly salient (Renn and Marshall 2016).

3.2. Methods

To investigate whether and how policy-induced technological change affects coalition change, we apply a mixed methods approach, proceeding in two steps: (1) In order to identify coalition change, we apply Discourse Network Analysis (DNA). (2) To explain this coalition change, we complement the DNA with theory-building process tracing.

(1) DNA is a combination of content analysis and social network analysis (Leifeld 2013; 2016). It fits well into the ACF conceptualization of coalitions and is commonly used to identify advocacy coalitions. Based on the coding of text, the method creates two-mode affiliation networks by linking actors (such as firms, NGOs, political parties, etc.) to concepts (see Figure 7 in the appendix for a graphical overview; for a detailed description of the method, see Leifeld (2016)). In our case, concepts are attitudes and arguments in favor of energy technologies. With such an actor-technology network, we apply network tools in order to visualize the change in networks over time. To do so, we proceed in three steps. First, using DNA software (Leifeld 2016), we produce unstandardized two-node actor-technology affiliation networks. Importantly, here, we focus on *support* affiliation networks, not additionally analyzing *rejection* affiliation networks[12] (as done by Metz, Leifeld, and Ingold 2018). Next, using the software *visone* (Brandes and Wagner 2004), we visualize these networks with the quick layout using stress minimization techniques. In order to facilitate visual analysis within and across networks, we color the actor-nodes according to their technology-specific support. In case of two or more supported technologies per actor, we color the node according to the most frequently

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[12] However, we report the rejection affiliation networks in Figure 8 in the appendix and the corresponding codebook containing the negative codes in Table 3.2. in the appendix.

supported technology, i.e. the highest tie weight between an actor and a technology. To provide a quality index for the partition of our networks into communities, we calculate modularity scores: Following Everett and Borgatti's (2013) dual-projection approach, we run a modularity analysis of the underlying one-mode actor congruence networks, using the Louvain algorithm[13] (Blondel et al. 2008).

(2) With process tracing, we seek to provide evidence that policy-induced technological change is a driver of coalition change and investigate the mechanisms underlying their relationship. As a distinct case-study methodology, process tracing attempts to identify the intervening causal process between variables (Collier 2011): it can be used "when we know an outcome (Y) but are unsure what caused it to happen (i.e., X is unknown)" (Beach and Pedersen 2013). Deductively building on existing theoretical work, theory-building process tracing investigates the empirical material in the case, using evidence as clues about the possible empirical manifestations of an underlying causal mechanism. To do this, process tracing focuses on events over time, taking snapshots of a series of specific moments, which in turn enables the analysis of change and sequence. Then, findings can be generalized in order to build theory. Here, in line with Collier's "Hoop test" (Collier 2011), the aim of process tracing is to affirm the relevance of policy-induced technological change as a necessary, yet not sufficient, factor of coalition change.

3.3. Data

For data collection, we followed the steps as described by Leifeld (2013). We draw on two data sources: newspaper articles for DNA and protocols from plenary debates in the German

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[13] The algorithm optimizes modularity, a value between -0.5 and +1 (Brandes et al. 2008), which measures the density of links within communities compared to links between communities. If the value is larger than 0.4, the differences among communities are considered meaningful. In the calculation, we take into account the tie weight between nodes. Analyzing the modularity of the underlying one-mode *technology* networks is not necessary, as it consists of only three aggregated nodes for FFT, NT and RET.

parliament for process tracing. First, we collected newspaper articles that enabled us to identify coalition change in the three periods. As source, we selected the Frankfurter Allgemeine Zeitung (FAZ) archive, since it is the only nation-wide German quality newspaper with an electronic archive that dates back to the 1980s[14]. We restricted newspaper articles to general energy policy topics in both the economy and politics sections of the newspaper (see Table 4 in the appendix for more details). With this filter method, we obtained a total of 3387 newspaper articles. Second, to link policy-induced technological change to coalition change, we complemented our dataset with protocols of the German parliament. Using the official archive of the German parliament, we filtered parliamentary processes according to the key word “nuclear energy”. We selected this keyword because debates on NT are the only constant topic on the German energy policy agenda from 1983-2013, including debates on the (re-)orientation of the national energy sector. Out of this corpus, based on qualitative assessment of their relevance, we selected protocols of 30 parliamentary debates (see Table 2 in the appendix). Next, we coded the newspaper articles and parliamentary protocols. We developed a codebook through an iterative process, based on existing literature and pre-analysis of newspaper articles (see Table 3.1. in the appendix). One researcher encoded the articles, while another controlled the coding. This four-eye principle ensures the validity and reliability of the coding process (Eisenhardt 1989). Apart from the control coding by a second researcher, we employed a full-text search based on regular expressions to find potentially missing statements (Leifeld 2013). The coding of the newspaper articles yielded 3900 coded statements made by 288 actors. In our coding, similar to previous research (e.g., Heikkila et al. 2018), we do not capture all three ACF belief levels but focus on policy core beliefs in a given policy subsystem.

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[14] Although being vulnerable to bias in favor of certain actors (Kukkonen and Broadbent 2017), media analysis offers several advantages for longitudinal research: consistency in data collection, replicability, and data access (Heikkila et al. 2018). Further, the consistent use of one newspaper should limit bias variation over time.

Such a simplification is necessary to be able to meaningfully analyze coalitions over time and across cases (Heikkila et al. 2019; Jenkins-Smith et al. 2014). We operationalize these beliefs as 1) *attitudes*, for example, preferences toward energy technologies and 2) *arguments* supporting these attitudes. For our analysis, we aggregated supportive attitudes and arguments specific to three technology groups: FFT (hard coal and lignite), NT, and RET (solar PV, wind on- and offshore, biomass, geothermal and hydro)[15]. We excluded natural gas and oil from FFT as these technologies were not salient issues of conflict in the German energy subsystem. Note that due to space limits, here, we focus on *positive* statements on these technologies in order to measure technology-specific *support* coalitions (refer to Table 3.1. in the appendix for the details of code aggregation).

4. Results

First, we present our findings on how coalitions in the German energy subsystem changed over the three periods. Second, we explain coalition change as the effect of policy-induced technological change.

4.1. Describing advocacy coalition change in the German energy subsystem

Figure 3 illustrates the two-mode actor-technology networks of each period[16]. In light of our research question, four observations can be made. First, through network visualization, we identified three advocacy coalitions around FFT, NT, and RET in all three periods (see colored nodes). Hence, there are coalitions in the German energy subsystem that coalesce around specific energy technologies. Second, these coalitions are not perfectly isolated from each other. On the contrary, a few actors within each coalition share energy technology-related

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[15] To visualize the complexity of the underlying data, we report more disaggregated one-mode actor congruence support networks in Figure 9 in the appendix.

[16] Please refer to Table 6 in the appendix for the list of actors (indicated with numbers in each node).

beliefs with other coalitions. This is particularly the case in the first and last networks[17]. Third, the three coalitions change considerably over time. In the first network, which represents the German energy subsystem from 1983-1987, most actors coalesce around FFT and/or NT, which constitute the predominant energy technologies in the subsystem. A substantive part of each of these FFT or NT actors supports both energy technologies. The RET coalition is fairly small in comparison, with only few ties to other coalitions. In the second network (1998-2002), both FFT and NT coalitions are still important. However, the ties between the FFT and NT coalitions became weaker as compared to the first network. Simultaneously, the RET coalition grew in terms of number of actors, and exhibits considerably more ties to both FFT and NT coalitions than in the previous period. In the third network (2009-2013), the RET coalition is the largest, both in terms of the number of actors and in terms of ties to other coalitions. At the same time, the FFT and NT coalitions became much smaller.

In other words, the FFT and NT coalitions show a strong gradual *decline* over the three periods, whereas the RET coalition exhibits remarkable *growth*. Although not observed empirically, these two patterns have two theoretical extreme points, namely coalition *dissolution* and coalition *formation*. Fourth, the results of the network analysis suggest that coalition decline and growth are the results of four different actor movements.

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[17] The underlying one-mode actor networks of the visualized two-mode networks differ in terms of their degree of modularity, with values ranging from 0.135 (1983-1987), 0.244 (1998-2002), and 0.085 (2009-2013). It is commonly assumed that coalitions can be meaningfully interpreted around 0.4 and higher (Kukkonen et al. 2018). In our view, the lower values do not pose a serious problem, since we are not claiming that these coalitions are isolated, and since we focus on coalition change rather than the perfect identification of coalitions at one point in time. For more network level statistics, see Table 5 in the appendix.

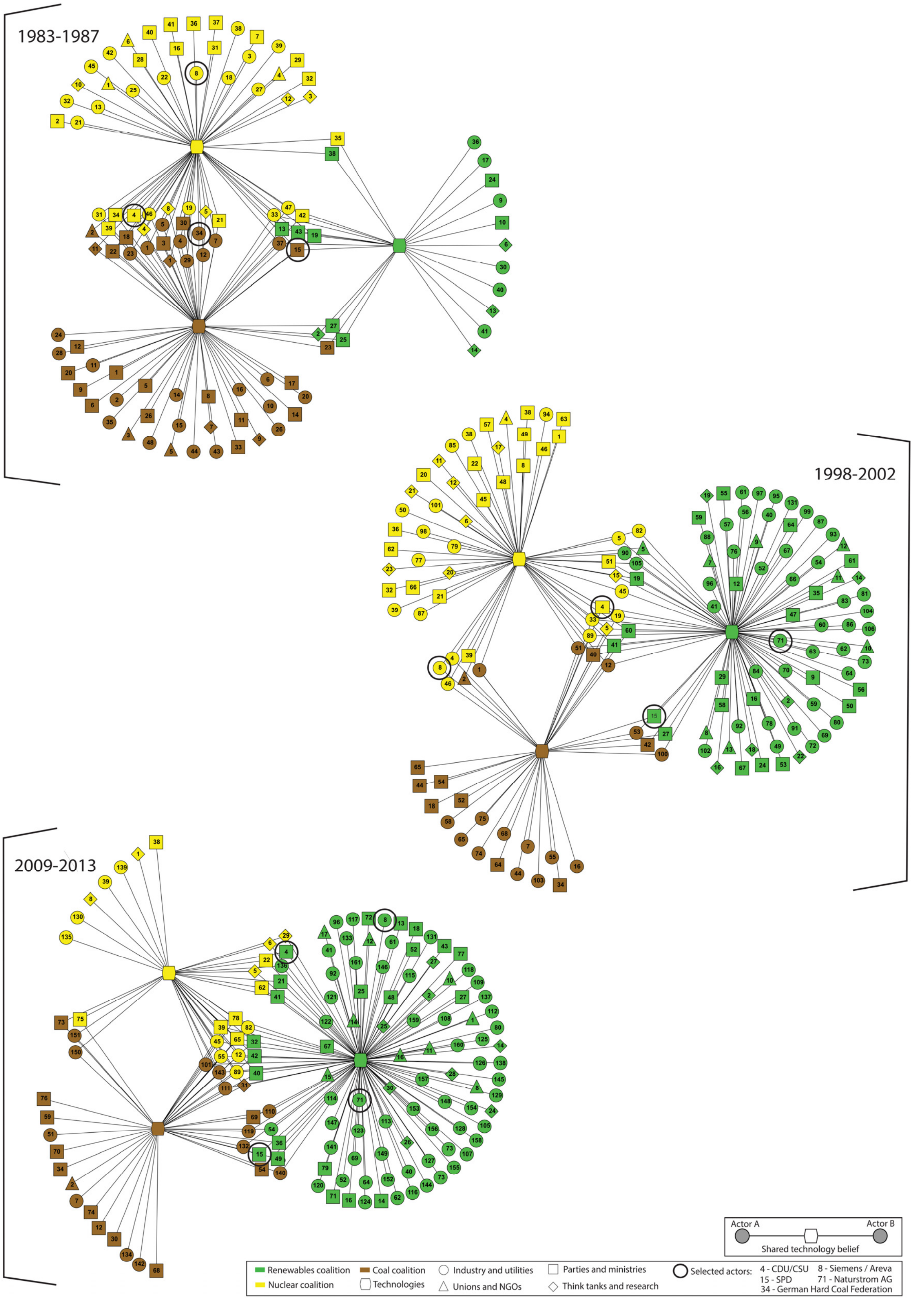

Figure 3: Change in advocacy coalitions in the German energy subsystem from 1983-2013. The two-mode support affiliation networks represent the German energy subsystem in three periods: 1983-1987, 1998-2002, and 2009-2013. Nodes are actors that coalesce around the aggregates of positive statements on energy technologies (FFT, NT, RET). Refer to Table 6 in the appendix for the list of actors. Networks are based on coding of 3387 newspaper articles, yielding 3900 coded statements of 288 actors. Note that the second-mode nodes are simplified aggregates of underlying, more complex, technology-support statements (see 3.2. for details on data and methods). Actor nodes are colored according to each node's most frequently supported energy technology. The graph layout is based on stress minimization.

A first identified movement is *actor disappearance,* which led to the decline of the FFT and NT coalitions. An example for actor disappearance is the nuclear branch of Siemens, Areva NP (see circled actor #8 in Figure 3)[18]. In contrast to actor disappearance that resulted in the decline of the FFT and NT coalitions, the RET coalition was strengthened through *actor appearance*. For example, the establishment of firms such as the Naturstrom AG and its appearance in the energy subsystem led to growth of the RET coalition. Apart from actor disappearance, *actor dissociation* from a coalition can also lead to coalition decline. For example, from the first to the second periods, the federal Social Democratic Party (SPD, circled actor #15) dissociated itself from the NT coalition. Similarly, apart from actor appearance, coalitions also grow as a result of *actor association*. For example, in the second period, the federal Conservative Party (CDU/CSU, circled actor #4) associated itself with the RET coalition (but did not yet dissociate itself from the FFT and NT coalitions).

In summary, the decline of the FFT and NT coalitions resulted from actor disappearance and actor dissociation. The growth of the RET coalition was the result of actor appearance and actor association from actors dissociating from the FFT and NT coalitions. Abstracting from these empirical findings, Figure 4 depicts a stylized visualization of the four actor movements from t_i to t_{i+1}. Note that dissociation from a coalition and association with another coalition can occur simultaneously, which would represent a *shift* between coalitions.

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[18] An example of actor disappearance from the FFT coalition is the German Hard Coal Federation (see circled actor #34). Although still in existence as such, this federation no longer appears in our media analysis in the second and third periods, arguably because its relevance in the FFT coalition diminished.

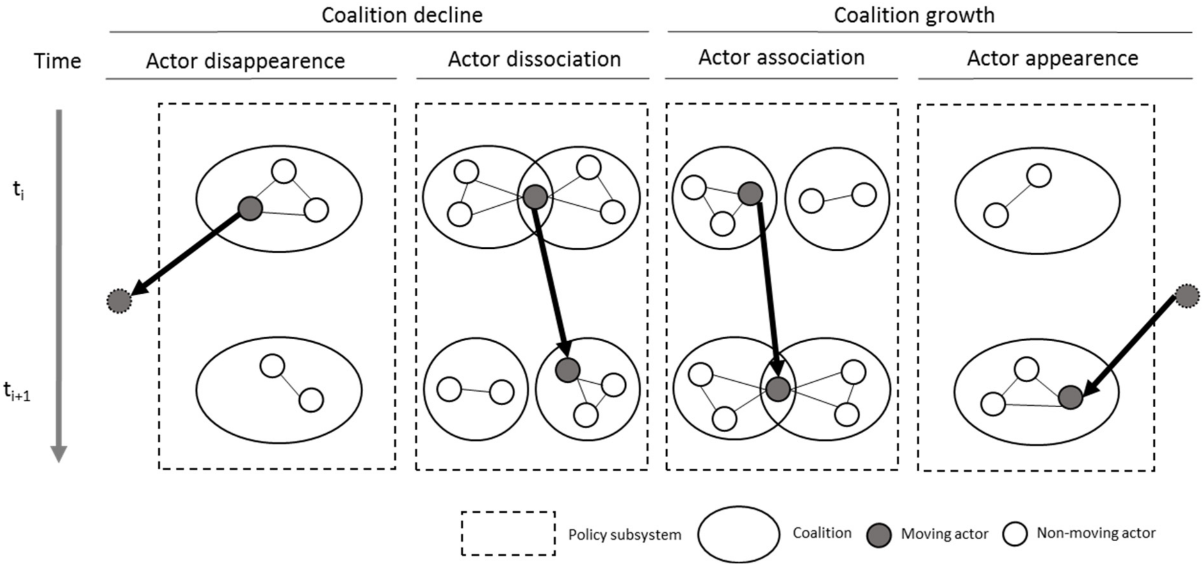

Figure 4: Stylized actor movements underlying coalition change.

In sum, we argue that the combination of these four actor movements can explain coalition decline and growth, and hence explain the changing topography of the German energy subsystem.

4.2. Understanding coalition change through policy feedback

In the next step, we qualitatively assess whether and how policy-induced technological change was a driver of the actor movements observed above. In keeping with theory-building process tracing (see section 3.2), we search for empirical manifestations of underlying causal feedback mechanisms (compare section 2.2 for the theoretical discussion of these mechanisms) between policy-induced technological change and the four actor movements. More specifically, we focus on the following actors: an NT industry technology firm, a new RET firm, the federal Social Democratic Party and the federal Conservative Party[19].

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[19] The Social Democratic Party (SPD) and the Conservative Party (CDU/CSU) were both governing parties in the second as well as first and third periods, respectively. For the analysis, we use newspaper articles and a second data set based on parliamentary protocols (see section 3.3). In the text, references to single newspaper articles or parliamentary debates are indicated in parentheses, referring to Table 7 (appendix). Additional evidence on the stance of parties on energy technologies can be found in Table 8 (SPD) and Table 9 (CDU/CSU) in the appendix.

Actor disappearance can – amongst others – be observed in the German nuclear industry. In hindsight, the NT industry was at its peak at the beginning of the first analyzed period (no new power plant was built after 1982), and was later affected by the nuclear accident in Chernobyl in 1986. In the second analyzed period, after years of intense conflict around NT, the decision by the Red-Green government to phase-out nuclear energy in 2002 triggered a steady decline of the nuclear industry, reinforced by the second phase-out decision by the Conservative-Liberal government in 2011 (Renn and Marshall 2016), that is, during the third analyzed period. As a result of these major policy changes, the installed capacity of this technology decreased from 22.4 GW in 2000 to 10.8 GW in 2015 (see Figure 2a). In turn, this policy-induced technological change led to substantial actor disappearance from the NT coalition between the second and third periods. For example, Siemens, a German engineering company which had built all 17 of Germany's nuclear power plants, completely discontinued its nuclear reactor business in 2011 (Renn and Marshall 2016). In other words, an important actor in the German energy subsystem disappeared, largely as a result of the policy-induced decline of its home market. At a higher level of abstraction, we reason that policy-induced technological change triggered actor disappearance through a *negative resource feedback mechanism*.

An example for actor appearance is the entry of new firms in the German energy subsystem (e.g., Naturstrom AG). As a result of early support policies between the first and second periods, new demand for RET emerged in the 1990s (Jacobsson and Lauber 2006), thereby triggering the entrance of early movers into the RET market (Strunz 2014). In addition, industry associations and research institutes were established, such as the German Wind Energy Federation or the Institute of Ecology. In the second period, the introduction of a more stringent feed-in tariff with technology-specific remuneration triggered an exponential growth of the RET sector (Hoppmann, Huenteler, and Girod 2014). As a result of this distributional policy, between 2000 and 2015, installed capacity of RET increased from 6.96 GW to 85.01 GW (cf. Figure 2a). As the RET market continued to grow, driven by sustained policy support, specialization and positive externalities further increased actor diversity (Steffen 2018). These new actors entered the energy policy subsystem, thereby resulting in a large RET coalition in the third period. To summarize, policy-induced technological change led to actor appearance through a *positive resource feedback mechanism*.

Further, changing beliefs on NT in the SPD illustrate how policy-induced technological changes leads to actor dissociation. In the first period, the SPD held mostly positive beliefs regarding NT (Reference (1) in Table 7 of the appendix). However, already in the beginning of the 1980s, beliefs within the SPD began to shift. A major reason was that the policy-induced phase-in and subsequent diffusion of NT represented a strong competition for FFT, traditionally an important constituency for the SPD (4, 6, 8)). The SPD justified opposition to NT due to the lack of technological improvements in this technology, for example highlighting the failure of the nuclear fast breeder technology (47). In the second period, the SPD justified its opposition to NT with decreasing economic competitiveness and the risks associated with NT (49). In the third period, competition between NT and RET was an important reason for the SPD to oppose the plan of the Conservative-Liberal party to slow down the nuclear phase-out (15). Hence, SPD’s increasing dissociation from NT is an example of the effect of *negative interpretive feedback mechanisms*. Notably, evidence suggests that the SPD’s dissociation from NT *precedes* truly exogenous shocks, such as the Chernobyl and Fukushima nuclear accidents, which only reinforced already existing negative interpretive feedback (2, 3).

To illustrate the role of policy-induced technological change for actor association, we use the example of the CDU/CSU. In the first period, the CDU/CSU was neither supportive nor fundamentally opposed to RET. However, the CDU/CSU argued that RET could not be a large-scale solution to replace any other energy technology. In order to support this argument, the party referred, amongst others, to experiences with publicly funded research and development projects, such as the failed wind turbine project “Growian” ((36) in Table 7). The party’s stance did not change much between the first and second periods. In the early 2000s, the CDU/CSU supported an energy concept based primarily on FFT and NT (29), with only a small role attributed to RET (31). The chances of RET to largely diffuse into the energy market, and for economic co-benefits to emerge, were estimated to be low (20 and43)). However, in the third period, the CDU/CSU’s opposition to RET had largely vanished. MPs of the party now referred to RET’s rising share in the electricity mix as an argument in favor of this technology (45). In contrast to earlier periods, the CDU/CSU highlighted co-benefits of increasing RET diffusion and underlined the strongly decreasing costs and increasing job creation (44). Hence, CDU/CSU’s association with the RET coalition is an example of the effect of *positive interpretive mechanisms*. Note that this association with RET *precedes* the Fukushima nuclear accident, which was a truly exogenous shock.

5. Implications for theories of policy change

5.1. Explaining advocacy coalition change with policy feedback

In section 4.1., we empirically detect two patterns of coalition change - decline and growth - which we explain with four actor movements: *disappearance, appearance, dissociation, and association*. In section 4.2., we identify four feedback mechanisms through which policy-induced technological change affects these actor movements, and hence coalition change: *negative resource, positive resource, negative interpretive, and positive interpretive*. We demonstrate that the actor movements that underlie coalition decline and growth are the effects of interpretive and resource feedback mechanisms. Combining the results of both analytical steps allows us to conceptualize the effects of policy feedback mechanisms on politics as patterns of coalition change and their underlying actor movements (see the 2x2 matrix in Figure 5). Developing an explanatory typology (Elman 2005), we argue that combinations of the two dimensions of feedback mechanisms can explain the four actor movements and, consequently, coalition decline and growth.

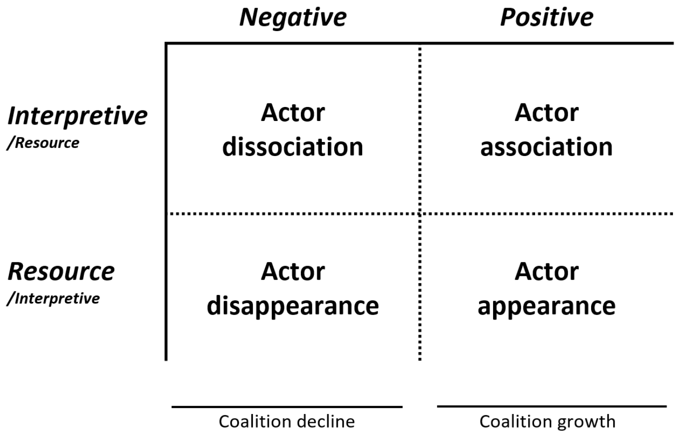

Figure 5: Feedback mechanisms (axes) and their effects on actor movements (quadrants).

We do not claim that patterns of coalition change and their underlying actor movements are *exclusively* triggered by these mechanisms; rather, we argue that resource and interpretive mechanisms are *more important* for specific actor movements, respectively: for actor disappearance and appearance, resource mechanisms are arguably more important because such changes require a (re)distribution of resources to nurture entrants and/or deprive incumbent actors. Interpretive mechanisms might be more relevant for actor dissociation and association because they are concerned with belief changes of the incumbent actors based on the perception of real-world changes, such as policy-induced technological change. Hence, the relative prevalence of a specific type of actor movement depends on whether resource or interpretive mechanisms are more important in a given policy subsystem.

5.2. Explaining policy change with coalition change and feedback mechanisms

In the following, we additionally develop theoretical propositions on how the patterns of coalition change detected above explain policy change and thus how to conceptualize the complete feedback loop (as presented in Figure 1). We suggest combining ideal-typical trajectories of policy change with ideal-typical patterns of coalition change and their underlying actor movements. Figure 6 illustrates how four ideal-typical policy trajectories relate to the 2×2 matrix that is depicted in Figure 5. As proposed by Jacobs and Weaver (2010), we distinguish between *policy stability*, *expansion*, *contraction*, and *transformation*. We understand policy expansion and contraction to be instances of positive and negative minor policy change, respectively, and policy transformation to be major policy change.

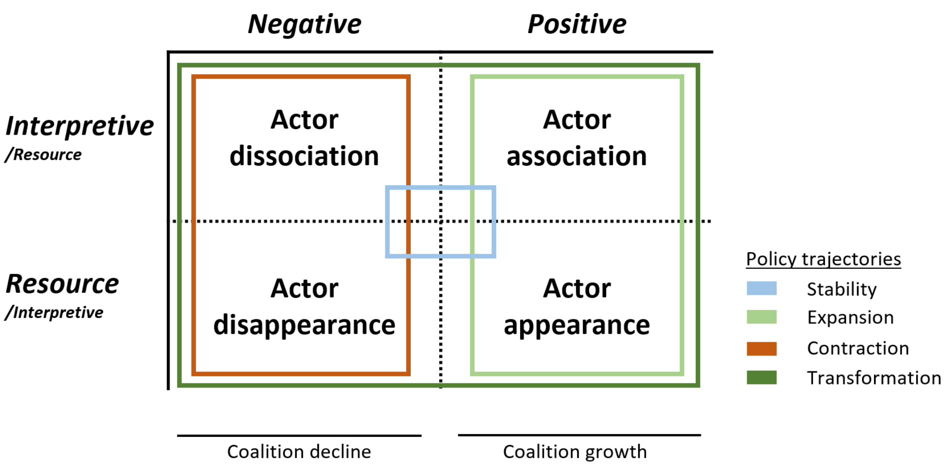

Figure 6: Feedback mechanisms (axes), their effects on actor movements (quadrants) and coalition change, and the link to policy trajectories (colors).

We posit that these four policy trajectories can be explained with different combinations of feedback mechanisms and their effects on actor movements, and consequently coalition change. We make four propositions: First, policy stability results from coalition stability, which itself results from either the balance between or the absence of positive and negative feedback mechanisms. Second, expansion of policy$_i$ is caused by the growth of coalition$_i$ (actor appearance and/or association), which, in turn, is caused by positive resource and interpretive mechanisms. Third, contraction of policy$_j$ results from a decline of coalition$_j$ (actor disappearance and/or dissociation), which itself results from negative interpretive and resource feedback mechanisms. Fourth, policy transformation represents the most complex policy trajectory: it requires both decline of coalition$_k$ and growth of coalition$_l$. Here, negative resource and interpretive feedback mechanisms lead to the disappearance of incumbents and/or their dissociation from status-quo coalition$_k$. Simultaneously, positive resource and interpretive feedback mechanisms trigger the appearance of new actors and/or the association of incumbents with pro-change coalition$_l$. These propositions advance the general understanding of policy change (Baumgartner et al. 2009; Cashore and Howlett 2007; Hall 1993; Kingdon 1995; Sabatier 1988) by conceptually integrating the politics of policy change and feedback mechanisms.

6. Discussion and conclusion

In this paper, we explain advocacy coalition change as a result of feedback from policy outcomes. This perspective contributes to the discussion in theories of policy change regarding minor and major policy change and the role of endogenous and exogenous factors therein (Baumgartner et al. 2009; Cashore and Howlett 2007; Hall 1993; Kingdon 1995; Sabatier 1988). As an alternative to this strict dichotomy between endogenous and exogenous factors behind policy change, we argue that certain factors that underlie policy stability and change are neither truly exogenous nor truly endogenous. Instead, we consider such factors an integral part of long-term feedback loops which comprise both endogenous and exogenous elements. In such loops, policy outcomes at ti+2 are the result of policy at ti+1, with subsequent effects on politics at ti+3 (see Figure 1). Here, in a different but complementary perspective to most extant literature, we focus on the link between such policy outcomes and subsequent politics. We argue that our understanding of the politics that underlie policy change can be advanced by conceptualizing the temporal dynamics in policy subsystems as a function of feedback mechanisms and their effects on politics. We build on the ACF to describe politics as the relative strength and structure of advocacy coalitions (Sabatier 1988). In our empirical case study on policy-induced technological change in the German energy subsystem, we identify coalition decline and growth. More specifically, we identify four actor movements that underlie these coalition changes: disappearance, appearance, dissociation, and association. To explain these actor movements, and thus coalition change, we draw on policy feedback literature (Béland 2010; Béland and Schlager 2019; Jacobs and Weaver 2015; Pierson 1993) to establish the mechanisms by which policy outcomes at ti+2 affect advocacy coalitions at ti+3. We found that policy outcomes, such as policy-induced technological change, can be drivers of coalition change through four feedback mechanisms: negative resource, positive resource, negative interpretive, and positive interpretive. Hence, patterns of coalition change are the effect, rather than the cause, of policy outcomes, offering an alternative perspective to the ACF and other general policy theories. Based on these findings, we developed propositions on how coalition change and feedback mechanisms are linked to four policy trajectories: stability, expansion, contraction, and transformation.

In addition to these general contributions, our paper also speaks to four specific literature streams. First, the focus on coalition change rather than stability provides a complementary perspective to existing ACF research. Considering the long-term dynamics of feedback mechanisms, we inductively develop patterns of coalition change, decline, and growth, and their four underlying actor movements, which might enrich the ACF’s description of coalition change. For example, our study confirms findings by Leifeld (2013), who found that coalition change is a non-linear process in which the power balance between coalitions changes incrementally, including a period of polarization, before a coalition can reach relative hegemony in the subsystem. To this perspective, we add a focus on actor movements and the underlying mechanisms that lead to such coalition changes. Although not a result of our empirical analysis, one theoretical outcome of the proposed mechanisms could be polarization. Further, by explicitly discussing how policy outcomes are linked to actor movements, and thus coalition change, we speak to the ongoing discussion within the ACF community regarding the mechanisms that link exogenous factors to policy change (Nohrstedt and Weible 2010; Weible and Jenkins-Smith 2016). The use of policy feedback concepts within the ACF shows how the integration of different approaches can help the framework to gain more descriptive and explanatory leverage (Pierce et al. 2017). Second, we contribute to feedback literature by highlighting the role of actors and advocacy coalitions, that is, agency, in long-term feedback loops. A classical policy feedback study might have underemphasized the political dynamics in its account of policy change. Further, we respond to calls for clearer definitions of feedback concepts (Campbell 2012) by distinguishing between interpretive and resource feedback mechanisms and their effects. By explicitly considering the direction of policy feedback and empirically showing that the directionality of feedback has an effect on subsequent politics, we contribute to the ongoing discussion about self-undermining and self-reinforcing feedback (Jacobs and Weaver 2015). As the existing feedback literature is mostly looking at mass politics (Béland and Schlager 2019; Larsen 2018), our focus on interest groups complements recent literature and helps fill this empirical gap (Goss, Barnes, and Rose 2019). With a focus on policy-induced technological change in the energy sector, we contribute to applying feedback concepts beyond well-trodden policy fields, such as social policy (Béland 2010; Béland, Rocco, and Waddan 2018). Third, through our empirical focus on the energy policy subsystem, we also contribute to the emerging literature on the importance of politics in energy transitions (Aklin and Urpelainen 2013; Brisbois 2019; Kern and Rogge 2018; Normann 2015; Rinscheid et al. 2019; Rosenbloom, Meadowcroft, and Cashore 2019; Schmidt, Schmid, and Sewerin 2019; Stokes 2016). Our paper directly responds to the research agendas set by Lockwood et al. (2017), Roberts et al. (2018) and Schmidt and Sewerin (2017), by applying two major policy theories to the subject of the politics of energy transitions (Meadowcroft 2009). Finally, understanding coalition change as the result of policy outcomes raises the question of whether and how such coalition change can be intentionally designed by forward-looking policymaking (Jordan and Matt 2014; Levin et al. 2012; Meckling et al. 2015; Pahle et al. 2018), i.e. creating a virtuous feedback loop that ensures the political sustainability of policies (Patashnik 2003). On a more general level, recent literature on policy design addressed similar questions of designing long-term policy trajectories (Capano and Woo 2017; Howlett, Mukherjee, and Woo 2015; Jacobs 2008). Whether such a feedback loop can be generated also depends also on the institutional setups that structure policymaking (Skogstad 2017).

While we believe that our contributions to these literature streams are conceptually relevant and empirically well-founded, we wish to highlight a few limitations of our study. First, our qualitative approach to explaining coalition change does not establish the relative explanatory power of policy-induced technological change as compared to other factors, such as single events, public opinion or party politics. Acknowledging this weakness, we assert that the purpose of this paper is to build theory and make propositions that can be tested in subsequent research. Second, in our analysis, we do not capture *coordination* between coalition actors, which is another other key component of advocacy coalitions, along with beliefs (Sabatier 1988). Although integrating both would have resulted in a more complete analysis, it is difficult to consistently measure coordination among actors in a longitudinal analysis. In keeping with the existing ACF research, we argue that shared beliefs correlate to a certain extent with coordinative behavior (Matti and Sandström 2011), therefore, our analysis is a meaningful application of the ACF framework’s main assumptions. Third, our focus on *aggregated* technology-related policy core beliefs - and on *support* coalitions - represents a simplification of the multi-layered belief structure of actors in the subsystem. However, we believe that such a level of granularity is necessary to be able to trace coalition change over time, which was the explicit focus of this paper.

To address these limitations and to build on the framework that was developed in this paper, future research should extend our analysis in at least three areas. First, to increase the validity of our conceptual propositions, research should expand the empirical scope to other countries and policy fields, while also considering other policy outcomes. We believe that our framework is applicable to policy subsystems in which induced change is not of technological nature, such as welfare, higher education, gender, or migration policy. For instance, in welfare policy, the introduction of private insurance schemes may lead to the creation of new firms, that is, actor appearance, through a positive resource mechanism. At the same time, such policies may lead to the disappearance of public insurance companies through a negative resource mechanism. The introduction of private insurance schemes may also trigger changing policy positions of political parties, which may lead to either actor association or dissociation through a positive or negative interpretive mechanism. Comparative studies could provide more insights into the differences of feedback across such policy fields. Second, future research that would test our propositions with a more quantitative research design would allow to disentangle the relative explanatory power of various factors of coalition change. Third, research could further substantiate patterns of coalition change, actor movements, and their drivers. For instance, an intriguing question is how a subsystem structure, i.e. coalition polarization or hegemony, is related to the feedback mechanisms and actor movements identified in this paper. Another important venue for future research could be to investigate the difficult distinction between interpretive and resource feedback mechanisms, as well as the conceptual difference between these feedback mechanisms and policy learning.

In this paper, we conceptualize the politics of policy change as an integral part of a complete feedback loop. By empirically showing that policy-induced technological change feeds back into advocacy coalition change, we highlight the dynamic interplay between policy outcomes and subsequent politics. Thus, we contribute to overcoming the strict dichotomy between endogenous and exogenous factors that drive minor and major policy change.

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8. Annex

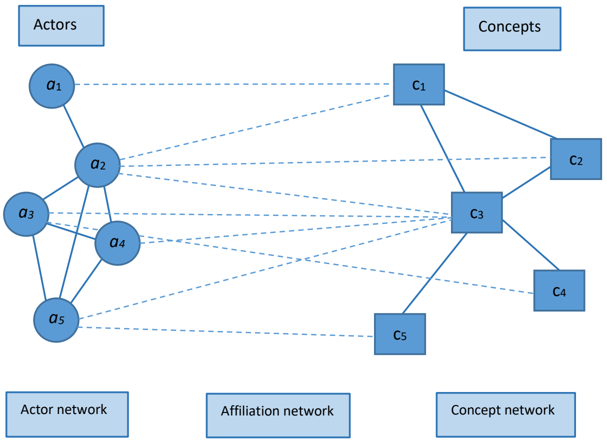

Figure 7: Schematic model of the Discourse Network Analysis method. It enables us to infer relations between actors (a1, a2 …), based on the affiliation network linking to a concept network (c1, c2 …). Source: (Leifeld 2016)

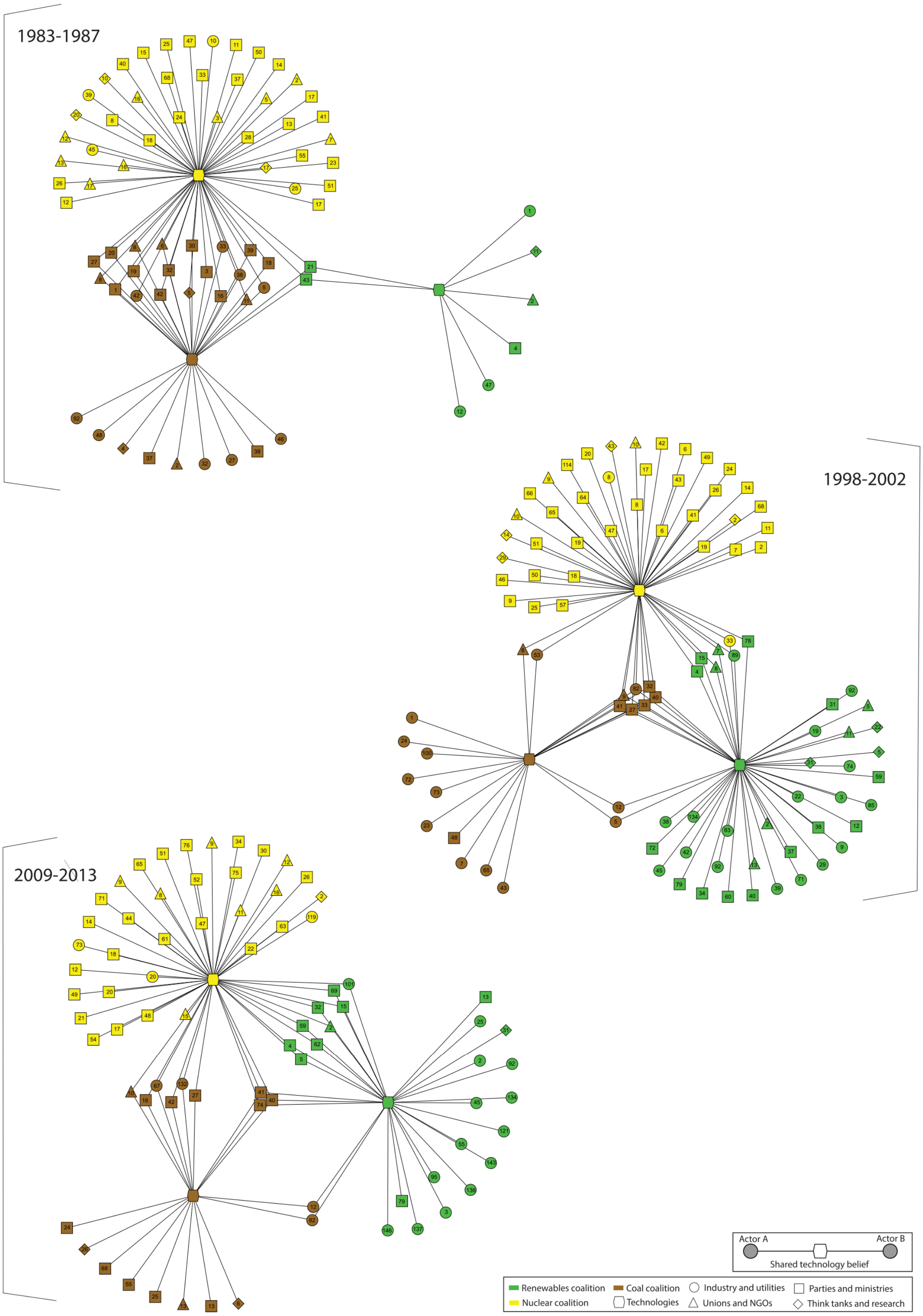

Figure 8: Change in advocacy coalitions in the German energy subsystem from 1983-2013. The two-mode rejection affiliation networks represent the German energy subsystem in three periods: 1983-1987, 1998-2002, and 2009-2013. Nodes are actors that coalesce around the aggregates of *negative* statements on energy technologies (FFT, NT, RET). Refer to Table 6 in the appendix for the list of actors. Note that the networks are a simplified aggregate of underlying, more complex, actor-technology networks (see 3.2.for details on data and methods). Coalitions are colored according to technology support. The graph layout is based on stress minimization. The rejection networks support our findings in the main text based on support networks, with regards to general patterns of coalition decline and growth, and concerning the actor movements.

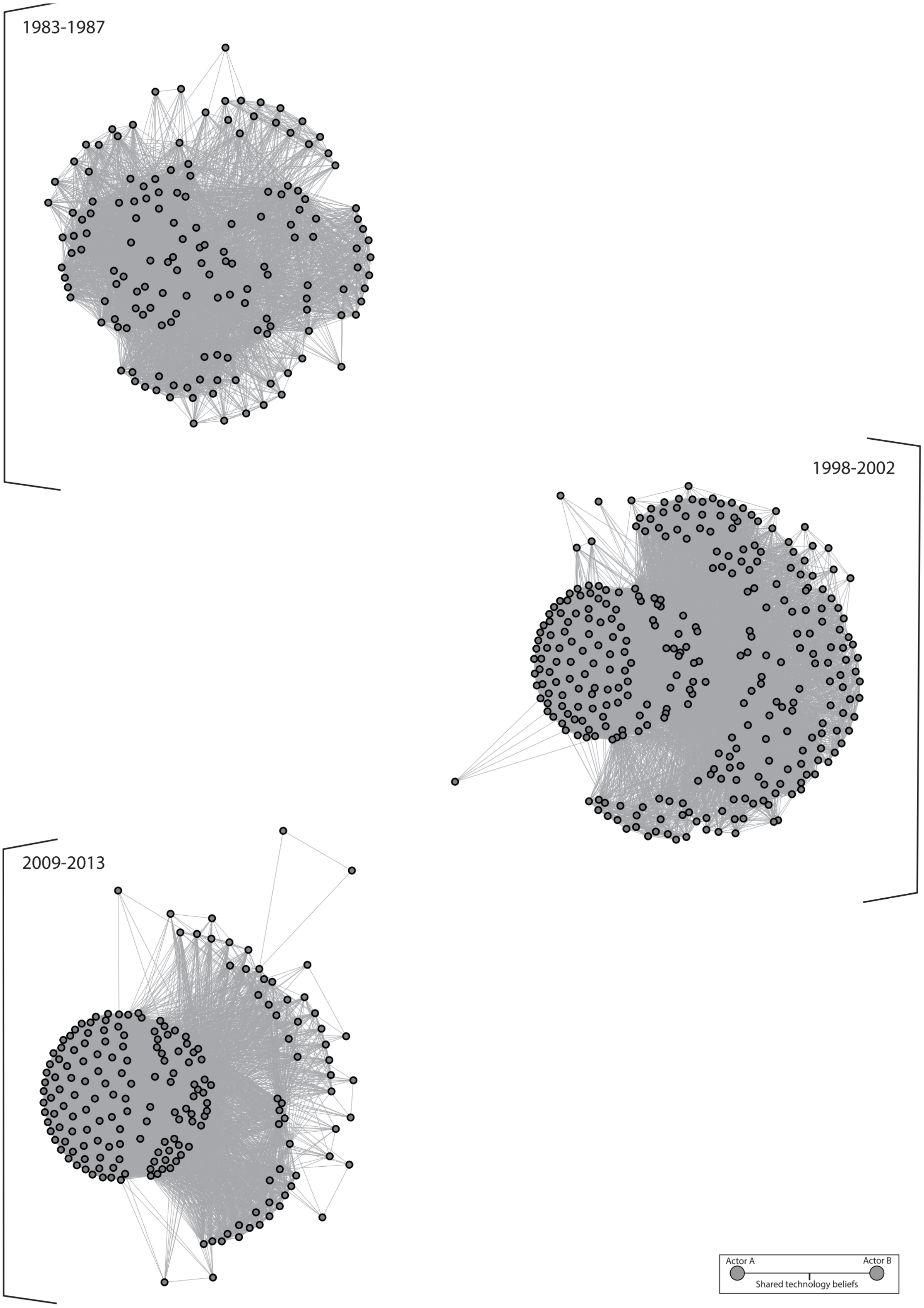

Figure 9: One-mode congruence actor networks. Nodes are actors that are linked through jointly voiced *positive* statements on energy technologies (FFT, NT, RET). Note that the networks are based on the same data than Figure 3. However, the data is less aggregated, as “subcategories” instead of “meta-categories” are used for the underlying concept-mode (see codebook, Table 3 in the appendix). The graph layout is based on stress minimization.

Hypotheses	**Description**
Coalition Hypothesis 1	On major controversies within a mature policy subsystem when policy core beliefs are in dispute, the lineup of allies and opponents tends to be rather stable over periods of a decade or so.
Coalition Hypothesis 2	Actors within an advocacy coalition will show substantial consensus on issues pertaining to the policy core, although less so on secondary aspects.
Coalition Hypothesis 3	Actors (or coalitions) will give up secondary aspects of their belief systems before acknowledging weaknesses in the policy core.
Coalition Hypothesis 4	Within a coalition, administrative agencies will usually advocate more moderate positions than their interest-group allies.
Coalition Hypothesis 5	Actors within purposive groups are more constrained in their expression of beliefs and policy positions than actors from material groups.
Policy Change Hypothesis 1	Significant perturbations external to the subsystem, a significant perturbation internal to the subsystem, policy-oriented learning, negotiated agreement, or some combination thereof are necessary, but not sufficient, sources of change in the policy core attributes of a governmental program
Policy Change Hypothesis 2	The policy core attributes of a governmental program in a specific jurisdiction will not be significantly revised as long as the subsystem advocacy coalition that instated the program remains in power within that jurisdiction – except when the change is imposed by a hierarchically superior jurisdiction.

Table 1: ACF hypotheses about coalitions and policy change, Source: (Jenkins-Smith et al. 2014)

#	Protocol number	Date	Content	Number of analyzed pages
1	10/53	1984-02-09	Negative externalities of nuclear and other energy technologies	67
2	10/72	1984-05-25	Future energy strategy and conflicts between nuclear vs. coal	32
3	10/87	1984-06-29	Changes of the nuclear energy law (Atomgesetz)	7
4	10/94	1984-10-25	Alternatives to nuclear energy, from energy efficiency to renewable energy and coal	14
5	10/98	1984-11-08	Changes of the nuclear energy law (Atomgesetz)	11
6	10/132	1985-04-18	Risks linked to the further development of the breeder technology (Schneller Brüter)	37
7	10/171	1985-11-07	Future energy policy and negative externalities of energy technologies	52
8	10/215	1986-05-14	Nuclear accident in Chernobyl	11
9	10/216	1986-05-15	Proposal on the immediate phase out of nuclear energy (Atomsperrgesetz)	31
10	10/236	1986-10-03	Proposal on the immediate phase out of nuclear energy (Atomsperrgesetz)	10
11	10/255	1986-12-10	Proposal on the immediate phase out of nuclear energy (Atomsperrgesetz)	17
12	14/16	1999-01-21	Nuclear phase out plans and their consequences for Germany	34
13	14/79	1999-12-16	Future energy policy with or without nuclear energy	7
14	14/61	1999-10-07	Changes of the nuclear energy law (Atomgesetz)	28
15	14/95	2000-03-23	Energy policy for the 21st century	7
16	14/98	2000-04-06	Changes of the nuclear energy law (Atomgesetz)	29
17	14/111	2000-06-29	Nuclear phase out – an opportunity for energy policy consensus in Germany	22
18	14/146	2001-01-25	Future energy policy for Germany and energy dialogue (Energiedialog)	24
19	14/153	2001-02-16	Future of nuclear energy and consequences of the phase out for Germany	25
20	14/190	2001-09-27	Nuclear energy phase out – potential problems and criticism	24
21	14/209	2001-12-14	Law on the ordered phase out of nuclear energy	24
22	17/55	2010-07-08	Taxing nuclear energy profits (Brennelementesteuer) and nuclear phase out	27
23	17/63	2010-10-01	Eleventh law on changes to nuclear energy (Atomgesetz) and energy concept 2050	62
24	17/68	2010-10-28	Twelfth law on changes to nuclear energy and energy concept 2050	33
25	17/96	2011-03-17	Thirteenth law on changes to nuclear energy and energy consensus in Germany	24
26	17/106	2011-04-15	Program for a reliable, safe and sustainable energy system in Germany	35
27	17/114	2011-06-09	Future energy policy and thirteenth law on changes to nuclear energy, Fukushima	45
28	17/117	2011-06-30	Law on faster nuclear phase out	29
29	17/228	2013-03-14	Strong energy infrastructure for Germany	21
30	17/229	2013-03-15	Fukushima and nuclear phase out in Germany	19
				∑ 808

Table 2: Selected parliamentary debates.

Categories	Sub-categories	Code	Description	Meta-categories*
Arguments on energy technologies	Energy security	National energy source coal	Coal is a national energy source, and hence secure in its provision	FFT
		Energy autonomy nuclear	Deployment of nuclear power increases German energy autonomy (also: since it reduces dependence on oil and gas)	NT
		Nuclear energy imports nuclear	German nuclear phase out would lead to increasing imports from nuclear power plants abroad (e.g. France)	NT
		Supply security nuclear	Nuclear power increases supply security for industries and households due to its steady production	NT
		Grid stability renewables	Deployment of renewable energy technologies does not necessarily make the energy grid unstable, rather stable energy supply is possible	RET
		National autonomy renewables	Higher deployment of renewable energy technologies such as wind and solar lead to increasing national energy autonomy	RET
	Energy cost	Energy costs hard coal	Hard coal is a cheap energy source	FFT
		Energy costs lignite	Lignite is a cheap energy source	FFT
		Energy costs nuclear	Nuclear energy as cheap energy resource	NT
		Energy costs renewables	Renewable energy (also if only single energy technologies such as solar or wind) is the cheapest solution for the future energy system	RET
	Environment	Environment coal	Clean coal (no specification for lignite / hard coal) is possible and it can be – after modernization - in line with environmental standards and climate change goals	FFT
		Environment nuclear	Nuclear energy is CO_2-neutral and thus a solution for combatting climate change	NT
		Nuclear risk	Nuclear risk is not too high, German security standards are very strict and can ensure a safe deployment of nuclear energy	NT
		Environment renewables	Renewable energy has benefits for the environment since it reduces CO_2 emissions by replacing fossil fuels in the energy production	RET
	Energy industry	Employment nuclear	Nuclear energy is providing jobs (directly and indirectly), phase-out of this technology would cost many of them	NT
		Industry policy nuclear	Nuclear energy technology is important for Germany because it ensures leadership in nuclear industry policy and future technological development	NT
		International competitiveness nuclear	Nuclear energy technology is an important factor of international competitiveness of Germany as location for business and industry	NT
		Employment renewables	Renewable energy technologies (including solar, wind, biomass, hydro, geothermal) have benefits in terms of employment: Renewable energies are creating jobs in Germany	RET
		Industry policy renewables	Growth of renewable energy technologies leads to the development of a new industrial sector in Germany	RET
		International competitiveness renewables	Deployment of renewable energy has benefits in terms of Germany's competitiveness, since it makes Germany a world-leader in green technology	RET
		International competitiveness coal	Coal has benefits in terms of international competitiveness	FFT
		Employment coal	Coal has benefits in terms of employment: Coal is creating more jobs than other energy technologies	FFT
Attitudes on energy technologies	Coal	Lignite	Lignite as important part of energy mix (if used specifically as Braunkohle)	FFT
		Hard coal	Important role for hard coal (Steinkohle)	FFT
		Refined coal	Refined coal as important pillar of the energy system (Kohleveredelung), also: Kohleverflüssigung	FFT
	Nuclear	Nuclear	Important role for nuclear energy	NT
		Breeder reactor	Important role for the so-called breeder reactor, Schneller Brüter	NT
	Renewables	Solar	Important role for solar: PV, CSP	RET
		Wind	Important role for wind: Offshore and onshore wind energy	RET
		Hydro	Hydro energy: also pumped storage power plant	RET
		Biomass	Important role for biomass: All kinds of biomass, however no traditional biomass	RET
		Geothermal	Geothermal will play a significant role in Germany's future energy mix	RET
		Renewables as replacement	Renewables will be able to replace another primary energy source (mainly used in the context of nuclear energy, as replacement of the base load	RET
		Mix of renewables	If renewable energy technology is not specified, but only mentioned as renewables, or renewable energy technologies	RET

* as used in our analysis (Figure 3)

Table 3.1.: Codebook for positive statements on energy technologies.

Meta-categories	Categories	Code	Description	Meta-categories
Arguments on energy technologies	Energy security	Non-renewable energy source coal (N)	Fossil fuel resources are not renewable, e.g. they are available only up to a limited amount	FFT
		Energy autonomy nuclear (N)	Deployment of nuclear power does not increase German energy autonomy (since uranium needs to be imported)	NT
		Nuclear energy imports nuclear (N)	German nuclear phase out would lead to increasing imports from nuclear power plants abroad (e.g. France)	NT
		Renewable energy source nuclear (N)	Uranium supply is not unlimited, thus not a renewable energy source	NT
		Grid stability renewables (N)	Increasing use of renewable energy technologies lead to increasing grid instability due to high supply volatility	RET
		Supply security renewables (N)	Renewable energy technologies such as wind and solar are not capable of providing enough energy for the German energy system to function (without nuclear and/or fossil fuels)	RET
	Energy cost	Energy costs hard coal (N)	Hard coal is becoming increasingly expensive / it is too expensive compared to other energy sources	FFT

		Energy costs nuclear (N)	Nuclear energy is not a cheap energy source	NT
		Over-capacity nuclear (N)	Generally, there is over-capacity in the system, this is why nuclear does not need to be extended – without major consequences for energy pricing	NT
	Environment	High investment nuclear (N)	Nuclear energy is as cost-intensive and highly subsidized technology, as such it is not profitable	NT
		Energy costs renewables (N)	Renewable energy (also if only single energy technologies such as solar or wind) is expensive	RET
		Environment coal (N)	Clean coal (no specification for lignite / hard coal) is not possible – it causes too much emissions and pollution	FFT
		Environment nuclear (N)	Nuclear energy is not a solution for combatting climate change	NT
		Nuclear risk (N)	Nuclear risk is too high to justify use of nuclear power, includes radiation, waste and other nuclear hazard	NT
	Energy industry	Employment nuclear (N)	Nuclear energy is not providing many jobs compared to other energy technologies (e.g. such as wind and solar)	NT
		Outdated technology nuclear (N)	Nuclear is the wrong technology choice since nuclear power plants will not provide industrial advantages in the future	NT
		Breaking monopolies nuclear (N)	Nuclear phase-out is good for competition between energy technologies and utilities. It decreases the power of oligopoly of nuclear power providers, leading to a more diverse energy sector in Germany	NT
		Employment renewables (N)	Renewable energy technologies (including solar, wind, biomass, hydro, geothermal) are not creating (many) jobs in Germany (especially compared to other energy technologies)	RET
		International competitiveness renewables (N)	Growth of a renewable energy sector does not lead to higher competitiveness of the German industry	RET
Attitudes on energy technologies	Coal	Lignite (N)	Lignite needs to be phased out and will not play an important part in the energy mix of the future	FFT
		Hard coal (N)	Hard coal needs to be phased out and will not play an important part in the energy mix of the future	FFT
		Refined coal (N)	There is no need to deploy technologies based on refined coal, it should not be part of the energy mix of the future	FFT
	Nuclear	Nuclear (N)	Nuclear energy should be phased out	NT
		Breeder reactor (N)	Breeder reactors should not be deployed at all	NT
	Renewables	Solar (N)	Solar cannot and will not play an important role in the future energy mix	RET
		Wind (N)	Wind cannot and will not play an important role in the future energy mix	RET
		Biomass (N)	Biomass cannot and will not play an important role in the future energy mix	RET
		Geothermal (N)	Geothermal will not play a significant role in Germany's future energy mix	RET
		Renewables as replacement (N)	Renewable energy technologies are not able to replace fossil fuel and nuclear energy technologies in the future	RET

Table 3.2.: Codebook for negative statements on energy technologies.

Criteria	Selection
Scope	FAZ supra-regional only + restricted to Germany
Topics	Economy and politics
Subject area (FAZ classification)	Energy
Publication periods	01.01.1984 – 31.12.1986; 01.01.1999 – 01.06.2002; 01.07.2010 – 01.09.2011; 01.01.2013 – 01.05.2013
Article type	Only regular newspaper articles, no readers' letter, comments, interviews or book reviews
Excluded key words (FAZ classification)	Articles tagged with: Nuclear waste disposal, single nuclear waste transports, technical details of nuclear power plants, fuel elements, single nuclear power plants, single hydro power plants, single fossil power plants, energy law

Table 4: Selection criteria for newspaper articles.

Number of nodes in max core	1983-1987: 11; 1998-2002: 13; 2009-2013: 18
Average degree	2.772; 2.484; 2.676
Density	0.025; 0.016; 0.018
Max core	3; 3; 3
Modularity (of underlying one-mode actor network)	0.135; 0.244; 0.085

Table 5: Network statistics.

Cluster	Number	Actor
Think tanks and research	1	International Energy Agency (IEA)
	2	Oeko-Institut
	3	International Atomic Energy Agency (IAEA)
	4	Battelle Memorial Institute
	5	Halle Institute for Economic Research
	6	University of Stuttgart
	7	Nuclear Research Centre in Karlsruhe (KIT)
	8	University of Cologne
	9	Kiel Institute for the World Economy
	10	Institute for Ecological Economy Research
	11	Prognos
	12	Ifo Institute for Economic Research
	13	The Research Center for Energy Economics
	14	German Aerospace Center
	15	Helmholtz Association of German Research Centres
	16	DEWI Group
	17	Jülich Research Centre
	18	University of Flensburg
	19	The International Business Forum Regenerative Energies
	20	Technical University of Munich
	21	Academy for Technology Impact Assessment, Stuttgart)
	22	Institute for Solar Energy Supply Technology
	23	International Comission for Nuclear Technology
	24	International Renewable Energy Agency (IRENA)
	25	Intergovernmental Panel on Climate Change (IPCC)
	26	German Advisory Council on Global Change
	27	Fraunhofer Society
	28	German Advisory Council on Environmental Issues
	29	Centre for European Economic Research
	30	World Energy Council
	31	German Economic Institute
Unions and NGOs	1	German Metalworkers' Union
	2	German Mining, Chemical and Energy Industries Union
	3	German Trade Union Confederation Saarland
	4	German Public Services and Transport Union
	5	German Trade Union Confederation
	6	Unions of German Utilities
	7	German Federal Association of Environmental Citizens Groups
	8	Friends of the Earth Germany
	9	Nature and Biodiversity Conservation Union
	10	Greenpeace
	11	World Wide Fund for Nature (WWF)
	12	Environmental Action Germany
	13	German Nature Conservation Ring
	14	Greenpeace Energy
	15	German Bishops' Conference
	16	Central Committee of German Catholics
	17	Federation of German Consumer Organizations
Parties and ministries	1	Ministry for Economic Affairs of North Rhine-Westphalia
	2	Ministry for Economic Affairs of Lower Saxony
	3	Ministry for Economic Affairs of Hesse
	4	Centre-Right Christian Democratic Political Alliance (CDU/CSU)
	5	German Conference of Environmental Ministers
	6	Ministry for Environmental Affairs of Saarland
	7	Ministry for Environmental Affairs of Rhineland-Palatinate
	8	Ministry for Environmental Affairs of Hesse
	9	German Environment Agency
	10	City of Freiburg
	11	Social Democratic Party of Germany (SPD) Saarland
	12	Social Democratic Party of Germany (SPD) North Rhine-Westphalia
	13	Social Democratic Party of Germany (SPD) Hesse
	14	Social Democratic Party of Germany (SPD) Baden-Wuerttemberg
	15	Social Democratic Party of Germany (SPD)
	16	Federal State Government of Schleswig Holstein
	17	Federal State Government of Saarland
	18	Federal State Government of North Rhine-Westphalia
	19	Federal State Government of Lower Saxony
	20	Federal State Government of Hesse
	21	Federal State Government of Bavaria
	22	Federal State Government of Baden-Wuerttemberg
	23	Senate of Hamburg
	24	Greens North Rhine-Westphalia
	25	Greens Hesse
	26	Greens Baden-Wuerttemberg
	27	Greens
	28	Ministry of Finance Hesse
	29	Free Democratic Party (FDP) Lower Saxony
	30	Free Democratic Party (FDP) Hesse
	31	Free Democratic Party (FDP) Baden-Wuerttemberg
	32	Free Democratic Party (FDP)
	33	Christian Democratic Union of Germany (CDU) Saarland
	34	Christian Democratic Union of Germany (CDU) North Rhine-Westphalia
	35	Christian Democratic Union of Germany (CDU) Lower Saxony
	36	Christian Democratic Union of Germany (CDU) Hesse
	37	Christian Democratic Union of Germany (CDU) Hamburg
	38	Christian Democratic Union of Germany (CDU) Baden-Wuerttemberg
	39	Christian Democratic Union of Germany (CDU)
	40	German Ministry for Economic Affairs
	41	German Ministry for Environmental Affairs
	42	German Government
	43	Federal Ministry of Education and Research
	44	Ministry for Economic Affairs Saxony
	45	Ministry for Economic Affairs Bavaria
	46	Ministry for Economic Affairs Baden-Wuerttemberg
	47	Minsitry for Environmental Affairs Schleswig-Holstein
	48	Minsitry for Environmental Affairs Bavaria
	49	Minsitry for Environmental Affairs Baden-Wuerttemberg
	50	Social Democratic Party of Germany (SPD) Lower Saxony
	51	Party of Democratic Socialism (PDS)
	52	Federal State Government of Saxony
	53	Federal State Government of Mecklenburg-Hither Pomerania
	54	Federal State Government of Brandenburg
	55	Greens Lower Saxony
	56	Ministry of Finance Lower Saxony
	57	Ministry of Finance Baden-Wuerttemberg
	58	European Parliament
	59	European Commission
	60	European Court of Justice
	61	German Association of Towns and Municipalities
	62	Christian Social Union in Bavaria (CSU)
	63	Christian Democratic Union of Germany (CDU) Rhineland-Palatinate
	64	Federal Council of Germany
	65	Federal Chancellery of Germany
	66	Federal Ministry of the Interior, Building and Community
	67	Federal Ministry of Finance
	68	Social Democratic Party of Germany (SPD) Saxony
	69	Federal State Government of Thuringia
	70	Federal State Government of Saxony
	71	Federal State Government of Rhineland-Palatinate
	72	KfW Banking Group (KfW)
	73	Free Democratic Party (FDP) Saxony
	74	German Energy Agency
	75	Christian Democratic Union of Germany (CDU) Saxony
	76	Federal Network Agency
	77	Federal Ministry of Construction
	78	Federal Foreign Office
	79	Federal Agency for Nature Conservation
Industry and utilities	1	Vereinigte Elektrizitätswerke Westfalen AG
	2	South West German Association of Energy Trading
	3	Association of the German Energy and Power Sector
	4	Veba AG
	5	Association of the German Electricity Industry
	6	Thermo-Consulting Heidelberg
	7	Steag AG
	8	Siemens AG
	9	Schleswag AG
	10	Saarbergwerke AG
	11	Saacke GmbH
	12	RWE AG
	13	Ruhr-Zink GmbH
	14	Ruhrgas AG
	15	Ruhrchemie AG
	16	Rheinische Braunkohlewerke AG
	17	Reinhard Solartechnik GmbH
	18	Fuel Assemblies Union
	19	PreussenElektra AG
	20	Preussag AG
	21	Nukem GmbH
	22	Nordwestdeutsche Kraftwerke AG
	23	Neckarwerke AG
	24	Main-Kraftwerke AG
	25	Lecli-Elektrizitätswerke AG
	26	Krupp Koppers GmbH
	27	Kraftwerk Union AG
	28	Kommunales Elektrizitätswerk Mark AG
	29	Isar-Amperwerke AG
	30	Heizstoffwerk Speyer GmbH
	31	Chamber of Industry and Commerce North-Rhine-Westphalia
	32	Chamber of Industry and Commerce Hamburg
	33	Hamburger Elekrtizitätswerke AG
	34	General Association of the German Coal Industry
	35	General Association of Energy Trading Germany
	36	Society for the Promotion of Wind Energy
	37	Energie-Versorgung Schwaben AG
	38	Association of German Chambers of Industry and Commerce
	39	German Atomic Forum
	40	The German Wind Energy Association
	41	German Solar Industry Association
	42	Federal Union of Energy Consumers
	43	Stadtwerke Bremen AG
	44	Braunschweigische Kohlen-Bergwerke AG
	45	The Federation of German Industries
	46	Bayernwerk AG
	47	Badenwerk AG
	48	Babcock International
	49	Wasserkraft und Regenerative Energieentwicklung AG
	50	VIAG AG
	51	VGB PowerTech
	52	Vestas Wind Systems A/S
	53	VEAG AG
	54	Mechanical Engineering Industry Association
	55	Vattenfall AB
	56	UVA Solar
	57	Umweltkontor AG
	58	Southern Energy Company, Inc.
	59	Solvis Energiesysteme GmbH
	60	SolarWorld AG
	61	Solarstrom AG
	62	Solar Millennium AG
	63	Royal Dutch Shell plc
	64	S.A.G. Solarstrom AG
	65	RAG AG
	66	Plambeck Neue Energien AG
	67	Ökofinanz Frankfurt GmbH
	68	NRG Energy, Inc.
	69	Nordex SE
	70	New Power
	71	Naturstrom AG
	72	NaturEnergie AG
	73	MVV Energie AG
	74	Mitteldeutsche Braunkohlegesellschaft mbH
	75	Lausitzer Braunkohle AG
	76	Harpen AG
	77	Gesellschaft für Nuklear-Service mbH
	78	Siemens Gamesa Renewable Energy
	79	Gamesa Corporación Tecnológica S.A.
	80	Elektrizitätswerke Schönau Vertriebs GmbH
	81	European Association for Renewable Energy (Eurosolar)
	82	E.ON SE
	83	Enron Corporation
	84	Enertrag AG
	85	Energiewerke Nord GmbH
	86	Energiekontor AG
	87	National Initiative for Bioenergy
	88	EnerCom, Inc.
	89	EnBW AG
	90	Électricité de France S.A. (EDF)
	91	DeWind Inc.
	92	Deutsche Bank AG
	93	Conergy Group
	94	Cogema S.A.
	95	Central Association for Plumbing, Heating and Air Conditioning
	96	German Renewable Energy Association
	97	BTM Consult
	98	British Nuclear Fuels plc
	99	Borsig Energy GmbH
	100	Bewag AG
	101	German Association of Energy and Water Industries
	102	Bayerische Wasserkraft AG
	103	Ares Energie AG
	104	Aerodynamic Energysystems
	105	ABB Ltd.
	106	wind 7 AG
	107	Opel Automobile GmbH
	108	Südhessische Energie AG
	109	Climate and Renewables
	110	Central Federation of the German Construction Industry
	111	German Building Materials Association
	112	Deutsche Biogas AG
	113	PNE Wind AG
	114	European Investment Bank
	115	Stadtwerke Lübeck GmbH
	116	Stadtwerke Duisburg GmbH
	117	International Solar Energy Society (ISES)
	118	The Blackstone Group L.P.
	119	Trianel GmbH
	120	LichtBlick SE
	121	CENTROSOLAR Group AG
	122	Desertec Foundation
	123	Munich RE AG
	124	juwi AG
	125	European Wind Energy Association (EWEA)
	126	German Agricultural Society
	127	Federal Association of Biogenic and Regenerative Fuels
	128	German Union for the Promotion of Oil and Protein Plants (UFOP)
	129	AgriCapital Corporation
	130	Amprion GmbH
	131	The German Farmers' Association
	132	The German Association of Municipal Enterprises
	133	German Insurance Association
	134	German Metal Industry Association
	135	50Hertz Transmission GmbH
	136	TenneT Holding B.V.
	137	Deutsche Bahn AG
	138	Bard Holding GmbH
	139	Federal Association of the German Gas and Water Industry,
	140	Association to Foster Economic Growth in the German Ruhr Area
	141	Bilfinger + Berger Bau AG
	142	Technical Inspection Association (TüV)
	143	BASF SE
	144	Innogy SE
	145	badenova AG & Co. KG
	146	Thoga AG
	147	Enercon GmbH
	148	Repower AG
	149	ABO Wind AG
	150	thyssenkrupp AG
	151	Bayer AG
	152	Stadtwerke München GmbH
	153	wpd AG
	154	PNE AG
	155	Next Kraftwerke GmbH
	156	Subitec GmbH
	157	Windreich GmbH
	158	German Association for Wood Energy
	159	Ritter Energie- und Umwelttechnik GmbH & Co. KG
	160	Viessmann GmbH & Co. KG
	161	EWE AG

Table 6: List of actors depicted in Figure 3

ID	Date	Identification
	Newspaper articles	
(1)	31.08.1984	NN-FAZ-Artikel-840831_FAZ_0006_6_0003
(2)	06.03.1985	NN-FAZ-Artikel-850306_FAZ_0004_4_0004
(3)	13.05.1985	Klaus_Broichhausen-FAZ-Artikel-850513_FAZ_0013_13_0003
(4)	10.05.1986	NN-FAZ-Artikel-860510_FAZ_0001_1_0001
(5)	28.05.1986	NN-FAZ-Artikel-860528_FAZ_0001_1_0001
(6)	11.08.1986	NN-FAZ-Artikel-860811_FAZ_0001_1_0007
(7)	12.08.1986	NN-FAZ-Artikel-860812_FAZ_0001_1_0006
(8)	01.09.1986	NN-FAZ-Artikel-860901_FAZ_0004_4_0004
(9)	12.01.1999	Hohenthal_Carl_Graf-FAZ-Artikel-F19990112HALATO-100
(10)	20.01.1999	Schwenn_Kerstin-FAZ-Artikel-F19990120ENNKONS100
(11)	04.06.1999	Hohenthal_Carl_Graf-FAZ-Artikel-FR11999060488849
(12)	29.09.1999	Hohenthal_Carl_Graf-FAZ-Artikel-FR119990929177632
(13)	26.02.2000	Hohenthal_Carl_Graf-FAZ-Artikel-FR220000226345060
(14)	18.08.2010	Sattar_Majid-FAZ-Artikel-FD2201008182806540
(15)	21.02.2013	Mihm_Andreas-FAZ-Artikel-FD2201302213797833
(16)	13.05.1986	NN-FAZ-Artikel-860513_FAZ_0001_1_0008
(17)	13.05.1986	NN-FAZ-Artikel-860513_FAZ_0001_1_0008
(18)	08.07.1999	Hohenthal_Carl_Graf-FAZ-Artikel-FD319990708107626
(19)	26.11.1999	Hohenthal_Carl_Graf-FAZ-Artikel-FR219991126242783
(20)	26.02.2000	Hohenthal_Carl_Graf-FAZ-Artikel-FR220000226345060
(21)	26.02.2000	Hohenthal_Carl_Graf-FAZ-Artikel-FR220000226345060
(22)	21.02.2013	Mihm_Andreas-FAZ-Artikel-FD2201302213797833
(23)	23.03.1984	NN-FAZ-Artikel-840323_FAZ_0006_6_0001
(24)	02.01.1986	NN-FAZ-Artikel-860102_FAZ_0013_13_0014
(25)	23.05.1986	NN-FAZ-Artikel-860523_FAZ_0004_4_0003
(26)	21.11.1986	NN-FAZ-Artikel-861121_FAZ_0013_13_0004
(27)	14.01.1999	Hohenthal_Carl_Graf-FAZ-Artikel-F19990114HALMWE-100
(28)	30.01.1999	Hohenthal_Carl_Graf-FAZ-Artikel-F19990130RAD3DOK
(29)	30.01.1999	Hohenthal_Carl_Graf-FAZ-Artikel-F19990130RAD3DOK
(30)	29.05.1999	Hohenthal_Carl_Graf-FAZ-Artikel-FR21999052986259
(31)	17.12.1999	Hohenthal_Carl_Graf-FAZ-Artikel-FR119991217266873
(32)	07.05.1999	Hohenthal_Carl_Graf-FAZ-Artikel-FD21999050776093
(33)	11.08.2010	Mihm_Andreas-FAZ-Artikel-FD2201008112798691
	Plenary protocols	
(34)	08.11.1984	Parliamentary protocol 10/98
(35)	08.11.1984	Parliamentary protocol 10/98
(36)	25.05.1984	Parliamentary protocol 10/72
(37)	14.05.1986	Parliamentary protocol 10/215
(38)	16.02.2001	Parliamentary protocol 14/153
(39)	23.03.2000	Parliamentary protocol 14/95
(40)	09.06.2011	Parliamentary protocol 17/114
(41)	17.06.2011	Parliamentary protocol 884
(42)	16.03.1999	Parliamentary protocol 14/79
(43)	29.06.2000	Parliamentary protocol 14/111
(44)	14.12.2001	Parliamentary protocol 14/209
(45)	28.10.2010	Parliamentary protocol 17/68
(46)	30.06.2011	Parliamentary protocol 17/117
(47)	15.03.2013	Parliamentary protocol 17/229
(48)	07.11.1985	Parliamentary protocol 10/171
(49)	03.10.1986	Parliamentary protocol 10/236
(50)	21.01.1999	Parliamentary protocol 14/16
(51)	16.02.2001	Parliamentary protocol 14/153
(52)	06.04.2000	Parliamentary protocol 14/98
(53)	15.04.2011	Parliamentary protocol 17/106
(54)	14.03.2013	Parliamentary protocol 17/228
(55)	10.12.1986	Parliamentary protocol 10/255
(56)	28.11.1986	Parliamentary protocol 571

Table 7: Newspaper articles and parliamentary protocols,

	Period	Quotes		Person	Source
Interpretive	80	*Let us stop the development of the fast breeder. We save billions if we do not use this breeder-technology in Germany. This technology is a failed research project.*	-	Josef Vosen (MP)	(47)
		There is no doubt that, if you like it or not, both in the lignite and in the hard coal sector, there is a harsh competition between nuclear energy and coal. Just look at the numbers.	-	Volker Hauff (MP)	(48)
		It will never be the case that wind energy will replace any of the existing primary energy sources. (...) The utopia of a wind-supplied Germany, which is at the heart of your proposal, will always remain a utopia.	-	Klaus Lennartz (MP)	(47)
	90	*Why should we not build a nuclear power plant anymore? It is not about ideological reasons. It is no longer economically viable and in a competitive economy – as it was introduced in the electricity sector - it will not be profitable for a long time, for many reasons.*	-	Werner Müller (Minister of Economy)	(49
		The 100 000-Roofs-Program for the photovoltaic industry brought a big boost for this technology. With this policy, we want to lower the prices of electricity generated by photovoltaic panels and develop a long-term perspective for panel manufactures.	+	Horst Kubatschka (MP)	(50)
		We want to boost renewable energies, energy efficiency and energy saving and implement the exit from a dangerous, non-controllable and hazardous power generation at the same time.	+	Rainer Brinkmann (MP)	(51)
	00	*Those who believe that the old energy policy of "coal and nuclear energy" is cheaper, and who say that renewable energies are more expensive, are liars.*	-	Matthias Miersch (MP)	(46)
		People want to get out of nuclear energy fast and to enter the era of renewable energies quickly: it is undeniable.	+	Rolf Hempelmann (MP)	(52)
		We face the days when the sun does not shine and the wind does not blow with many problems concerning the security of supply and the stability of the grid.	-	Sigmar Gabriel (MP)	(53)
Resource	80	*Opting out of the nuclear energy program will of course have an impact on the job market, Mr Lenzer. However, you should also know that nuclear energy is the most capital-intensive technology and that it requires the least employees.*	-	Bernd Reuter (MP)	(54)
		The Federal Government is of course aware that they accept that thousands of jobs in coalmines and supply industries will be lost, in areas, which are already affected by unemployment and structural problems.	-	Reimut Jochimsen (Minister Economy NRW)	(55)
		The coalmine Zollverein in Essen with 4000 employees will run out at the end of the year. The simple reason for it is that RWE produces less electricity from lignite; instead, the utility connects the nuclear power plant of Mülheim-Kaerlich to the grid.	-	Johannes Rau (Prime Minister NRW)	(48)
	90	*In the law, we present a security mechanism for Combined-Heat-and-Power of municipal utilities, which is threatened by your legislation. Your policy would lead to a large-scale loss of jobs in some power plant sectors and in several cities.*	-	Ernst Schwanhold (MP)	(41)
		Just one last word concerning jobs. The subject has already been mentioned here a couple of times. We should maybe underline renewable technologies will lead to the creation of new jobs. It is assumed that in the last years 20 000 jobs have been created in this technology sector.	+	Ulrike Mehl (MP)	(41)
		However, that one always thinks that the new technologies only lead to the loss of old jobs, without referring to the new jobs created at big scale, especially in the small and medium sized firms, if we subsidize decentralized energy technologies, such as renewable energies, that is not good. In total, we expect the creation of 1.2 million new jobs.	+	Hermann Scheer (MP)	(41)
	00	*In the last years and months, I have been traveling through the industry heartland Baden-Württemberg, visiting many firms. Of these firms, none would like to build nuclear power plants with great pleasure. However, many firms are eager to produce high-performative wind turbines and photovoltaic panels, and export these technologies in the whole world. That is the chance for the future of the industry location Baden-Württemberg.*	+	Nils Schmid (Minister of Finance BW)	(45)
		300 000 new jobs have meanwhile been created thanks to the development of renewable energies in Germany.	+	Sigmar Gabriel (MP)	(44)
		Pushing out nuclear energy, billions of dollars in investments and 400 000 jobs in Germany are all factors tied to the Renewable Energy Act.	+	Ulrich Kelber (MP)	(39)

+ / - Directionality of feedback mechanism

Table 8: Statements on energy technology of SPD members of parliament

	Period	Exemplary quote		Person	Source
Interpretive	80	*Nuclear energy is the most secure form of power generation. There are 300 nuclear power plants all over the world. We have gathered 30 years of excellent experience in this field.*	+	Alexander Warrikoff (MP)	(34)
		Do you not know that the adoption of nuclear energy in base load will represent - in the future - a cost advantage compared to domestic coal? Moreover, do you know that nuclear energy has some environmental advantages?	+	Josef Bugl (MP)	(35)
		Who wants to phase out nuclear energy now cannot hide behind solutions such as wind or solar energy. Research has been carried out since 1973. The destiny of GROWIAN, the biggest wind turbine of all time, is well known.	-	Friedrich Zimmermann (Minister of Interior)	(36)
	90	*In Germany, you know that power generation from nuclear sources was a factor of international competitiveness. You also know, that the phase-out will lead to higher electricity prices, which will lead to decreasing competitiveness in the sector of electricity-intensive production.*	+	Dagmar Wöhrl (MP)	(37)
		The question is how to replace nuclear energy. It cannot be solar energy. We want to develop solar energy, but you cannot simply replace nuclear energy.	-	Klaus W. Lippold (MP)	(38)
		The replacement of nuclear energy in the base load through renewable energies is absurd.	-	Kurt-Dieter Grill (MP)	(38)
	00	*Fukushima has changed my attitude towards nuclear energy.*	-	Angela Merkel (Chanc.)	(39)
		Over a period of ten years, there was a multiplication of the ratio of renewable energies. Now we want to reach a further doubling or a triplication. Ten years ago, the share of renewable energies did not reach 17 percent of electric power. This percentage has considerably increased. The technological-industrial and economical bulkiness we have today are a sign that we have a big chance.	+	Norbert Röttgen (Minister of Environment)	(39)
		I strongly believe that the increasing competition and the decentralization of the power supply will have a positive impact on energy prices.	+	Horst Seehofer (Prime Minister Bavaria)	(40)
Resource	80	*In the sector of nuclear industry, including its supply industry, there are 150 000 jobs, jobs that are among the safest and involve highly qualified labor. You would destroy these jobs with a nuclear phase out.*	+	Alexander Warrikoff (MP)	(34)
	90	*40 000 employees work for the nuclear energy industry. However, it is not just about them. If we lose the ability to compete, 150 000 jobs in the steel, non-ferrous metals, chemistry, paper, glass and cement sectors will be endangered. These are the economic impacts we have to deal with if we opt out too quickly.*	+	Gunnar Uldall (MP)	(41)
		This nuclear phase-out works at the expenses of climate protection, of training capacity and professions, as well as at the expenses of the German technological progress.	+	Angela Merkel (MP)	(42)
		It is also not credible to play with numbers in the renewables sector, when it comes to jobs. Here the projections overturn: some reach 200 000, other 500 000 jobs. However, there is no reliable computation.	+	Christian Ruck (MP)	(43)
	00	*We go through this transformation of the energy sector because we are convinced that this will lead to modernization, innovation, to the development of new markets and that it will lead to the creation of new jobs, to the consolidation of competitiveness and to securing the future.*	+	Norbert Röttgen (Minister of Environment)	(44)
		To this day, 350 000 jobs have been created through the energy transition. There will be more, because through the transition of the energy supply we promote domestic value chains.	+	Norbert Röttgen (Minister of Environment)	(45)
		We have transformed the energy transition into a motor for employment. In the last three years, we have created 100 000 jobs in the sector of renewable energies. In the area of energy efficiency, 340 000 jobs – mainly craftwork – were secured and created. Moreover, that was not at the expenses of industries.	+	Thomas Bareis (MP)	(46)

Table 9: Statements on energy technologies of CDU/CSU members of parliament*

+ / -

Directionality of feedback mechanisms

* Note concerning the coding: The quotes in these tables show that sentences can vary according to their complexity and ambiguity. Sentences might include several statements at the same time, they might be interpreted differently if put in another context, or contain linguistic styles such as irony. The following two sentences can serve as an example for the differences in complexity and ambiguity: A) Table 9 in the appendix, row 2: "*Do you not know that the adoption of nuclear energy in base load will represent - in the future - a cost advantage compared to domestic coal?*" B) Table 9 in the appendix, row 10: "*In the sector of nuclear industry, including its supply industry, there are 150 000 jobs, jobs that are among the safest and involve highly qualified labor. You would destroy these jobs with a nuclear phase out.*" Statement B) was coded as "job argument in favor of nuclear technology". Statement A) is more complex, as it contains a rhetorical question (ambiguity) and more than one statement per sentence (complexity). Here, we coded as "low cost argument in favor of nuclear technology" and "low cost argument against coal technology".

Paper 2: Governing complex societal problems: The impact of private on public regulation through technological change

Authors: Nicolas Schmid*[1], Leonore Haelg[1], Sebastian Sewerin[1], Tobias S. Schmidt[1], Irina Simmen[1]

* Corresponding author: nicolas.schmid@gess.ethz.ch

[1] ETH Zurich, Department of Humanities, Social and Political Sciences, Energy Politics Group, Haldeneggsteig 4, CH-8092 Zurich, Switzerland

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Abstract:

When addressing complex societal problems, public regulation is increasingly complemented by private regulation. Extant literature has provided valuable insights into the effectiveness of such complex governance structures, with most empirical studies focusing on how public regulation influences private regulation. Conversely, the impact of private on public regulation is less well studied. Here, we investigate this impact with a focus on technological change as possible mechanism. Based on a case study of energy efficiency in buildings in Switzerland, we find evidence of a symbiotic interaction between public and private regulation that leads to ratcheting-up of regulatory stringency. We identify technological change as the mechanism linking private and public regulation. We discuss the relevance of our findings for governance literature and regulators.

1. Introduction

Societies face increasingly complex and dynamic problems, with climate change being one of the most notable examples of such "super-wicked" problems (Levin et al. 2012). To address these problems, complex governance structures have emerged in which traditional public regulations (i.e., mandatory command-and-control instruments) are complemented by private regulations (i.e., voluntary market-based instruments) (Cashore 2002; Loorbach 2010; Potoski and Prakash 2005). This has resulted in complex and polycentric structures of governance (Jordan et al. 2015; Levi-Faur 2006; Meadowcroft 2007). In such structures, regulatory governance occurs on various levels and involves both public and private actors who implement a wide range of public and private regulatory instruments (Hsu et al. 2019).[20]

Complementing public regulation with private regulation may increase the adaptability, accountability, and effectiveness of such governance structures (Keohane and Victor 2011) and potentially resolve the fundamental tension between regulatory rigidity and flexibility (Duit and Galaz 2008). At the same time, private regulation may erode the scope and authority of public regulation, resulting in less effective governance (Malhotra *et al.* 2019). Much of the existing governance literature is concerned with the question of whether these claims about the merits and pitfalls of private regulation hold true (Bernstein and Cashore 2007; Green 2010; Mattli and Büthe 2005; Schleifer 2017; van der Heijden 2020). Yet, since the effectiveness of private regulatory instruments also depends on their impact on other regulatory instruments, an emerging research stream focuses on the *interaction between public and private regulation* (Eberlein et al. 2014; Gulbrandsen 2014). This research has shown that public regulation plays a crucial role in facilitating the emergence, implementation, and enforcement of private

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[20] In our paper, we use governance and regulatory governance interchangeably, following Levi-Faur's (2012) definition of regulatory governance as the organized attempt to steer the behavior of targeted actors through both public and private regulatory instruments (see also Eberlein et al. 2014).

regulation (Héritier and Eckert 2008). However, the reverse effect, i.e., the *impact of private regulation on public regulation,* remains understudied (Malhotra et al. 2019).

We argue that in order to fully comprehend the effectiveness of private regulation, an improved understanding of its impact on public regulation is required. To reach this understanding, the underlying mechanisms linking public and private regulation need to be fully understood (van der Heijden et al. 2019). While several mechanisms may exist, here we focus on the role of technological change and its feedback on regulation. Although technological change is a crucial factor in both creating and solving current societal challenges, its role for the interaction between regulatory instruments remains understudied.[21] In extant regulation literature, technology is predominantly seen as an exogenous factor (Porter 2014; Snir and Ravid 2016) or a tool to improve the performance of regulatory instruments (Auld et al. 2010; Fukuyama 2016; Grabosky 2013) rather than a target of regulation itself. This conception of technological change as an exogenous factor arguably stems from the empirical focus of most studies on "disruptive" technologies (Hasselbalch 2018), such as information technologies (Culpepper and Thelen 2020; Kenney et al. 2019; Yeung 2018) and nanotechnologies (Sylvester et al. 2009). For such technologies, regulation may be more *reactive* – as opposed to actively steering innovation – and less influential than in the case of "incremental" technological change, such as in the building sector. In contrast to this conception, and in line with innovation studies (Hoppmann et al. 2014; Kivimaa and Kern 2016; Schmidt and Sewerin 2018), we conceptualize technology as the *target outcome* of a policy, meaning that the goal of the policy is to induce technological change. We draw on policy feedback literature (e.g. Béland and Schlager 2019; Pierson 2000; Schmid et al. 2019) to discuss how private regulation can, over time, feed back into public regulation through technological

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[21] Here, technological change is understood as the invention, innovation, and large-scale diffusion of new technologies (Jaffe et al. 2002).

change. In this context, technological change may constitute one of several important *mechanisms* that explains the impact of private regulation on public regulation. We aim to complement existing governance literature by exploring the role of technological change as a mechanism and by asking the following research question: *How does private regulation influence public regulation, and how does technological change affect this relationship*?

To address this question, we build on theoretical discussions in governance literature regarding regulatory instrument interaction as well as innovation studies and policy feedback theory. Empirically, we focus on the case of energy efficiency in the Swiss building sector, which provides a suitable case for an exploratory theory-building study. To understand the impact of private regulation on public regulation, we employ a mixed-methods approach to analyze changes in the *regulatory stringency* of two Swiss regulatory instruments over time—namely, public building standards and a private building label.[22] First, we construct a novel and extensive dataset on both public regulation across 23 Swiss Cantons (i.e., subnational jurisdictions) and private regulation over more than 30 and 20 years, respectively. Second, we conducted 27 semi-structured expert interviews to understand the drivers behind public and private regulatory stringency. We find that the stringency of both public and private regulatory instruments increases over time, with the latter being more stringent. Crucially, our analysis provides substantial evidence for a symbiotic interaction between public and private regulatory instruments. Private regulation can, through fostering technological innovation in niches, drive higher stringency in public regulation at a subsequent time. Thus, we show that, under certain conditions, combining public and private regulation can increase overall governance performance through a mutual ratcheting-up process. This finding puts into context the ongoing debates in regulatory and governance studies about whether public or private

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[22] We define regulatory stringency along the lines of Carley and Miller (2012) as different levels of standards or limit values in regulatory instruments.

regulation is more effective in isolation. Our main finding also highlights the role of technological change as a mechanism explaining this symbiotic ratcheting-up process: Technological change induced by private regulation increased the political feasibility of more stringent public regulation by expanding the availability of technically feasible and economically affordable technologies, which constituted positive feedback effects in the regulatory process. Further, we present contextual factors that moderate instrument interaction through technological change—namely, institutional and political differences between cantons and technological differences between building components. Finally, we discuss the theoretical relevance of our findings for governance literature as well as the practical relevance of our findings for regulators.

2. Instrument interaction and the role of technological change therein

In light of increasingly complex societal problems, various research streams have investigated the shift "from government to governance", i.e., from sole state-authority in governing to the involvement of non-state stakeholders (Cashore 2002; Eberlein et al. 2014; Fukuyama 2016; Levi-Faur 2012; Potoski and Prakash 2005; Steurer 2013). Generally, most studies investigate the nature and effectiveness of private regulatory instruments (Auld et al. 2015; Darnall et al. 2017; Dietz et al. 2019; Szulecki et al. 2011; van der Heijden 2020). The debate regarding whether private regulatory instruments have a positive, neutral, or negative effect on governance performance is still ongoing (Carrigan and Coglianese 2011; Chan et al. 2019; Hoffmann 2011; Howlett and Rayner 2007, Matschoss and Repo 2018). The extant literature is mostly comparing private regulatory instruments across jurisdictions or sectors (Judge-Lord et al. 2020; van der Heijden 2020). However, these studies has resulted in inconclusive empirical findings (Hsu et al. 2019). Reaching more conclusive findings might necessitate research designs that take into account the *interaction* between public and private regulatory instruments.

2.1. Regulatory instrument interaction in governance literature

A growing research stream therefore specifically focuses on these interactions (Andanova et al. 2017; Bartley 2018; Dietz et al. 2019; Gulbrandsen 2014; Trencher and van der Heijden 2019), showing that the emergence, implementation, and enforcement of private regulation is strongly influenced by existing public regulatory instruments (Auld et al. 2014; Héritier and Lehmkuhl 2008; van der Heijden 2015; Verbruggen 2013; Vogel 2008). Although this research has provided important insights into instrument interaction, existing studies primarily focus on "one-way interactions" from public to private regulation (Trencher and van der Heijden 2019). We argue that in order to fully understand the nature and effectiveness of private regulation, more empirical research into the reverse effect – i.e., private on public regulation – is needed (Arcuri 2015; Malhotra et al. 2019). On a theoretical level, public regulation may benefit from engaging with private regulation since it enables regulators to combine the competencies of public and private actors (Abrams et al. 2018). While some scholars suggest that private regulation enables experimentation and learning (Matschoss and Repo 2018), other scholars argue that private regulation may "crowd out" or preempt more stringent public regulation (Malhotra et al. 2019) or even undermine public regulation altogether (Baron 2014). This could potentially limit the overall scope of regulation, that is, how much of the relevant regulatory targets are addressed. Such crowding out may be even more prevalent with the growing complexity of societal problems: The regulation of "super-wicked" problems (Levin et al. 2012) may be biased towards the preferences of private actors because of information asymmetry and principal–agent problems between public administrations and private actors (Héritier and Eckert 2008; McCarty 2015). These asymmetries may be even more pronounced if technology is involved in addressing the societal problem (Eberlein 2008; Mattli and Büthe 2005), such as in the case of climate change mitigation through technological change (Gilligan and Vandenbergh 2020). Hence, the effect of private regulation on public regulation depends also on the governance capacity of public regulators (Howlett and Rayner 2006; Knill and Lehmkuhl 2002).

2.2. Technological change as mechanism linking public and private regulatory instruments

Given the important role of technology in both creating and solving problems in various regulatory fields (Jaffe et al. 2002), it is surprising that the influence of technological change in shaping the impact of private regulation on public regulation remains largely uncovered (Auld et al. 2010). Although the role of private regulation for the regulation of technology has been central to academic debates in the 1970s and 1980s (Bailey 1987; Buchanan and Tullock 1975; Quirk 1982; Stigler 1971), it has been absent from more recent governance literature: If considered at all in this literature, technology is mostly seen as an exogenous factor that remains relatively independent from regulation (Porter 2014; Schmid et al. 2019; Snir and Ravid 2016). This conception of the role of technology arguably stems from the empirical focus of most studies on "disruptive" technologies (Hasselbalch 2018), such as information technologies (Kenney et al. 2019; Yeung 2018) and nanotechnologies (Sylvester et al. 2009). For such technologies, regulation may be more *reactive* – as opposed to actively steering innovation – and less influential than in the case of "incremental" technological change, such as in the building sector. Other scholars understand technology as a tool, i.e., *mechanic,* used to improve the performance of regulatory instruments (Fukuyama 2016; Grabosky 2013). For instance, Auld et al. (2010) investigate how innovative GPS tracking technology or DNA testing can improve the environmental performance of private regulation in complex global supply chains. The authors argue that private regulation "may play a role as technology incubator, potentially facilitating and fostering, rather than bypassing, traditional public policy efforts at the domestic or global levels" (p. 24). However, they acknowledge that how exactly private regulation influences public regulation through technology remains an open question for future research.

Here, we attempt to address this question by conceptualizing technology as a *target outcome* rather than a tool or mechanic of regulation. In this view, which is in line with innovation studies literature (e.g., Hoppmann et al. 2014; Kivimaa and Kern 2016; Schmidt and Sewerin 2018), technological change can be seen as a mechanism linking different regulatory instruments over time. Insights from policy feedback literature can help to further describe how exactly technology may connect public to private regulation. The classical argument of this literature is that changes in regulation at t_i can affect the politics of subsequent changes in regulation at t_{i+1} (Jordan and Matt 2014; Pierson 2000). Recent studies have looked at the role of technological change in such feedback processes. Based on a case study of the German electricity sector, Schmid et al. (2019) have developed a framework in which technological change is conceptualized as a regulatory outcome that influences subsequent political processes through feedback mechanisms. Meckling et al. (2015) have argued that industrial regulation can create positive feedback through the creation of green industries that support subsequent regulation targeted at the decarbonization of the economy. Importantly, this literature suggests that such positive feedback can be intentionally created by smart regulatory design. Regulators that aim at increasing the political feasibility and stickiness of subsequent regulatory instruments in a regulatory mix (Howlett 2019; Jordan and Matt 2014) can, for example, follow an instrument sequencing approach (Meckling et al. 2015, 2017; Schmidt et al. 2019; Taeihagh et al. 2013). These insights from literature on technological innovation and policy feedback have important implications for theories of regulatory governance: In many regulatory fields, both public and private regulation influence technology, meaning that technological change may strongly mediate instrument interaction and should thus be conceptualized as a mechanism rather than tool or mechanic (see Figure 1 below).

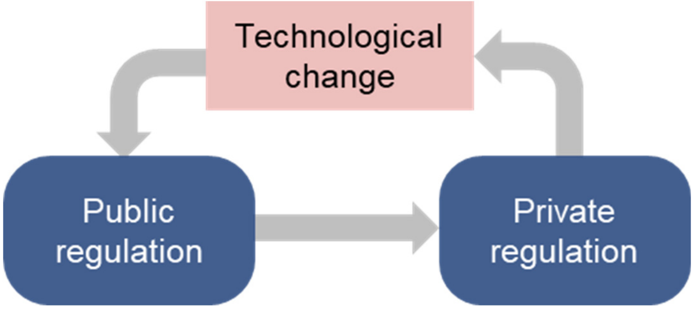

Figure 1: The impact of private regulation on public regulation through the mechanism of technological change.

Hence, explicitly conceptualizing technological change as a mechanism may help analyze the impact of private regulation on public regulation. Considering this impact may enable more valid assessments of overall governance effectiveness. In a theory-building endeavor, this paper explores whether and how private regulation has an impact on public regulation through the mechanism of technological change. Note that we focus on changes in regulatory stringency (Judge-Lord et al. 2020) in order to capture instrument interaction.

3. Case selection and methodology

3.1. Case selection

To analyze the effects of private on public regulation through technological change, we chose the field of *energy efficiency of buildings*, for three reasons. First, our case is suitable for investigating the link between technology and regulation as increasing efficiency in the building sector represents a very complex societal problem for which technological change represents the most important solution (International Panel on Climate Change [IPCC] 2014).[23] Yet, multiple barriers hamper the diffusion of energy efficient technologies. Such barriers include the high upfront cost of technologies, high transaction costs, strong lock-in effects, and the principal–tenant problem (Gillingham and Palmery 2014; Rosenow et al. 2017). Because of these barriers, public and private regulation are needed to increase energy efficiency in the building sector (Asensio and Delmas 2017; Girod et al. 2017; Noailly 2012). Note that most current regulatory instruments target new buildings only. As a consequence, the focus of our paper is on the governance of new buildings and we thus disregard regulations on building retrofits. Second, from an instrument interaction perspective, the case of energy efficiency remains a poorly studied phenomenon as most studies on energy efficiency focus on the effectiveness of regulatory instruments (but see Kern et al. 2017; Rosenow et al. 2017; Trencher and van der Heijden 2019). Third, increasing the energy efficiency of buildings can substantially contribute to climate change mitigation. The building sector accounts for 19% of direct and indirect global greenhouse gas emissions, and it is the regulatory field with the highest potential for energy efficiency improvements (IPCC 2014). Given the length of investment cycles in this sector, fast regulatory intervention is important for climate change mitigation.

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[23] In this paper, we use Pérez-Lombard et al.'s (2013) definition for energy efficiency, who state that "efficiency is the ability to achieve a desired result wasting minimum resources." Energy efficiency is thus always a relative number as opposed to energy savings, which indicate the absolute reduction in energy use.

Further, we chose the case of *Switzerland* for three reasons. First, energy efficiency governance in Switzerland is effective compared to other countries, as the final energy consumption of buildings has decreased for new buildings (Kemmler et al. 2018). Second, the empirical case offers a high level of data variance regarding public and private regulatory instruments due to substantial and long-lasting regulatory activity in this field. This facilitates the analysis of instrument interaction over time. Public building standards were established early on (i.e., starting after the oil crises in the 1970s) and subsequently diffused across jurisdictions (Sager et al. 2014; Strebel 2011; Strebel and Widmer 2012). Twenty-six different public building standards are enacted in Switzerland because subnational entities are responsible for building regulation. The federal level intervenes only as a facilitator of coordination between cantons (Casado-Asensio and Steurer 2016). Although efforts to align standards through model regulations were expanded over time, these model regulations offer extensive freedom in relation to the speed and extent of their adoption (Grösser 2012; Strebel 2011). Hence, standards are heterogeneous across jurisdictions and time. In addition, standards contain different requirements depending on the target technology (e.g., windows or insulation materials for walls). Besides public regulation, the existence of an influential private regulatory instrument makes it possible to analyze the impact of private regulation on public regulation. An association called Minergie was founded in 1998 by private individuals, together with firms and banks, and received the support of cantonal building administrations (Aeberhard 2018; Lange et al. 2019). Since its creation, Minergie has issued a nationwide label to certify buildings - independent from other international labels, such as the Leadership in Energy and Environmental Design label. The purpose of this private building label was to build a trusted trademark with enforced compliance in order to create incentives for the diffusion of highly energy-efficient technologies. Third, the existence of a strong and diversified Swiss construction industry means that technological change happens mostly within the jurisdictional borders (Bättig and Ziegler 2009). Although we cannot exclude spillover effects from other countries, the leadership of local firms in energy-efficiency technologies on the Swiss market means that such effects should be marginal.

3.2. Methods and data

In this study, we applied a mixed-methods approach combining quantitative analyses on public and private regulatory instruments with qualitative analysis from semi-structured interviews. We proceeded in two steps. First, in a major effort of data collection, we constructed a novel cross-sectional and longitudinal dataset on the stringency of both public and private regulatory instruments. Public building standards set requirements on the minimum level of insulation of different building components, measured with the so-called U value. The U value represents the amount of heat that is transferred by the surface of a building component at a given temperature difference (measured in W/m^2K). Accordingly, the U value decreases with increasing regulatory stringency. The data was collected from cantonal energy departments, construction departments, and energy offices. In total, we obtained data from 23 of the 26 cantons, for the period between 1975 and 2018. For the private building label, we collected the stringency values reported as systemic efficiency values as well as, where applicable, the U values for individual building components. In the second step, we conducted semi-structured interviews with experts and stakeholders to understand the drivers behind changes in public and private regulatory instrument stringency. The interviewees listed in Table 1 were identified by desk research following a combination of positional, decisional, and reputational approaches (Knoke 1996). We conducted twenty in-depth expert interviews, with each interview lasting between 40 and 100 minutes. Additionally, we conducted seven interviews, with each interview lasting between 10 and 30 minutes, at a construction industry fair in Lucerne. All interviews took place between August and December 2018.

Table 1. List of interviewees.

Person	Category	Description
1	Civil servant	Director of the Department of Energy and Environment, the canton of Bern
2	Civil servant	Employee at the cantonal energy bureau, the canton of Zurich
3	Civil servant	Former employee at the cantonal energy bureau, the canton of Grisons
4	Civil servant	Employee of the Swiss Federal Office of Energy
5	Civil servant	Technical expert at the Intercantonal Conference of Energy Directors (ICED)
6	Civil servant	Director of the Department of Energy and Environment, the canton of Neuchatel Director of the Conference of the Swiss–French Energy Departments (CRDE)
7	Civil servant	Director of the Department of Energy and Environment, the canton of Basel-City
8	Policy consultant	Consultant on energy efficiency regulation in Switzerland
9	Politician	Head of the cantonal energy bureau, the canton of Grisons President of ICED (2003–2010)
10	Representative of individual company	Employee of a Swiss wood heating company
11	Representative of individual company	CEO of a Swiss heat pump company
12	Representative of individual company	CEO of a Swiss building and assembly company
13	Representative of individual company	Employee of a Swiss house ventilation company
14	Representative of individual company	Employee of a Swiss insulation material company
15	Representative of individual company	Employee of a Swiss window manufacturing company
16	Representative of individual company	Employee of a Swiss house ventilation company
17	Representative of industry association	Head of the Swiss Association for Windows and Facades (SZFF)
18	Representative of industry association	Member of the Swiss Association of Engineering and Architecture (SIA)
19	Representative of industry association	Member of the Swiss Association of Engineering and Architecture (SIA)
20	Representative of industry association	Employee of the Swiss Association of Building Technology (suissetec)
21	Representative of industry association	Employee of the Swiss Association of Home Owners (HEV)
22	Representative of industry association	Employee of the Swiss Association of Heat Pumps (FWS)
23	Representative of industry association	Employee of the Swiss Association of Building Envelopes
24	Representative of private building label	Co-founder of Minergie
25	Representative of private building label	Former director of Minergie
26	Representative of private building label	Director of Minergie
27	Representative of private building label	Former technical advisor to Minergie

4. Results

4.1. The Swiss building sector: Dynamics in public and private regulatory stringency

Figure 2 summarizes the results of our data collection and shows the evolution of public building standards for different building components (Figures 2A–D), as well as the evolution of the stringency of the private building label (Figure 2E). Based on this novel dataset, three general observations can be made. First, public building standards have become more stringent and more aligned across cantons over time. The standards were adapted multiple times over the past 40 years in order to increase their stringency. Especially for windows, steep reductions in U values and thus increases in stringency can be detected (i.e., from 3.0 W/m^{2}K in 1977 to 1.0 W/m^{2}K in 2018; see Figure 2A). Although weaker, increases in stringency can also be detected for walls and floors (Figures 2B–D). Additionally, public standards have become more aligned over time. Early on, many different U values existed for each technology within Switzerland, but their number as well as their range decreased later (e.g., windows had five different prescribed U values between 2.0 and 3.3 W/m^{2}K in 1992 and three between 1.0 and 1.5 W/m^{2}K in 2011; see Figure 2A)[24]. Second, we find large differences in public building standards across target technologies in terms of the stringency of standards and changes in stringency over time. On the one hand, standards for windows were much higher at the outset than for walls and floors (e.g., U values between 3.1 and 3.3 W/m2K for windows and U values between 0.4 and 0.8 W/m2K for walls and floors in the 1980s; see Figures 2A–C). On the other hand, the standards for windows were adapted more often and decreased at a higher rate than the standards for walls and floors (e.g., 11 different U values for windows and seven different U values for outside walls to air over the complete period; see Figures 2A–B). In total, the standards for windows decreased to a greater extent (i.e., from 3.0 W/m2K in 1977 to 1.0 W/m^{2}K in 2018) compared to a smaller decrease in walls to air (i.e., from 0.6 W/m^{2}K in 1977 to 0.2 W/m^{2}K in 2018).

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[24] Note that the almost linear reduction of U values observed in Figure 2 represents above business-as-usual technological progress, which tends to slow down over time (Nagy et al. 2013), including in building technologies (Jakob and Madlener 2004).

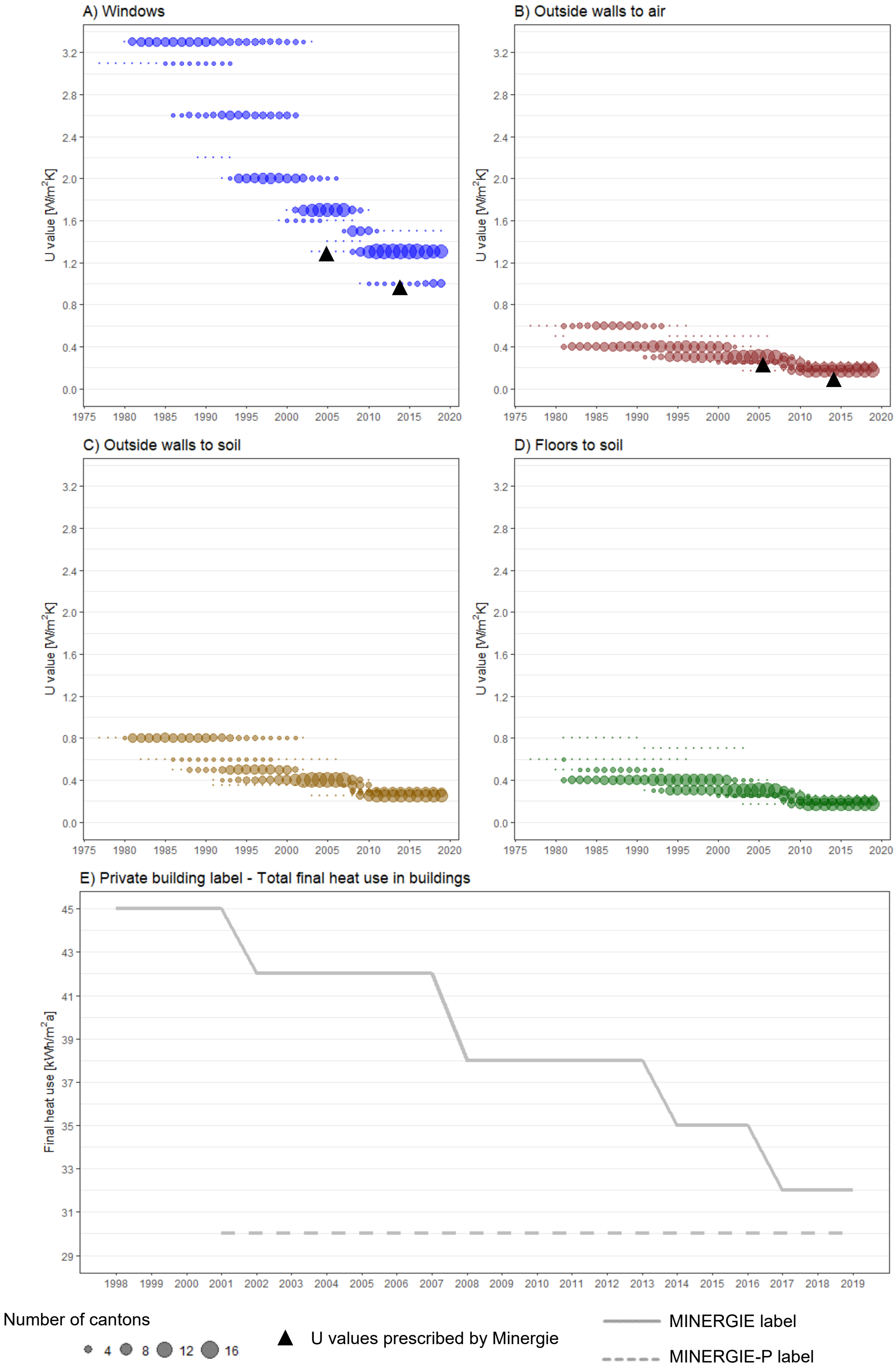

Figure 2: Public building standards for (a) windows (blue); (b) outside walls to air (red); (c) outside walls to soil (ocher); and (d) floors to soil (green) for each year. Decreasing values correspond to increasing stringency of the standard and label. The bubble size corresponds to the number of cantons with the same value (ntotal = 23). The black triangles correspond to the U values prescribed by the private building label. (e) Private building label's prescribed total final heat use in new residential buildings for standard buildings (solid line) and for buildings meeting specific requirements regarding the building shell (dashed line). The final heat use includes the weighted energy use for heating, ventilation, air conditioning, and hot water.

Third, as visualized in Figure 2E, the private Minergie label has become more stringent over time, similar to public building standards (i.e., from 42 kWh/m^{2}a in 1998 to 35 kWh/m^{2}a in 2019).[25] Depicted as a triangle in Figures 2A and 2B, the Minergie U values are lower in comparison to public building standards, and they predate the subsequent increase in the stringency of standards. In 2001, a more stringent additional label, Minergie-P, was created.

4.2. Changes in public and private regulation and the role of technological change

The regulatory goal of both public and private regulatory instruments is to phase out less-efficient and phase in better-performing building components, thereby shifting the overall distribution of building components towards higher efficiency (see red arrow in Figure 3). To do so, the stringency of these instruments has to increase over time. In the following section, we discuss whether and how technological change has acted as a mechanism in explaining the increase in stringency of these instruments as well as their interaction. Figure 3 summarizes the three arguments below.

First, technological change was important in shaping public building standards. These standards set mandatory efficiency levels for components of new buildings thus effectively banning the most inefficient building components (see Figure 3). In setting these standards, regulators could only adopt stringency levels for which corresponding building parts were technically feasible and economically available (Interviewees 1, 6). Interviewee 2 stated in this regard that "*only when a technological development is acknowledged by the architects and engineers, you can start drafting a new standard. Politicians will ask these experts' opinion and, only when these experts know the new technology, you will obtain a majority.*" In the early phase

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[25] Due to data availability, we do not report specific U values for the private building label but show the more systemic measure of total final heat use per square meter per year (kWh/m2a). U values mandated by the private building label for specific building components are only available for some years and technologies.

of building regulation, efficiency gains were achieved by incrementally improving existing technologies. For instance, in the 1970s and early 1980s, two-glazed windows with U values of around 2.5 W/m^{2}K were mainly used for new buildings. At the same time, cantons with standards mandated values of between 3.1 and 3.3 W/m^{2}K. In the following years, improvements in glass and filling gas led to reductions in the thermal conductivity of windows (Interviewee 2), and standards were consequentially lowered to values of around 2.0 W/m^{2}K. Similar trends can be reported for wall insulation: Early efficiency gains for walls were achieved by increasing the thickness of the insulation material (Interviewees 2, 5). However, neither the efficiency of two-glazed windows nor wall thickness could be indefinitely increased for technical reasons and due to opposition by artisans and architects (Interviewees 1, 2, 15). In the 1990s, however, innovative firms pushed through technological change. On the one hand, they introduced three-glazed windows that substantially reduced the U values (Interviewee 1). On the other hand, manufacturers of insulation material adapted their materials and could thus provide some efficiency gains per volume of insulation material (Interviewees 2, 14). Once these technologies were widely diffused on the market, regulators could increase the regulatory stringency of public building standards to account for this development. As stated by Interviewee 2, "*the standards represent the state of the technology. [...] In some years, they will have developed further, and we will need to revise the standards to account for the [new] state of the technology.*"

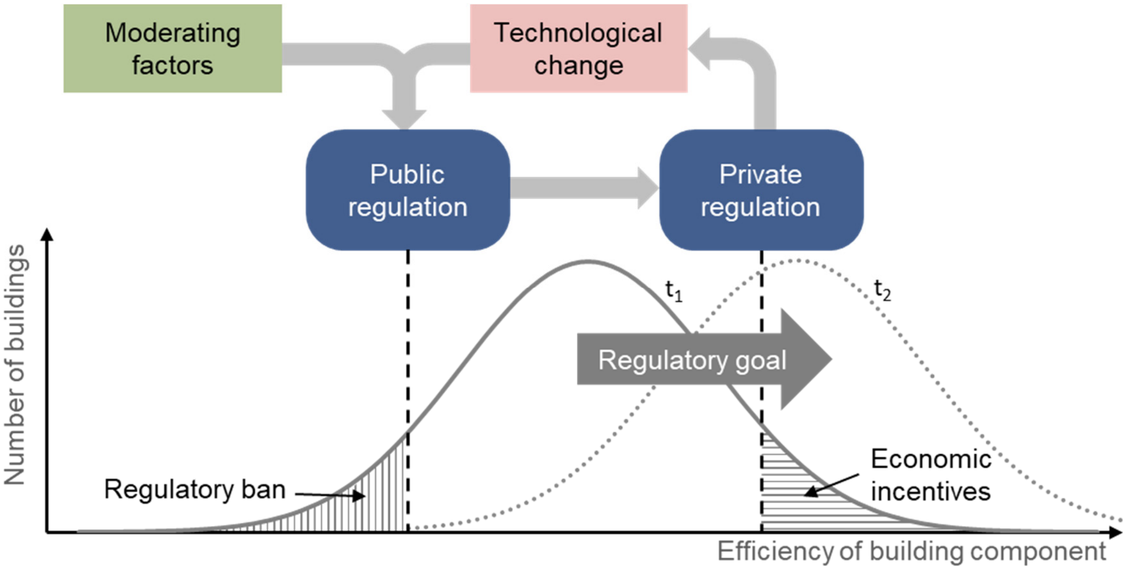

Figure 3: Interaction between public and private regulation through the mechanism of technological change. The regulatory goal to increase overall efficiency of building components over time (time 1 to time 2) is driven, on the one hand, by the private building label, which increases the economic incentives and feasibility of more efficient building components, and on the other hand, by public building standards, which ban inefficient building components (adapted from Interviewee 2).

Second, technological change itself was shaped and triggered by the private building label. As argued above, the diffusion of new technologies led to increasingly stringent public building standards. However, technological change did not occur in a vacuum. Rather, the most important driver of innovation in and diffusion of energy efficient technologies in the Swiss building sector was the private building label. The label was introduced in 1998 with the specific intention to foster innovation in the construction industry and diffuse new energy-efficient technologies in the market (Aeberhard 2018) by creating economic incentives for and improving the economic feasibility of more efficient building components (see Figure 3). From the beginning, the private building label received strong support from administrative cantonal actors, who perceived the label as a complementary technology-pull instrument to the demand-push public building standards (Interviewee 6). The label's effects on technological change were manifold. It created a high-performing benchmark and premium for the industry, thus ensuring a safe market for the industry's high-tech products (Interviewees 12, 13, 8). Interviewee 24 stated, "*Minergie created a market where there was no market before.*" By continuously increasing the label's stringency, the producers of energy efficient technologies were additionally incentivized to keep improving their technologies. By educating and certifying artisans and architects, the private building label not only ensured the competent installation and use of the new technologies but also offered these actors more network and reputation benefits compared to artisans and architects relying on conventional technologies (Interviewees 1, 24). Hence, it was an additional source of value creation and quality control for several actors along the supply chain in the building sector. Interviewee 2 stated, "*Minergie managed to create added value. A Minergie-certified house can be sold at a higher price per square meter than a house without the label.*" The private building label also decreased the information asymmetry between artisans and homeowners (Interviewee 27). Overall, the private building label incentivized firms to innovate and homeowners to invest in new high-end building components, such as three-glazed windows and thicker wall insulation. Only thanks to this niche market could new and efficient technologies diffuse widely and drive down their learning curves.

Third, and bringing both findings together, technological change can explain the interaction between public and private regulatory instruments (see Figure 3). The private building label influenced public building standards by showing what was technically feasible and improving the economic viability of high-end products (Interviewees 2, 21). Technological change triggered by this niche market could, in turn, result in more stringent public building standards. Interviewee 5 stated in this regard, "*Minergie was a guiding player that paved the way for cantonal energy legislation. They brought products and technologies into large application that were back then not standard yet. […] This fueled technological change and led to a technological standard that could be enacted in our Energy Law with a time lag.*" Interestingly, public regulation, in turn, influenced the private building label. As a result of increasing public regulatory stringency, the association issuing the label needed to increase its stringency in order to maintain its benchmark function (Interviewees 4, 25). Interviewee 4 stated in this regard, "*around 2008, [the canton of] Basel-Stadt tightened the mandatory standard for the building envelope by 10% which meant that the requirements by the private label had to become more stringent as well because it cannot be less strict than cantonal legislation. Thus, the two policies amplified each other*." Further, Interviewee 4 summarized this interaction between public and private regulation as follows, "*the individual policies determine each other. With its goal to try out new things, the private label sets the benchmark for the standards. The public standard always comes last. They prescribe the use of state-of-the-art technology and thus enforce them on the last 20–30% of constructors*." Official documents issued by cantonal and intercantonal institutions (AWEL 2018; BEG 2009; EnDK 2008, 2015) confirm these findings from interviews: For instance, the private label Minergie is consistently mentioned as benchmark-setter for public regulation.

4.3. Sub-national variations and differences across technologies: The moderating factors

In addition to the previously presented symbiotic relationship between private regulation, technological change and public regulation, we found moderating factors that influenced this interaction (see Figure 3). These factors are related to the complexity and contingency inherent in the regulatory field of energy efficiency in Switzerland. The public building standards differ across subnational entities in terms of their stringency, the year of implementation, and the number of adaptations (see Figures 2A–D). These differences can be explained by political and institutional factors as well as the influence of additional regulatory instruments (Interviewees 4, 25). First, in the early phase of standard implementation, frontrunner cantons often exhibited enhanced institutional capacities within their cantonal administrations (Interviewees 2, 4, 5, 9), which were capable of elaborating on and implementing such legislation. Whether a canton was a frontrunner in standard implementation also depended on political conditions, such as the party affiliation of the responsible minister or the composition of the cantonal parliament as well as the locus of implementation (i.e., whether it was enacted within the law or in subordinate ordinances) (Interviewees 4, 9). The increasing alignment between public building standards in the latter years is a result of regulatory harmonization and diffusion efforts by intercantonal institutions, notably the Intercantonal Conference of Energy Directors (Strebel 2011). Second, the energy bureaus of several cantons as well as the Federal Office of Energy implemented regulatory instruments other than public standards and the private label. Less influential than the private building label, these additional instruments were introduced mostly at the cantonal level. They included pilot and demonstration programs (Interviewees 4, 5, 6), subsidies for novel energy-efficient technologies (Interviewees 2, 4, 5, 6), financial incentives for homeowners to retrofit specific building parts (Interviewee 6), and information and education campaigns for artisans (Interviewee 3). Overall, the differences regarding political and institutional factors as well as additional regulatory instruments can explain the divergence in stringency, implementation, and adaptations across cantons.

Besides the intercantonal differences, Figure 2 also highlights the differences in regulatory stringency, implementation, and adaptations across technologies. These differences (e.g., between windows and wall insulation) can be explained by the different starting points and learning potentials of individual technologies as well as by the industry structure underlying these technologies. First, technology differences account for variation in regulatory stringency across technologies. As Interviewee 2 stated, "*[large] modifications [of the U values for windows] were enabled by technological progress. We did not treat windows more strictly, but we had more possibilities.*" As Interviewee 5 stated, "*the technological leaps did not take place at the same frequency or to the same decisive extent for insulation material than for windows.*" With the introduction of three-glazed windows in the 1990s, the U value of windows could be considerably reduced (Interviewee 2). Similar improvements were impossible for wall and floor insulation (Interviewee 2). Hence, in the case of wall insulation, the technical limits compromised further ratcheting up of regulatory stringency (Interviewee 14). Second, another factor for these technology differences is the structure of the Swiss construction industry. For instance, the value chain of windows includes a wide range of actors with different interest: On the one hand, Swiss glass manufacturers were highly interested in more stringent U values, as the latter resulted in the introduction of three-glazed windows and thus increased glass sales (Interviewees 2, 5, 25). On the other hand, local carpenters producing window frames opposed this technological change, since they had to invest in new equipment and expertise (Interviewees 2, 4, 5, 17, 25). They effectively resisted U value adaptations for windows in smaller cantons (Interviewees 2, 4). Conversely, Swiss companies leading in insulation material production were interested in reductions of the U value (Interviewees 2, 5) and were even active within Minergie (Interviewees 4, 25). Yet, some artisans mounting the insulation material as well as architects all opposed U value reductions, since thicker walls meant changes in their procedures and less freedom in the design, respectively (Interviewees 2, 3, 4, 18). Hence, the ratcheting-up process between the public and private regulatory instruments was conditioned both by institutional and political factors and technology-specific characteristics of the targeted building components.

5. Discussion and conclusion

We investigated the long-term interaction between regulatory instruments, specifically focusing on the impact of private on public regulation. We explored whether technological change can explain this impact. Based on a case study on energy efficiency in buildings in Switzerland, we find that both public and private regulatory instruments are becoming increasingly stringent with the same directionality. Over time, the public regulatory instruments' stringency approaches the private instrument's stringency. Hence, our results indicate an *increasing convergence* between regulatory instruments (Judge-Lord et al. 2020). Further, the interaction between public and private regulation suggests a symbiotic relationship. While the public instrument ensures a broad *scope* of the governance structure, the private instrument set the *benchmark* for the direction of changes in instrument stringency. Our findings indicate that the *mechanism* behind this relationship is positive feedback from technological change: The private regulatory instrument induced technological change in the building sector by creating niche markets for new high-end technologies. These niche markets enabled innovation in and diffusion of new energy-efficient technologies, such as three-glazed windows and improved wall insulation. These technologies became cheaper due to increased market diffusion and resulted in economies of scale and learning effects for the technology manufacturers, installers, and users (Dosi 1982; Sandén and Azar 2005). This wider range of technically feasible options and economically affordable technologies, in turn, constituted positive feedback effects for subsequent regulatory change.

On a more abstract level, our analysis reveals a successful case of a *ratcheting-up process* between both public and private regulation (Cashore et al. 2007; Judge-Lord et al. 2020; Meckling et al. 2017; Overdevest 2010; Pahle et al. 2018). As a consequence of technological change induced by private regulation, regulators were able to subsequently increase the stringency of public regulation. Hence, conversely to skepticism towards the benefits of private regulation in governance literature (Mayer and Gereffi 2010), we show that private regulatory instruments can foster public regulation. However, this successful example of ratcheting-up hinges on private regulation actually being able to trigger technological change. In the absence of such an effect, we would not expect the necessary positive feedback to enable a ratcheting-up between public and private regulation. These new empirical and theoretical insights were possible by focusing on regulation-induced technological change. The case of energy efficiency technologies in the building sector is therefore distinct from studying “disruptive” technologies (Hasselbalch 2018; Kenney et al. 2019; Yeung 2018) for which regulation plays a more reactive than active role.

Importantly, as our results also highlight, instrument interaction through technological change does not happen in a vacuum, but it is moderated by political and institutional factors as well as differences between technologies. First, whether a symbiotic interaction between public and private instruments exists depends on the *governance capacity* of public and private regulatory instruments, i.e. “the formal and factual capability of public or private actors to define the content of public goods and to shape the social, economic, and political processes by which these goods are provided” (Knill and Lehmkuhl 2002, 43). In our case, both public and private regulatory instruments have high governance capacity, which makes it an example of *regulated self-regulation* (Knill and Lehmkuhl 2002). As such, it combines the rigidity of public regulation with the flexibility of private regulation, resulting in a better adaptive capacity for complex problems. According to Duit and Galaz (2008), the adaptive capacity of governance is understood as a combination of exploitation (i.e., the capacity to benefit from existing forms of collective action) and exploration (i.e., the capacity of governance to nurture learning and experimentation). Second, the specific type of governance capacities and interactions depend on three contextual factors (Knill and Lehmkuhl 2002): the *congruence* between the problem scope (local, national, or global) and the governance structure (local, national, or international regulatory bodies); the *type of problem* at hand (degree of complexity and coordination/conflict patterns); and finally, the *institutional context* (rules and norms influencing actor behavior and decision processes). Although technological change is generally a global phenomenon, technological change in the building sector remains highly localized in terms of supply chains, actor constellations, and specific regional and national use of environments and regulation.

Hence, national and regional regulatory instruments are arguably congruent to technological change in such a localized industry. Concerning the type of problem at hand, technological change represents a complex governance challenge, especially in the construction industry, which is characterized by relatively complex supply chains, a high diversity and multitude of actors involved, and technologies adapted to the specific use environment. As commonly argued, in regulatory fields with such high complexity, the integration of private regulation is likely to complement public regulation by adding flexibility to the rigidity of public regulation (Duit and Galaz 2008). Finally, the institutional setting in Switzerland is characterized by consensus-based regulation, dense regulatory networks (Sager et al. 2014), and the inclusion of interest groups in the regulatory process (Maggetti 2014), which is conducive to regulated self-regulation (Maggetti et al. 2011). In the case of energy efficiency governance in Switzerland, both the governance capacity and the three contextual factors discussed above enabled the symbiotic interaction between public and private regulation through technological change. We encourage future research that replicates our approach of studying the influence of private on public regulatory instruments in other regulatory fields and across jurisdictions. Such research could also provide more evidence on the necessary pre-conditions for a symbiotic instrument interaction through technological change.

Finally, our paper contains an important message for regulators in fields where technology is relevant: Depending on governance capacity and contextual factors, private regulation can serve as a lever to increase regulatory stringency over time through the mechanism of technological change. As such, the intentional introduction of private regulatory instruments could increase the political feasibility of public regulation in fields that are characterized by inertia and lock-in (Cashore et al. 2007; Judge-Lord et al. 2020; Levin et al. 2012; Meckling et al. 2015, 2017). Successfully leveraging this rationale, however, requires *technology-smart* governance (Beuse et al. 2018): Depending on the characteristics and maturity of a technology, as well as the capabilities of the local industry, different combinations of public and private regulatory instruments might be more effective and politically feasible than others (Breetz et al. 2018, Schmidt and Huenteler 2016). Our findings suggest that such technology smartness necessitates a robust governance structure combining regulatory rigidness and flexibility (Duit and Galaz 2008)[26]. We argue that such a differentiated approach to the role and the respective merits of public and private regulation is needed to better understand governance structures for solving complex societal problems such as climate change.

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[26] Findings of this paper should also be of interest for the policy design literature, which is concerned with how regulatory instruments can be designed to ensure their political feasibility and durability (Capano and Woo 2017; Haelg et al. 2019; Howlett 2019; Jordan and Matt 2014).

6. References

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Paper 3: A comparative and dynamic analysis of political party positions on energy technologies

Authors: Nicolas Schmid*[1]

* Corresponding author: nicolas.schmid@gess.ethz.ch

[1] ETH Zurich, Department of Humanities, Social and Political Sciences, Energy Politics Group, Haldeneggsteig 4, CH-8092 Zurich, Switzerland

Under review at *Environmental Innovation and Societal Transitions*

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Abstract:

Despite growing scholarship on the politics of sociotechnical transitions, the role of particularly relevant political actors – political parties – has been widely overlooked. To address this gap, using an exploratory research approach, this article examines how party positions on energy technologies change, and whether and how technological change drives such position change. Based on a novel dataset, we map party positions on energy technologies in Germany, France, and the United Kingdom from 1980 to 2017. We qualitatively explore whether and how technological change can explain changes in party positions. We find that changes in policy positions and their salience varied across energy technologies, party families, countries, and time. We discover that – moderated by party and party system characteristics – technological change is one factor affecting position change. We discuss the relevance of our findings for the politics of sociotechnical transitions and provide avenues for future research.

1. Introduction

Accelerating and deepening sociotechnical transitions through public policy is a main lever for addressing sustainability challenges such as climate change (Geels et al. 2017; Markard, Geels, and Raven 2020; Markard, Raven, and Truffer 2012). The crucial roles of policies and policy mixes for such transitions are widely acknowledged and increasingly well-documented (van den Bergh 2013; Kivimaa and Kern 2016; Rogge and Reichardt 2016; Schmidt and Sewerin 2019; Weber and Rohracher 2012). The politics underlying these policies remain, however, less well understood, and there have been multiple calls for addressing this gap (Hess 2014; Meadowcroft 2011; Smith and Stirling 2010).

Responding to these calls, transitions scholars have integrated politics into major transitions frameworks, such as the Multi-Level-Perspective (Geels 2014) and transition management approaches (Kern and Howlett 2009). Others have borrowed concepts from disciplines such as political science to conceptualize the interactions of policies, technological change, and politics (Edmondson, Kern, and Rogge 2019; Hoppmann, Huenteler, and Girod 2014; Kern and Rogge 2018; Markard, Suter, and Ingold 2016; Rosenbloom, Meadowcroft, and Cashore 2019; Schmid, Sewerin, and Schmidt 2019). A subset of this burgeoning literature on the politics of sociotechnical transitions has recently turned to the roles of actors and agency in response to the dominance of structural explanations in the transitions literature (Avelino et al. 2016; Duygan, Stauffacher, and Meylan 2019; Kivimaa et al. 2019; Sovacool et al. 2020; Wittmayer et al. 2017). Collectively, these contributions have improved our understanding of politics, actors, and agency in sociotechnical transitions.

Yet, so far these studies have not considered key political actors for sociotechnical transitions, namely political parties. There is a dearth of systematic research on the role of political parties as particularly central actor types in sociotechnical transitions. More specifically, there is a lack of research on how political parties position themselves toward sociotechnical transitions, how these positions change over time, and how transitions, in turn, affect party positions. Multiple recent review articles and research agendas on the politics and agency of transitions did either did not mention political parties or they were only treated with tangential reference (Fischer and Newig 2016; Köhler et al. 2019; Lockwood et al. 2017; Roberts et al. 2018; B. K. Sovacool and Brisbois 2019). The few studies examining party politics related to sociotechnical transitions have either examined single jurisdictions (Schmidt, Schmid, and Sewerin 2019), focused on specific party types such as center-right parties (Hess and Renner 2019), or analyzed the party politics of generic climate policy without accounting for sector and technology-specific party positions (Carter et al. 2018; Ćetković and Hagemann 2020). This lack of sector and technology-specific analyses of political party positions is problematic for two reasons.

First, as we know from the innovation and transitions literature, accounting for such sector and technology-sensitive differences is necessary for meaningful analyses and effective policy recommendations (Azar and Sandén 2011; Huenteler et al. 2016; Zeppini and van Den Bergh 2011). Second, we know from political science literature relating to party politics that, in democracies, they are not only key designers of public policy but they also mediate and navigate political conflict (Abou-Chadi, Green-Pedersen, and Mortensen 2020; Adams and Somer-Topcu 2009; Benoit and Laver 2006; Green-Pedersen 2019; Ware 1996). Crucially, party positions have been found to be reflected in subsequent policy change (Borghetto and Belchior 2020; Brouard et al. 2018). A systematic and dynamic assessment of political party positions on technologies is hence necessary for improving our understanding of the politics of sociotechnical transitions. Given the urgent need to accelerate policy change to address time-sensitive sustainability challenges (Kivimaa et al. 2020; Roberts et al. 2018), the rate and directionality of party position change is particularly relevant. With an empirical focus on the energy sector – a key sector for addressing sustainability challenges such as climate change – we chose to address this gap with the following research question: How do political parties change their positions on energy technologies, and how does technological change affect these positions?

To answer this question, we took an exploratory approach and examined party position changes related to energy technologies in a longitudinal and comparative case study of Germany, France, and the United Kingdom (UK) from 1980 to 2017. This diverse case selection approach with both within and cross-case variation is suitable for an inductive and exploratory research design (Seawright and Gerring 2008).

Methodologically, the paper proceeded in two steps. First, we mapped party position changes related to energy technologies based on a novel dataset that included all major parties in the three countries over a period of four decades. This dataset complements the established Party Manifesto Project (Krause et al. 2018) with technology-specific codes on both the niche and regime levels, including renewable energy technologies (RET), nuclear technology (NT), and fossil fuel-based technologies (FFT). Besides offering pro- and contra-positions on energy technologies, this dataset also allowed us to capture the salience of positions in party manifestos. Our analysis revealed differences relevant to individual energy technologies, party families, time, and countries. Compared to FFT and NT, party positions on RET were found to be relatively homogenous and increasingly supportive over time. With exceptions, Left to Center parties allocated more salience to energy technologies and were more opposed to FFT and NT than their Center-Right to Right counterparts. Generally, niche parties changed their positions on technologies faster than incumbent parties. Finally, while energy technologies were found to be a rather salient issue in Germany, they were seen as less salient in French and British party agendas. In addition, technology-specific patterns varied across countries. For example, NT was increasingly opposed in Germany while it remained relatively unchallenged in France, and was the subject of a renaissance in the UK.

Second, we qualitatively analyzed the collected data to examine the role of technological change in party position changes. We found that technological change – moderated by party characteristics and the type of party system – is one factor that drives party positions as well as the salience of these positions. We inductively identified three related mechanisms through which technological change affected the issue characteristics of energy technologies: perceived co-benefits or costs of a given technology; changes in the menu of policy options; and path dependence associated with existing technology and infrastructure. Here, we define issue characteristics as features of energy technologies, such as their relative costs, deployment, and localization, in terms of value chain and associated jobs and economic activity. We found that political parties refer to changes in these issue characteristics as an argumentative underpinning for their changes in positions on technologies. Based on the results of our exploratory analysis, we discuss the relevance of our findings for the politics of sociotechnical transitions, and provide avenues for future research.

2. Political parties as key political actors in sociotechnical transitions

2.1. Politics and agency in sociotechnical transitions

Sociotechnical transitions are inherently political processes because they come with both winners and losers of technological change (Meadowcroft 2011; Mokyr 1998). For instance, while the energy transition from fossil fuel-based to renewable energy technologies created winners in the form of new entrants in niche markets, it also threatened incumbent actors on the regime level and hence provoked political resistance (Geels 2014; B. Sovacool et al. 2020).

Criticism about the lacking attention to politics (Meadowcroft 2011) has led to increasingly numerous studies on politics and power in transitions (Ahlborg 2017; Avelino et al. 2016;

Avelino and Rotmans 2011; Brisbois 2019; Geels 2014; Kern 2011; Lockwood 2016; Raven et al. 2016; Rosenbloom, Berton, and Meadowcroft 2016; Smith and Stirling 2010; B. K. Sovacool and Brisbois 2019). To describe how politics shape sociotechnical transitions, scholars often draw on political science and public policy literature (Kern and Rogge 2018), such as discursive analysis approaches (Rosenbloom, Berton, and Meadowcroft 2016), policy network theory (Normann 2017), or the Advocacy Coalition Framework (Markard, Suter, and Ingold 2016). Studies building on policy feedback theory have highlighted that technological change underlying sociotechnical transitions also feeds back into subsequent politics (Edmondson, Kern, and Rogge 2019; Rosenbloom, Meadowcroft, and Cashore 2019; Schmid, Sewerin, and Schmidt 2019; Schmidt and Sewerin 2017). A subset of this literature on the politics of transitions is focused on the role of actors and agency in sustainability transitions (Farla et al. 2012; Fuenfschilling and Truffer 2016; Scherrer, Plötz, and Van Laerhoven 2020; Wittmayer et al. 2017). Various roles and types of actors have been analyzed, such as business actors (Jonas Meckling 2019), those belonging to social movements (Hess 2018), activists and communities (Seyfang and Smith 2007), intermediary actors (Kivimaa et al. 2019), and political activities of niche and regime actors (Geels 2014; Smink et al. 2015; Turnheim and Sovacool 2019).

While results from these studies have provided valuable insights into the agency and politics of transitions, there is a paucity of research relating to key political actors, namely political parties. For instance, in a systematic review of the roles of actors and agency in sustainability transitions by Fischer and Newig (2016), political parties are not mentioned. In a recent review of elite power in low-carbon transitions, Sovacool and Brisbois (2019) provided an extensive discussion of how transitions can exacerbate, reconfigure, or be shaped by elite power, yet they did so without explicitly discussing political parties as key actors with political power. Political parties are only tangentially referred to in the research agenda of Lockwood et al. (2017). The recent research agenda of the Sustainability Transitions Research Network by Köhler et al. (2019) does not explicitly mention political parties (neither do Roberts et al. 2018). In a special issue on actors in transitions by Farla et al. (2012), no study explicitly examines political parties. The few studies in which examining political party positions related to sociotechnical transitions either examine single jurisdictions (Schmidt, Schmid, and Sewerin 2019), focus on specific party types such as Conservative parties (Hess and Renner 2019) or analyze the party politics of generic climate policy without accounting for sector and technology-specific party positions (Carter et al. 2018; Ćetković and Hagemann 2020). Other scholars have provided a dynamic account of electoral politics of energy transitions; however, these were based on stylized models without empirical data on real-world party positions (Aklin and Urpelainen 2013; Dumas, Rising, and Urpelainen 2016).

The lack of sector and technology-specific analyses of political party positions is problematic for two reasons. First, in the innovation and transitions literature, scholars highlight the importance of such sector-specific and technology-sensitive analyses (Azar and Sandén 2011; Huenteler et al. 2016; Zeppini and van Den Bergh 2011). Technology characteristics such as maturity, design, and manufacturing complexity or modularity are fundamentally shaping politics because they affect the incentives for political actors to allocate resources and support a given technology (Breetz, Mildenberger, and Stokes 2018; Schmid et al. 2020; Schmidt and Huenteler 2016; Schmidt and Sewerin 2017; Wilson et al. 2020). Second, political parties have a crucial role with respect to the steering of technological change and sociotechnical transitions (Langhelle, Meadowcroft, and Rosenbloom 2019). In democracies, political parties are often the origin of, or at least substantially influence, policy mixes targeted at innovation and technological change (Simmons 2016). There is plenty of evidence for the key role of policy mixes in transitions (Kivimaa and Kern 2016; Rogge and Reichardt 2016), especially in the energy sector (Schmidt and Sewerin 2019). Hence, the (changes in) positions of political parties toward sociotechnical transitions generally, and individual technologies, such as niche and regime energy technologies specifically, are key elements of the transition processes.

2.2. Party politics

The main goal of the political science literature on party politics is to describe and explain changes in party positions as well as their salience (Adams and Somer-Topcu 2009; Walgrave and Nuytemans 2009). While party politics literature has largely neglected the topic of sociotechnical transitions and technological change, conceptual insights from this research stream can inform and complement the transitions literature discussed above. Several explanations for party position change have accumulated over the last few decades (for a review see Fagerholm 2016). For the purpose of this paper, we focused on three explanations deemed particularly useful for shedding light on party politics in the context of sociotechnical transitions. First, the evaluation of issue characteristics and related incentives for political parties has been shown to be a primary driver of positions and their relative salience in party agendas (Abou-Chadi, Green-Pedersen, and Mortensen 2020; Green-Pedersen 2019). While there are various competing definitions and typologies of issue characteristics (Green-Pedersen 2019), here, we defined issue characteristics as features of energy technologies, such as their relative costs, maturity, deployment, and localization in terms of value chain and associated jobs and economic activity. From a purely rational choice perspective, one could expect political parties to support these technologies with the “best” issue characteristics, based on a set of objective and commonly shared criteria. However, as Pierson (1993, 611) suggested, “…all actors have to cope with overwhelming complexity and uncertainty, and […] they use a wide range of cognitive shortcuts in order to make sense of the social world.” Complexity and uncertainty are high in the context of technological change (Tushman and Rosenkopf 1992), especially in the energy sector (Grubler, Wilson, and Nemet 2016); conflicts over policy goals and the means to achieve them loom large (Meadowcroft 2009; Schmidt, Schmid, and Sewerin 2019). Hence, party positions on technologies are the result of "puzzling and powering" (Lindblom 1959) rather than the product of purely rational decision-making (Winner 1980). In this view, party positions on different technologies are unlikely to be homogenous but moderated by a set of party and party system characteristics.

Second, party characteristics are classic explanatory factors for position change and – as discussed earlier – may moderate how parties react to changing issue characteristics. For instance, while governing parties are constrained by coalition agreements and their responsibility to implement election promises, opposition parties have more degrees of freedom in setting positions and allocating salience to them (Wagner 2012). Party politics scholars also differentiate between incumbent and niche parties: Compared to incumbent parties, niche parties are considered to be more flexible in their programmatic choices and they have incentives for focusing on new policy issues (Adams and Merrill 2006). Finally, left-right ideological positions of political parties are additional long-standing factors moderating position change (Gabel and Huber 2000). For instance, recent studies show that in some countries, Center-Right to Right parties are less progressive on climate policy than parties on the left end of the spectrum (Båtstrand 2015; Carter et al. 2018; Ćetković and Hagemann 2020; Geddes et al. 2020; Hess and Renner 2019).

Third, and related to the point above, traditional party politics literature has shown that the number, strength, and roles of political parties differ across party systems (Sartori 1976). The different designs of the electoral process, such as proportional or majoritarian rule, shape the openness of party systems for niche parties (Duverger 1951). These party system characteristics, in turn, can affect how parties relate to each other in terms of position and salience change on a given policy issue. Political parties may choose accommodative, adversarial, or dismissive strategies to react to other parties' changes in position (Meguid 2005). Importantly, strategies may systematically vary depending on the level of influence and ideological distance of niche parties (Abou-Chadi 2016). Overall, this implies that party positions often evolve in relation to one another, which highlights the importance of the "party system agenda" (Green-Pedersen 2019). These insights from the party politics literature complement those of the transitions literature and provide the theoretical background for analyzing party positions on sociotechnical transitions.

3. Case selection

In an exploratory approach, we examine party position change on energy technologies in Germany, France, and the United Kingdom (UK) from 1980 to 2017. We selected these cases for three reasons. First, the energy sector is a suitable policy area for examining party positions related to technology. The energy sector is a large and complex sociotechnical system characterized by path dependence, inertia, and interdependence with public policy (Geels et al. 2017). The so-called "carbon lock-in" makes it difficult for niche technologies such as renewable energy technologies to diffuse in the market without the support of public policy (Seto et al. 2016). At the same time, the energy sector is one of the most regulated sectors of the economy due to its relevance as well as several externalities and system failures (Gillingham and Sweeney 2012). Hence, over the last four decades, most sociotechnical changes in the energy sector were largely policy-induced (Kern and Howlett 2009; Nemet 2009; Rogge and Reichardt 2016). Table A1 in the appendix provides an overview on key energy policies in these three countries (Cointe 2015; Kern, Kuzemko, and Mitchell 2014; Lauber and Jacobsson 2016; Lockwood, Mitchell, and Hoggett 2019; Renn and Marshall 2016; Schmid, Sewerin, and Schmidt 2019).

Second, we selected these countries because they are similar in terms of broad socio-economic variables but demonstrate relevant variation. Germany, France, and the UK are all advanced liberal democracies with comparable levels of economic development and (in the study period) common membership in the European Union. At the same time, though, the countries vary on two dimensions pertinent to this study: the type of party system and the structure of the energy system and its dynamics. The countries also have different party systems (Ware 1996): Germany is a classic case for proportional representation with a multi-party system that includes influential niche parties, such as the Greens. France is considered a multi-party system; however, it has relatively weak niche parties due to the majoritarian representation system. The UK is often described as a two-and-a-half party system due to the presence of a weak federal niche party and the dominance of two major parties. Figure A.1 in the annex shows the share of parliamentary seats of individual parties in all three countries over time, as well as their participation in government. The three countries also have significantly different resource endowments, energy system structures, and dynamics over time. Figure 1 (A to C) shows the share of cumulative installed capacity of electricity-generating technologies in Germany, France, and the UK.

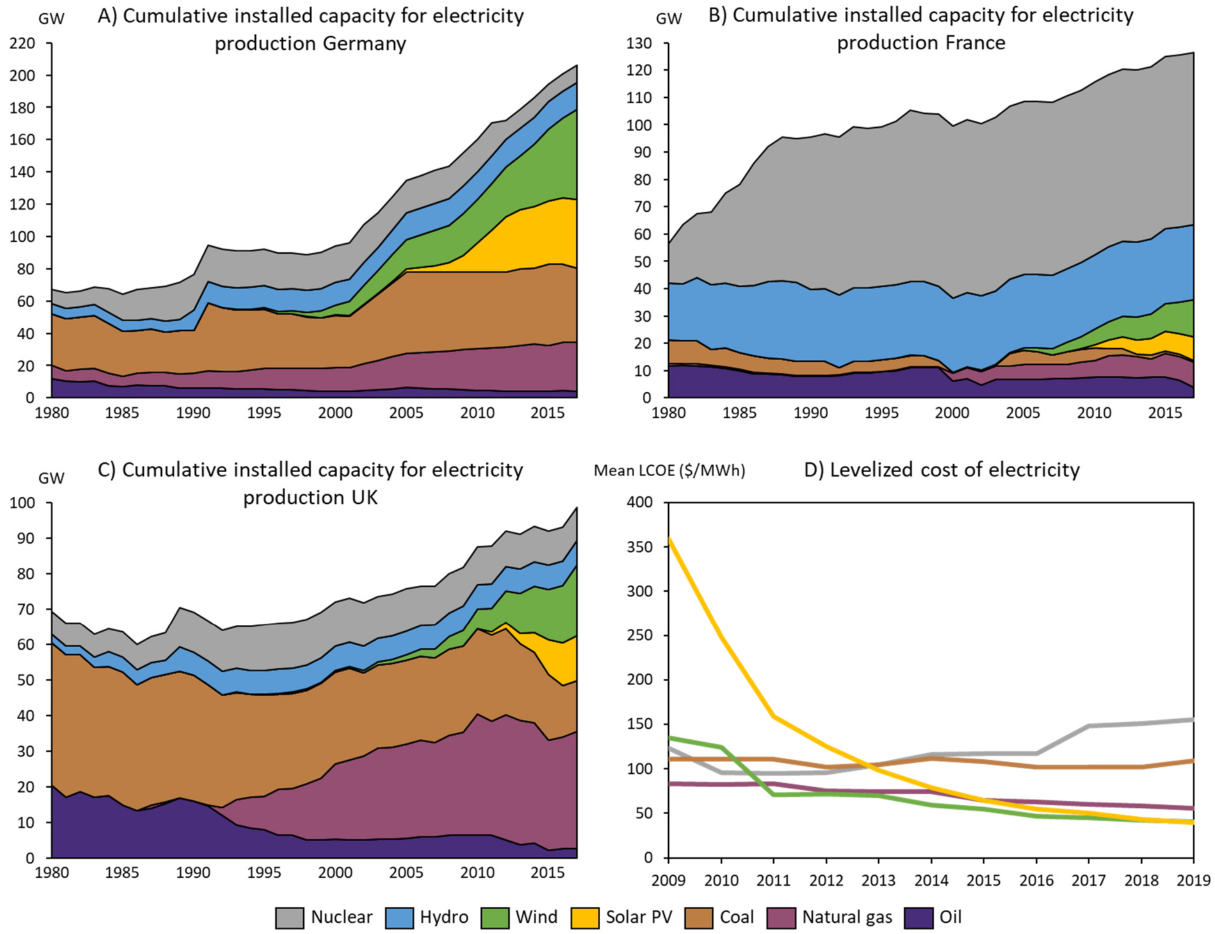

Figure 1: Technological change in the energy sector. A)-C): Cumulative installed net capacity of electricity-producing technologies and energy carriers (in % of total installed capacity). Source: International Energy Agency (IEA 2019). **D) Proxy for cost development of different energy technologies: Levelized cost of electricity (LCOE).** Unsubsidized LCOE analysis reflecting the average of the high and low LCOE for each respective technology in each year in the United States 2009 - 2019. Including sensitivities for subsidies, fuel prices and costs of capital. Other costs, such as grid-related or regulation-related costs are not included. Source: Lazard (2019).

Germany's electricity mix was historically dominated by coal and nuclear power, but with the strongly increasing capacity of RET and a decreasing capacity in NT. France's profile is distinct in that NT represents a large share of installed capacity; fossil fuel-based electricity generation only plays a minor role, which is mostly due to the low resource endowment in coal and other fossil fuels. At the same time, the transition to (non-hydro) RET has been slow in France. In the UK, similar to Germany, electricity generation has been dominated by coal and nuclear power, with a "dash for gas" starting in the 1990s and a growing deployment of RET in the 2010s, combined with a decrease in the installed capacity of coal.

Third, we chose to examine the years 1980 through 2017 because this period captures significant changes in the energy sector. Besides changes in the installed capacity discussed above, Figure 1(D) depicts changes in the levelized cost of electricity (LCOE). Costs developed differently across technologies: RET such as solar photovoltaic have displayed strong cost decreases. At the same time, FFT and NT have experienced stagnating or even increasing costs. These differences in technological change – in installed capacity and cost development illustrated here, but also in terms of job provision, etc. – alter the issue characteristics linked to a given technology. Overall, such a diverse case selection with within-case and cross-case variation on theoretically relevant dimensions is suitable for the exploratory research design used in this paper (Seawright and Gerring 2008).

4. Method and data

Methodologically, the paper proceeds in two steps. First, we map party position and salience change on energy technologies based on a novel dataset including all major parties in Germany, France, and the UK from 1980 to 2017. Major parties are defined as those that either participated in government or that have won at least 5% of the parliamentary seats in at least one election of the analyzed period (see Figure 1.A in the annex). The exclusion of smaller parties can be justified on two grounds: Often, they do not exist over a long period, and they are insignificant for political issue competition and the policymaking process.

We collected the data in line with the methodology of the established Party Manifesto Project (Krause et al. 2018). Party manifestos are an appropriate data source because they are published regularly, endorsed officially, and representative of the key signals to voters before elections. Manifestos may reveal party positions even more clearly than policy outputs, which are often the result of inter-party compromises (McDonald, Mendes, and Budge 2004). We complemented the Party Manifesto Project dataset with technology-specific codes on RET, NT, and FFT). We aggregated different FFT (lignite, hard coal, natural gas, oil) because there were only rare cases in our dataset in which political parties had contrasting positions on different FFT, and often parties alluded to fossil fuels in the aggregate. The same rationale held for RET (onshore and offshore wind, solar PV, biomass, geothermal). We coded quasi-sentences of manifestos according to their substantive pro- or contra-positions on energy technologies. Controlling for the length of party manifestos (number of quasi-sentences) allowed us to measure the salience allotted to these positions, which is an established method in party politics literature (Adams and Somer-Topcu 2009).

Figure 2.A in the appendix depicts the coding scheme and decision tree used for the coding. Based on these two measures (party positions and their salience), we then constructed a 2 x 2 matrix dividing party positions into the categories of pro- and contra-, as well as high and low salience. For the distinction between high and low salience, we used a threshold value on the party level (50th percentile of overall salience allocated to energy technologies by a party).

Next, we qualitatively analyzed the data to examine the role of technological change in party position change. The aim of this qualitative analysis was to affirm the empirical relevance of technological change as a sufficient factor of party position change, not to claim that it represents a necessary factor for it. Given that this was an exploratory study, we did not aim to account for alternative explanations for party position change but to raise these points in the discussion section. Inductively and based on our coding scheme, we substantiated three mechanisms through which technological change affected party positions.

We labeled political parties according to the left-right spectrum based on the PartyFacts project (see Döring and Regel 2019). We categorized parties as Left, Center-Left, Center, Center-Right, and Right. For visualization purposes, we labeled Greens and the Scottish National Party (SNP) separately. Although the naming and organizational structure of French parties changed over time, it was possible to sort them into a coherent continuum (see Guinaudeau and Persico 2013). Table 1 contains details about the empirical corpus and the abbreviations for parties used in this paper (see caption). Table A.2 in the annex shows the collected frequencies per country, party, year, and technology.

∑ Number of analyzed party manifestos	136
Germany	*50*
France	*46*
United Kingdom	*40*
∑ Number of major parties (government participation or > 5% of parliamentary seats in one election in the study period)	22
Germany	*6*
Die Linke (Left), Die Grünen (Greens), SPD (Centre-Left), FDP (Centre), CDU/CSU (Centre-Right), AfD (Right)	
France	*7 (13)*
PCF/ FdG (Left), Les Verts/ EELV (Greens), PS (Centre-Left), UDF/MoDem (Centre), LREM (Centre), RPR/UMP/LR (Centre-Right), FN/RN (Right)	
United Kingdom	*4*
SNP (Regional), Labour Party (Centre-Left), Lib Dems (Centre), Tories (Centre-Right)	
∑ Number of party manifesto pages	6843
Germany	*4441*
France	*1147*
United Kingdom	*1255*

Table 1: Characteristics of the empirical corpus. Abbreviations of political parties: Germany: Social Democratic Party Germany (SPD), Free Democratic Party (FDP), Christian Democratic Union / Christian Social Union (CDU/CSU), Alternative for Germany (AfD). France: Communist Party France (PCF), Europe Ecology Les Verts (EELV), Socialist Party (PS), Union for French Democracy (UDF), Democratic Movement (MoDem), The Republic Forward (LREM), Rally for the Republic (RPR), Union for a Popular Movement (UMP), The Republicans (LR). UK: Liberal Democrats (Lib Dems), Conservative Party (Tories), Scottish National Party (SNP).

5. Results

5.1. Mapping political party positions and their salience on energy technologies

In a first step, we mapped changes in political party positions and their salience. Figure 2 (A-C) below depicts the changes in salience allocated to energy technologies in each election year (bars), split by party family (colors) from 1980 to 2017. The gray lines indicate salience levels of other policy issues from the Manifesto Project. In light of our research question, four observations can be made. First, salience levels varied across countries. While energy technologies accounted for, on average, 2.4% of party manifesto text in Germany, they accounted for only 1.1% in France and 0.7% in the UK. Second, salience levels changed over time. Most notably, German parties allocated considerably more salience to energy technologies from 1987 to 1994. While salience levels increased in France beginning in 1993, energy technologies were completely absent from party agendas in the election year of 1986. In the UK, salience decreased continually from 1983 to 2001 and then increased again through 2017. Third, salience levels differed between party families. In Germany, except for the years 1980 and 1987, parties from the Center-Left to Left dominated the party system agenda on energy technologies. This was also true in France where the Green party accounted for the most salience relating to energy technologies starting in 1993. In the UK, center and regional parties emphasized energy technologies more than others. Fourth, the salience of energy was considerably lower than that of generic policy issues such as environmental protection and the welfare state, which are indicated with lines on the secondary axis with different scales. Salience on environmental protection was approximately 2 to 4 times higher depending on the country and year, with an even higher discrepancy between energy and the welfare state. In Germany, in contrast to France and the UK, salience levels of environmental protection aligned with salience allocated to energy technologies. In sum, Figure 2 depicts cross-country, temporal, and party family differences in salience levels. In the next step, we zoomed in on technology differences and differentiated between the pro- and contra-positions of political parties.

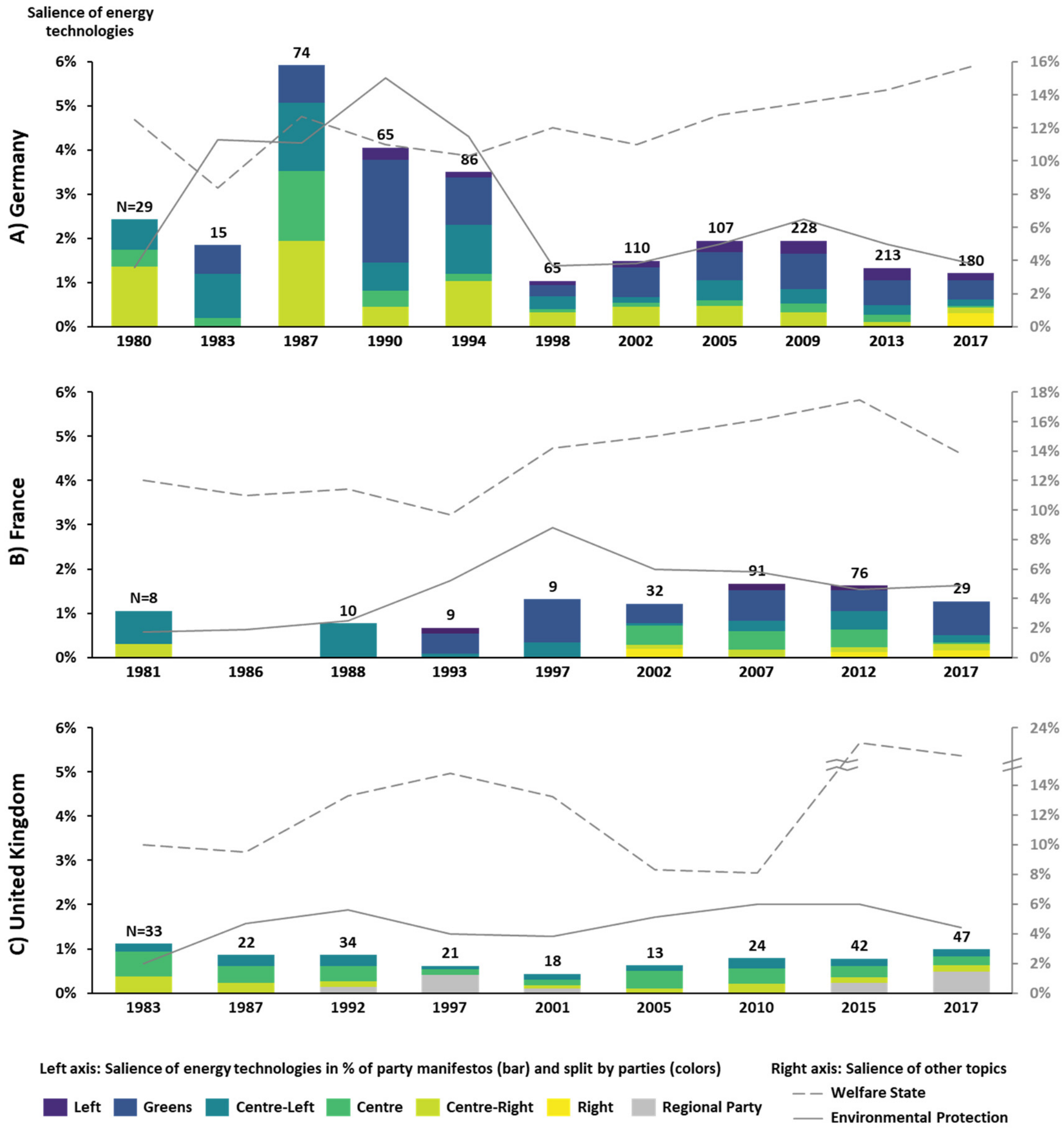

Figure 2: Salience of energy technologies in party manifestos by party family in Germany (A), France (B), and the United Kingdom (C) from 1980 to 2017 and in comparison to other topics. Salience measured as the share of quasi-sentences in a party manifesto (number (N) of coded sentences on energy technologies indicated above bars). Data on salience of Welfare State [variable ID: welfare] and Environmental Protection [variable ID: 501] taken from the Manifesto Project (Krause et al. 2018), and depicted on a secondary axis (right) at a different scale.

Figure 3 depicts party positions and salience levels across technology groups, individual parties, time, and countries (see legend, caption and section 4 for methods). Four observations can be made. First, patterns differed widely across technology groups. While FFT were increasingly contested in Germany, they were almost absent from the political agenda in France. In the UK, most political parties were supportive of FFT with variation only in the salience they attributed to the issue. Patterns were equally diverse for NT: While German parties increasingly opposed NT with decreasing salience, French political parties only punctually allocated salience to this technology with mostly supportive positions. In the UK, NT developed from a contentious issue with varying salience levels to a low-salient issue supported by all parties during the study period. In contrast to FFT and NT, the patterns for RET were relatively clear. In all three countries, most political positions evolved from low salient to highly salient support with the exception of Right parties in Germany and France. RET also punctually vanished from some political agendas in France and the UK. Second, there were also differences across party families. With some exceptions, left, Green, center-left, regional, and center parties shifted to opposition against FFT and NT with comparatively high salience levels. Center-right and right parties tended to be in favor of FFT and NT at low levels of salience. Third, positions on energy technologies changed considerably over time with differences between technologies and parties. While the switch from supportive to opposed positions on FFT was shown to be a more recent phenomenon in Germany and France, opposition to NT emerged comparatively early in all three countries and most significantly in Germany. In terms of the sequencing of positions, NT in the UK presented an interesting non-linear case: All political parties previously opposed to NT supported the technology again in the 2010s. Compared to FFT and NT, position changes on RET were more unidirectional. Concerning party differences, the patterns suggested that with some exceptions, niche parties changed their positions earlier

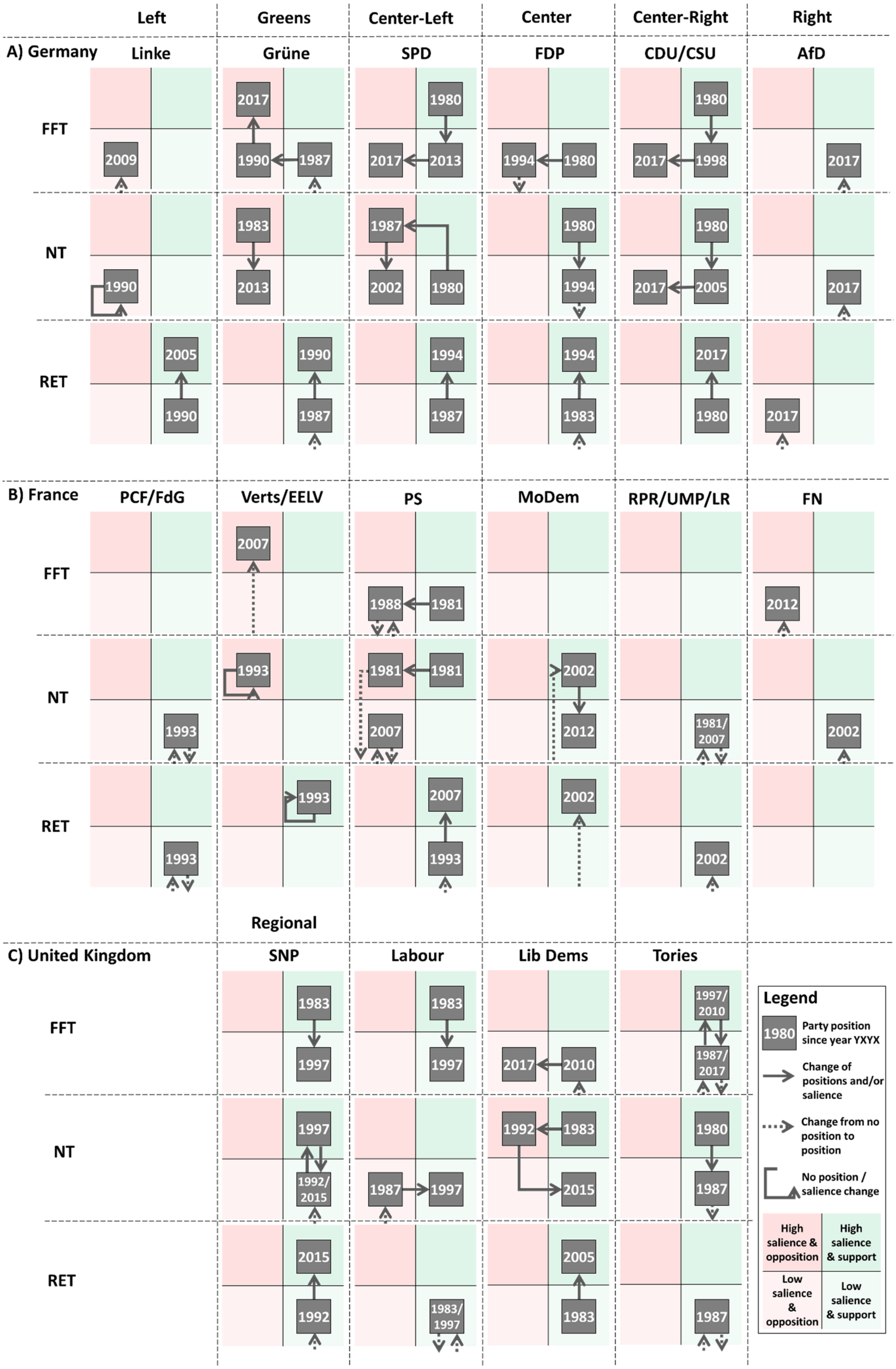

Figure 3: Positions of political parties on energy technologies and their salience in Germany, France and the United Kingdom from 1980 to 2017. Stylized visualization of collected data (see Table A.2 in the annex). Threshold value for low and high salience: 50th percentile of salience distribution per party (based on the share of quasi-sentences allocated to the individual technology group divided by the total quasi-sentences per manifesto).

than incumbent center-right and center-left parties. Among incumbent parties, center-left parties changed positions earlier. Fourth, party positions and salience levels evolved in relation to one another rather than in isolation. With exceptions and time lags, political parties in the three countries tended to converge to closer positions at comparable salience levels for all technology groups.

5.2. Exploring the role of technological change for position and salience change

In a second step, we explored whether and how technological change affected the changes in party positions and their salience, as identified in 5.1. We discovered three related mechanisms through which issue characteristics influenced party agendas: the perceived co-benefits or costs of a given technology; changes in the scope of the menu of policy options; and path dependence associated with existing technology and infrastructure.

First, the perceived *relative co-benefits or costs* of technologies affected the position changes of parties (see Table 2, individual quotes referenced in the text with [statement ID]). In Germany, the exponential growth of RET and associated technological learning and economic benefits have led to increasing support for these technologies by left to center-left parties [statement ID 3, 4, 6, 7], and, with some time lag, the center-right party [2]. At the same time, certain parties opposed technologies such as hard coal and nuclear power because of the growing perception of their costs and risks [3, 5]. The arrival of a right party in the German system challenged the broad consensus regarding the benefits of RET, as the AfD strongly emphasized costs and landscape effects related to them [1]. We observed similar trends in France, where only the right party openly challenged RET and put forward arguments in favor of NT [14]. The perceived benefits of NT were, however, a non-partisan issue in the French party system with supportive statements on energy independence and climate change mitigation across the left-right spectrum [13, 15, 16]. With the exception of recent, low-salient opposition by the center-left party, no major party openly dissociated from NT. In the UK, while parties had temporarily opposed NT, we observed a turnaround in favor of increasing support for it in the 2010s (see Figure 3 above). This support, however, was challenged by niche parties such as the SNP on the grounds of perceived costs and risks associated with it [12]. British niche parties were also among the first to highlight the co-benefits of RET in terms of jobs and economic growth [11].

Country	Exemplary quotes
Germany	*"Germany's electricity prices inevitably continue to increase with each additional wind and solar power plant and network expansion."* (AfD, 2017) [1]
	"The expansion of renewable energies has shifted considerable economic activity and value creation back to rural areas." (CDU/CSU, 2017) [2]
	"German hard coal is a non-competitive energy source. Coal subsidies are economically irresponsible." (FDP, 2002) [3]
	"In the long term, renewable energies from wind power (offshore and onshore) and solar energy are the most cost-effective form of energy generation." (SPD, 2017) [4]
	"The use of nuclear energy is too risky." (SPD, 2009) [5]
	"More than 250,000 people work in the renewable energy sector, more than in the coal industry." (Grüne, 2009) [6]
	"Today, Germany is the global market and technology leader in wind power and photovoltaics." (Grüne, 2005) [7]
	"New technological developments - such as hydrogen technology and other forms of renewable energies - offer the opportunity to make East Germany an important location for environmentally friendly energy generation." (Die Linke, 2017) [8]
France	*"Nuclear power equipment allows our country to be more independent from ups and downs of oil prices."* (PS, 1988) [13]
	"Maintaining our energy independence and good performance in terms of CO_2 emissions requires conserving nuclear energy in the medium term." (FN, 2012) [14]
	"We will keep a significant share of nuclear energy production, which does not emit greenhouse gases. Neither Fessenheim nor any other power plant will close, except for safety and security considerations." (LR, 2017) [15]
	"Nuclear is an effective response to climate change, provided that the necessary research and development is carried out to find a solution to the waste issue." (MoDem, 2002) [16]
United Kingdom	*"Since 1983 productivity in the coal industry has risen by over 50 per cent. Coal will continue to meet much of the steadily rising demand for electricity."* (Tories, 1987) [9]
	"Wind power is hopelessly inefficient and wind farms rely heavily on reserve back-up from conventional power sources." (UKIP, 2017) [10]
	"Scotland has a wealth of onshore and offshore renewable energy potential which, if unlocked, can support thousands more jobs and further economic growth." (SNP, 2017) [11]
	"If built, electricity generated by Hinkley C will be sold for more than twice the current retail price. SNP MPs will hold the UK government to account over its support for the Hinkley white elephant." (SNP, 2017) [12]

Table 2: Exemplary quotes on how technological change affects party positions: Changes in the perceived co-benefits and costs of technologies. Sources in brackets (party manifestos of legislative elections), ID for reference in text in square brackets.

Second, these changes in the relative costs and benefits of technologies resulted in extending or limiting the *menu of policy options* (Jacobs and Weaver 2015) for technologies (see Table 3, individual quotes referenced in the text with [statement ID]). In all three countries, niche parties such as the German Greens, British Lib Dems, and French UDF first highlighted the technical maturity of solar PV [27, 31]. In the following years, the growing technical and economic feasibility of RET increased the ambitiousness of target setting beyond these niche to incumbent parties in the three countries. For example, the German CDU/CSU increased their ambition steadily over the decades, evolving from an undefined commitment for RET in 1987 to a specific target of 12.5% renewables in 2005 [21-24]. Similar trends could be observed in the UK [29, 30] and France [32, 33, 36], where even the right party FN embraced RET as opportunities [34, 35]. Hence, the increasing technical maturity and falling costs increased the menu of policy options available to these incumbent parties. The increasing deployment of RET also resulted in the need for further technological developments, which was reflected in the parties' agendas. For instance, in the 2010s, parties in Germany and the UK emphasized the need for grid expansion and deployment of energy storage technologies because of RET localization and fluctuation [19, 29]. Besides RET, parties' agendas also reflected developments in FFT. For instance, innovations in fracking technology enabled the exploitation of shale gas, which some center-right to right parties in Germany and the UK conceived of as an opportunity [25, 28]. Of course, these menu effects can also have negative directionality. For instance, the nuclear phase-out in Germany led to a subsequent decrease in the salience of positions relating to NT (see Figure 4), as this technology was removed from the menu of feasible policy options.

Country	Exemplary quotes
Germany	*"To ensure that electricity will always be available at any place and at any time, we are supporting the expansion of the power grids and the development of new storage technologies."* (CDU/CSU, 2013) [19] *"We see nuclear energy as a bridge technology, because today climate-friendly and inexpensive alternatives are not yet sufficiently available."* (CDU/CSU, 2009) [20] *"We have set ourselves ambitious goals in the area of expanding renewable energies (20 percent by 2020)."* (CDU/CSU, 2009) [21] *"We should achieve at least 12.5% renewable energies in German electricity consumption."* (CDU/CSU, 2005) [22] *"We want to double the share of renewable energies in electricity supply by 2010."* (CDU/CSU, 1998) [23] *"Wind and solar energy and other renewables can increasingly contribute to our energy supply."* (CDU/CSU, 1987) [24] *"Shale gas fracking is an opportunity that can contribute to the success of the energy transition."* (FDP, 2013) [25] *"Gas should be used as a temporary solution to compensate for fluctuations in energy supply."* (Grüne, 2013) [26] *"Converters for solar panels and silicon solar cells are now technically mature."* (Grüne, 1994) [27]
France	*"We will promote the rise of renewable energies by supporting the creation and development of industrial activity in this sector."* (PS, 2012) [32] *"The potential of solar energy, biomass, and wind turbines is considerable."* (PS, 2012) [33] *"We will massively develop the French renewable energy sectors thanks to intelligent protectionism, economic patriotism, public and private investment and deploying EDF."* (FN, 2017) [34] *"Apart from hydropower, so-called "green" energies are not realistic today as such: For example, it would be necessary to install 275,000 wind turbines, or 5 billion square meters of photovoltaic panels (an average department) to produce the electricity necessary for France."* (FN, 2012) [35] *"We will strengthen the development of renewable energy in line with our commitment to produce more than 20% renewable energy by 2025."* (LR, 2017) [36]
United Kingdom	*"We believe that shale energy has the potential to do the same thing in Britain, and could play a crucial role in rebalancing our economy. We will therefore develop the shale industry in Britain."* (Tories, 2017) [28] *"We will support investment in energy storage and smart grid technology to enable this higher reliance on renewables."* (Lib Dems, 2015) [29] *"Set a target for 40 per cent of UK electricity to come from clean, non-carbon-emitting sources by 2020, rising to 100 per cent by 2050."* (Lib Dems, 2010) [30] *"The Liberal Democrats will make sure that at least 20 per cent of the UK's electricity comes from a full range of renewable sources by the year 2020."* (Lib Dems, 2005) [31]

Table 3: Exemplary quotes on how technological change affects party positions: Changes in the menu of policy options. Sources in brackets (party manifestos of legislative elections), ID for reference in text in square brackets.

Third, *path dependence* (Arthur 1989), related to existing deployment and infrastructure around technologies, can slow down or even hinder that changing menus of policy options are exploited by political parties (see Table 4, individual quotes referenced in the text with [statement ID]). Statements on the need for continued support for FFT (especially coal) and NT were often based on their pre-existing dominant roles in energy systems, rather than on specific arguments regarding their benefits and/or costs. For instance, in the 1980s and 1990s, center-left parties in Germany and the UK defended coal technology against NT on such grounds [49, 53]. Today, mostly right parties emphasize the need to protect FFT against competition by other technologies because of the historic role of this group [54]. Similarly, in France, and later in Germany and the UK, parties defended NT based on its historic role in the energy sector [45, 52, 55]. Some parties also explicitly stated their intention to overcome such lock-in linked to path dependence. For instance, after the oil crisis, overcoming dependence from the oil supply was a widespread argument in Germany [47]. Center-left to left parties mentioned path dependence linked to FFT and NT as key impediments to an accelerated transition toward the deployment of more RET [50, 51, 57, 58, 59, 61]. Finally, path dependence is not limited to incumbent energy technologies, but also to their low-carbon alternatives. Traces of the effects of path dependence on party agendas can already be detected for RET, especially in Germany [46, 48, 66]. The salience of positions is low in the absence of infrastructure related to technologies. France has almost no resource endowment in fossil fuels, and consequently a weak path dependence in FFT, which partially explains why the issue remained almost absent from the political agenda.

Country	Exemplary quotes
Germany	*"We need nuclear energy as a transition technology until renewable energies can generate a sufficient amount of base load-capable electricity or until CO2 capture and storage for coal-fired power plants is available."* (FDP, 2009) [45]
	"The Renewable Energy Sources Act, which was adopted by the red-green coalition in 2000, has led to an unprecedented expansion of renewable energies - today their share of electricity consumption is already over 25 percent." (SPD, 2013) [46]
	"We will gradually reduce our dependence on oil." (CDU/CSU, 1980) [47]
	"With our Renewable Energy Sources Act, we will trigger around 20 billion euros in new investments by 2010 and also become the world's industrial leader in solar and wind power technology." (SPD, 2005) [48]
	"Domestic coal should come before nuclear energy in heat supply and power generation." (SPD, 1983) [49]
	"New coal-fired power plants, and extending the lifespan of nuclear power plants, are blocking the necessary expansion of renewable energies." (Grüne, 2009) [50]
France	*"We will reduce the share of nuclear energy in electricity production from 75% to 50% by 2025, by guaranteeing the maximum safety of the installations and by continuing the modernization of our nuclear industry."* (PS, 2012) [57]
	"We will reduce the share of nuclear energy by increasing the share of renewable energies in our final energy consumption to 20% in 2020 and to 50% in the longer term." (PS, 2007) [58]
	"We want to phase-out nuclear power by 2031 and the immediate cessation of plutonium and MOX production, reprocessing and transport of nuclear materials." (Les Verts/EELV, 2012) [59]
United Kingdom	*"Labour will ban fracking because it would lock us into an energy infrastructure based on fossil fuels, long after the point in 2030 when the Committee on Climate Change says gas in the UK must sharply decline."* (Labour, 2017) [51]
	"The UK has the world's oldest nuclear industry, and nuclear will continue to be part of the UK energy supply." (Labour, 2017) [52]
	"We will secure the long-term future of the coal industry by reducing imports, stopping the 'dash for gas' and reining back on open-casting." (Labour, 1992) [53]
	"The British coal industry once employed one million miners. Now, all three remaining deep coal mines in Britain are set to close by 2016, at a cost of 2,000 jobs, despite having many years of productive life left and regardless of our continuing need for coal. 30 per cent of our electricity is still produced from coal and we will be dependent on fossil fuels for many more years to come." (UKIP, 2017) [54]
	"We will support further nuclear projects and protect nuclear workers' Jobs and pensions." (Labour, 2017) [55]
	"In the next Parliament, the interests of the whole country require Britain's massive coal industry, on which we depend for the overwhelming bulk of our electricity generation, to return to economic viability." (Tories, 1983) [56]

Table 4: Exemplary quotes on how technological change affects party positions: Path dependence. Sources in brackets (party manifestos of legislative elections), ID for reference in text in square brackets.

6. Discussion and conclusion

In this paper, we took an exploratory approach to examine how political parties positioned themselves toward energy technologies and how much salience they allocated to these positions. We also examined how technological change affected these changes. Empirically, we focused on party positions on energy technologies in Germany, France and the UK from 1980 to 2017. Methodologically, our analysis proceeded in two steps.

In a first step, we mapped the changes in party positions and salience levels. We find that the energy sector is a less salient issue compared to more generic policy issues such as environmental protection or social welfare. However, our analysis reveals strong differences of salience and positions across individual energy technologies, party families, time, and countries. Compared to FFT and NT, party positions on RET are relatively homogenous and increasingly supportive over time. With exceptions, Left to Centre parties allocate more salience to energy technologies and are more opposed to FFT and NT than their Centre-Right to Right counterparts. The finding that niche parties changed their positions on technologies faster than incumbent parties underlines the role of party characteristics, such as the size and ideological leaning of parties (Adams and Merrill 2006; Gabel and Huber 2000). It also suggests that niche parties often act as policy entrepreneurs (Green-Pedersen 2019) in the energy sector. As a reaction to position shifts by policy entrepreneurs, incumbent parties in all countries tended to follow these parties in an accommodative strategy (Meguid 2005), with center-left parties doing so faster than center-right parties. Finally, differences across countries were considerable in terms of both position change and salience levels. While energy technologies were a rather salient issue in Germany, they were less salient in French and British party agendas. In addition, technology-specific patterns varied across countries, revealing that despite temporary diverging positions among parties and room for agenda-setting by niche parties, the overall pattern on the country level and in the longue durée was one of relative policy convergence.

Essentially, party positions co-evolved within the limits of a commonly shared party system agenda (Abou-Chadi, Green-Pedersen, and Mortensen 2020; Green-Pedersen 2019). With exceptions and some time lag, political parties in the three countries tended to converge to closer positions for the three technology groups. These findings emphasize the key role of contextual factors such as the type of party systems and country-specific characteristics of technology deployment and resource endowment.

In a second step, we qualitatively analyzed the collected data to explore the role of technological change in party position change. We show that technological change is one factor that affects party position change. We inductively substantiate three related mechanisms through which issue characteristics affect party positions. First, technological change shapes the technical feasibility and economic competitiveness of technologies, and hence affects how parties perceive the relative co-benefits and costs associated with these technologies (Schmidt, Schmid, and Sewerin 2019). We find that the increasingly supportive positions on RET across all countries was often underpinned by arguments on their co-benefits. Second, these changes in the perceived co-benefits and costs, in turn, extended or limited the menu of policy options (Jacobs and Weaver 2015). We find that as RET became increasingly economically and technically competitive these technologies therefore became politically attractive and expanded the menu available to political parties. Yet, evidence also suggested that party characteristics moderated this channel: The timing of emphasized benefits and costs associated with technologies depended on the party family, with some niche parties embracing co-benefits earlier than center-right incumbent parties. Compared to Germany, this agenda push has been less marked in France and the UK, whose party systems have comparatively weak niche parties. At the same time, the menu of policy options can also decrease because of technology declines or phase-outs. As a case in point, the German nuclear phase-out led to a subsequent decrease in the salience of NT. Finally, the extent and speed to which political parties adapted to these changes in the menu of policy options also depends on path dependence resulting from pre-existing infrastructure and resource endowments. For instance, the low dependence on FFT in France can partially explain the absence of political conflict around this issue, while past investments in infrastructure and capabilities around NT made it politically unattractive for French parties to oppose this technology. However, niche parties, such as the British Liberal Democrats and the German and French Greens, explicitly addressed the need to overcome path dependence created by FFT and NT infrastructure. Overall, these findings suggest that – moderated by party characteristics and party systems – technological change is a factor for party position change.

On a more abstract level, our paper makes three important contributions. First, to the best of our knowledge, this is the first study that systematically maps political party positions on energy technologies. Our sector-specific focus on individual technologies provides a more granular approach compared to party politics research, which is typically focused on more generic policy issues such as climate policy (Båtstrand 2015; Carter et al. 2018; Ćetković and Hagemann 2020; Farstad 2018).

Second, our paper also contributes to the growing literature on politics, actors, and agency in sociotechnical transitions as it represents a response to the calls for more research in this vein (Köhler et al. 2019; Lockwood et al. 2017; Meadowcroft 2009; Roberts et al. 2018; Rosenbloom, Meadowcroft, and Cashore 2019; B. K. Sovacool and Brisbois 2019; Wittmayer et al. 2017). With the focus on party politics, this study complements previous research on the role of political actors such as those involved with social movements (Hess 2018), intermediary actors (Kivimaa et al. 2019), or advocacy coalitions (Markard, Suter, and Ingold 2016). These findings enrich discussions about the role of (political) incumbents vs. newcomers in transitions

(Geels 2014; B. Sovacool et al. 2020). We have shown that niche parties changed their positions faster than incumbent parties, even in light of high uncertainty linked to niche technologies such as RET. The existence of such policy entrepreneurs suggests that party systems with stronger niche parties may be more adaptive and flexible in steering emerging technologies compared to more rigid two-party systems. These insights point to the importance of institutional factors in transition processes (Fuenfschilling and Truffer 2016): In the context of sociotechnical transitions, political systems more hospitable to niche parties may have a “comparative political advantages” (Breetz, Mildenberger, and Stokes 2018) in the development of niche technologies and the acceleration of sociotechnical transitions.

Third, our analyses shed light on how technological change drives party positions. Our findings indicate that, to varying degrees, political parties are updating their positions on technologies in what can be called a learning process (Goyal and Howlett 2020). Such learning by political parties suggests that policymakers may intentionally foster long-term political party support for renewable energy technologies by improving their underlying issue characteristics, such as costs, through the establishment of protective spaces (Lockwood 2016). In other words, by inducing technological change, policymakers may trigger a virtuous feedback loop in which policy-induced niche technologies are increasingly supported by political parties, which may subsequently lead to more ambitious and stringent types of policy outputs (Levin, Cashore et al., 2012; Rosenbloom et al., 2019). While this line of argument is central to the emerging literature on the co-evolution and feedback among policy, technology, and politics (Edmondson, Kern, and Rogge 2019; Foxon 2011; J. Meckling et al. 2015; Schmid, Sewerin, and Schmidt 2019), the role of political parties in such loops has not yet been discussed explicitly. Our analysis of the party politics behind sociotechnical transitions provides a critical building block for this subset of the transitions literature.

While we believe that our exploratory study is conceptually relevant and empirically well-founded, we wish to highlight limitations that also provide guidance for future, related research. First, given the exploratory nature of this study, we cannot not account for explanations other than technological change as a driver of party positions. As mentioned above, alternative explanations such as party-industry ties or public opinion have been shown to influence party positions in other issue areas and should be relevant in the energy sector as well. Future research could tackle these questions with a more quantitative research design that allows them to assess the relative weight of different explanations for party position change. Such research could be built on the findings in this paper for the generation of specific hypotheses related to energy technologies and political parties. Second, while our empirical focus on energy technologies was fine-grained compared to much of the extant party politics research, we know from policy design literature that the even more detailed settings and calibrations of policies and corresponding technology characteristics matter for policy outcomes (Haelg, Sewerin, and Schmidt 2019; Haelg, Waelchli, and Schmidt 2018; Howlett 2014). While party manifestos do not allow for such analyses, future research should be conducted to identify other ways to zoom into the party politics of designing policy mixes, for example by conducting expert interviews or using other data sources such as newspaper articles or policy documents. Finally, although insights from party politics literature suggest that party positions influence subsequent policy outputs and changes, whether and how this is the case in the energy sector remains an open empirical question. Future research could build on this study by assessing the links among party position changes, salience levels, policies, and policy mixes targeted at niche and incumbent energy technologies.

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8. Annex

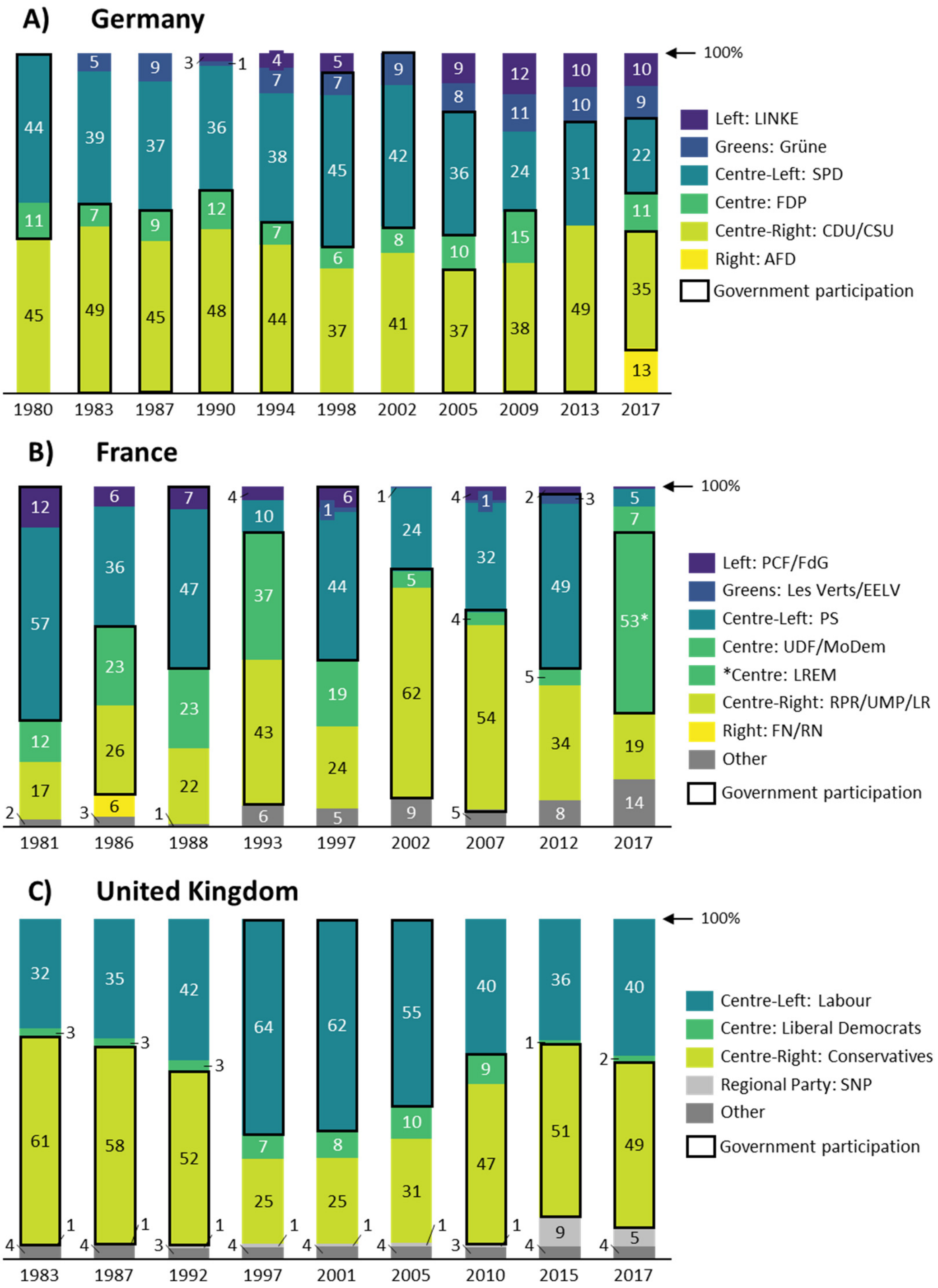

Figure A.1: Share of parliamentary seats (in %) and government participation of political parties analyzed in this paper. Own illustration based on data from http://www.parlgov.org (see Döring and Regel 2019).

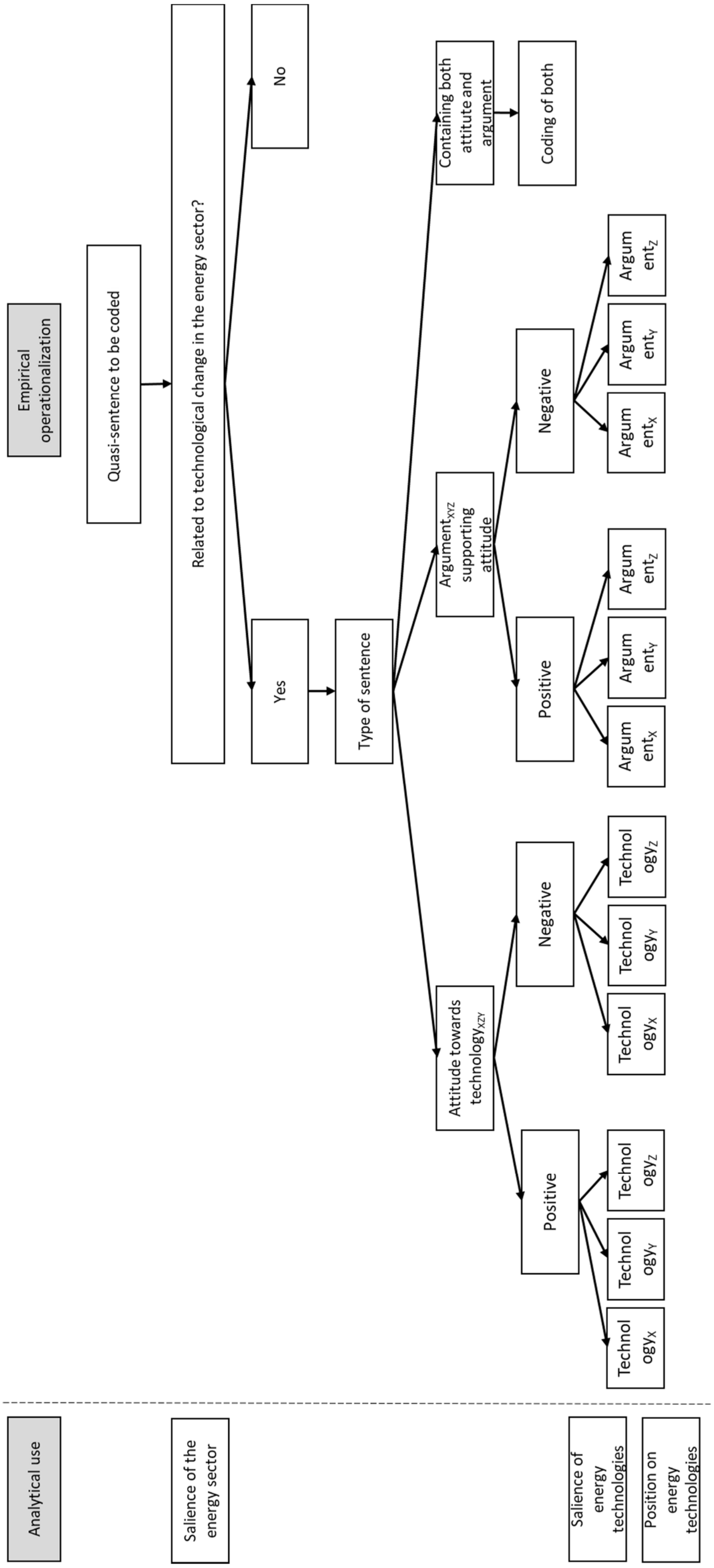

Figure A.2: Coding scheme. The scheme distinguishes between analytical use (left) of data collected and the operationalization (right) and provides an overview on the coding procedure in chronological order from top to bottom.

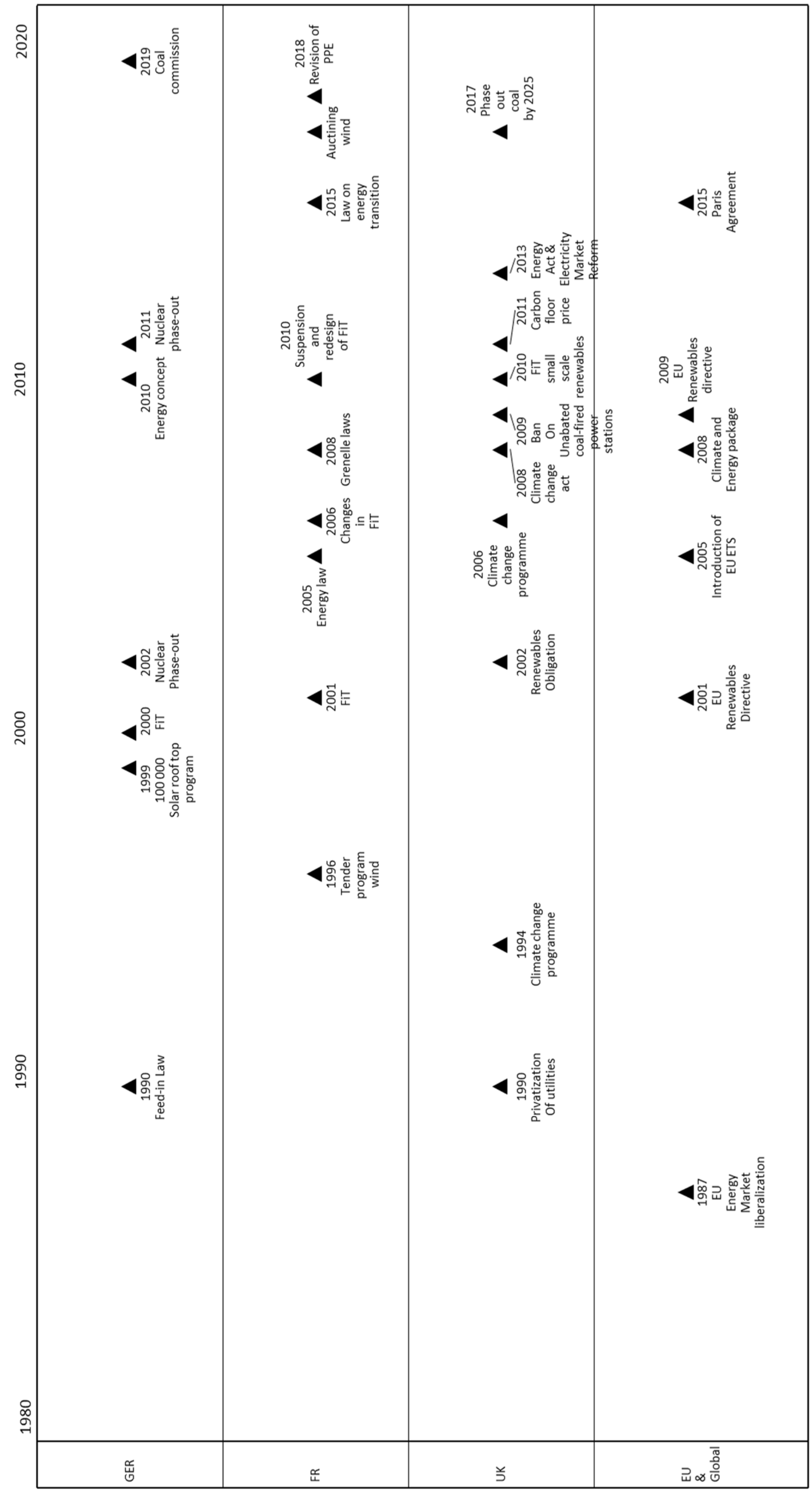

Table A.1: Timeline of selected policy interventions in the energy sector in Germany, France, and the United Kingdom. Own illustration based on (Cointe 2015; Kern, Kuzemko, and Mitchell 2014; Lauber and Jacobsson 2016; Lockwood, Mitchell, and Hoggett 2019; Renn and Marshall 2016; Schmid, Sewerin, and Schmidt 2019).

Germany												
		1980	1983	1987	1990	1994	1998	2002	2005	2009	2013	2017
Centre-Left: SPD	Fossil fuels	3	7	3	2	3	3	2	4	7	2	-4
	Nuclear	2	1	-16	-8	-6	-6	-3	-5	-9	-4	-6
	Renewables	2	1	0	3	10	7	5	10	16	20	11
	Total statements	7	9	19	12	19	16	10	19	32	26	21
	Total sentences	285	237	281	263	303	998	1610	882	2208	2898	2645
Left: LINKE	Fossil fuels	0	0	0	1	0	0	0	0	-2	-15	-14
	Nuclear	0	0	0	-2	-1	-2	-2	-4	-9	-7	-19
	Renewables	0	0	0	4	1	3	4	3	10	8	20
	Total statements	0	0	0	7	2	5	6	7	21	29	33
	Total sentences	0	0	0	359	289	936	844	573	1664	2472	3939
Left: Greens	Fossil fuels	0	0	3	-5	-8	-5	-4	-7	-30	-29	-25
	Nuclear	0	-4	-12	-15	-20	-13	-22	-27	-44	-43	-28
	Renewables	0	0	3	4	13	10	30	20	43	57	33
	Total statements	0	4	18	24	41	28	56	55	127	129	96
	Total sentences		164	492	144	684	2153	1660	1867	3596	5430	3875
Centre-Right: CDU/CSU	Fossil fuels	4	0	2	3	5	3	7	2	4	3	-1
	Nuclear	8	0	18	1	6	4	15	10	7	0	-2
	Renewables	1	0	3	1	5	3	7	5	18	8	6
	Total statements	13	0	23	5	16	10	29	17	29	11	9
	Total sentences	264	137	273	152	276	567	1315	777	2006	2574	1342
Centre-Right: FDP	Fossil fuels	6	0	0	2	-2	-2	-4	0	3	5	0
	Nuclear	3	1	9	5	2	2	3	6	7	0	0
	Renewables	0	1	5	10	4	2	2	3	9	13	4
	Total statements	9	2	14	17	8	6	9	9	19	18	4
	Total sentences	645	275	205	687	905	1605	1982	1419	2247	2579	2077
Right: AfD	Fossil fuels	0	0	0	0	0	0	0	0	0	0	1
	Nuclear	0	0	0	0	0	0	0	0	0	0	3
	Renewables	0	0	0	0	0	0	0	0	0	0	-13
	Total statements	0	0	0	0	0	0	0	0	0	0	17
	Total sentences										73	1004

France										
	Years	1981	1986	1988	1993	1997	2002	2007	2012	2017
Centre-Left: PS	Fossil fuels	2	0	-2	0	0	0	-2	0	0
	Nuclear	3	0	8	0	-3	0	-2	-4	0
	Renewables	0	0	0	2	3	2	6	6	2
	Total statements	5	0	10	2	6	2	10	10	2
	Total sentences	264	164	232	250	286	696	601	428	152
Left: PCF, Front de Gauche	Fossil fuels	0	0	0	0	0	0	0	-2	0
	Nuclear	0	0	0	2	0	0	4	0	0
	Renewables	0	0	0	2	0	0	2	6	0
	Total statements	0	0	0	4	0	0	6	8	0
	Total sentences	84	119	55	294	70	80	600	1494	457
Les Verts/EELV	Fossil fuels				0	1	0	-7	-3	-2
	Nuclear				-2	-1	-3	-11	-16	-2
	Renewables				1	1	3	15	11	9
	Total statements				3	3	6	33	30	13
	Total sentences				65	48	266	653	1130	220
Centre-Right: RPR / UMP / LR	Fossil fuels	0	0	0	0	0	0	-2	0	0
	Nuclear	3	0	0	0	0	0	14	4	4
	Renewables	0	0	0	0	0	2	8	2	2
	Total statements	3	0	0	0	0	2	24	6	6
	Total sentences	224	79	47	127	61	426	1902	944	514
Right: Front National	Fossil fuels					0	0		0	-2
	Nuclear					0	6		4	4
	Renewables					0	0		0	0
	Total statements					0	6		4	6
	Total sentences		670	372.5	372.5	75	624	1225	594	516
Center: UDF/MoDEM	Fossil fuels				0	0	0	0	-2	
	Nuclear				0	0	6	8	4	
	Renewables				0	0	10	10	12	
	Total statements				0	0	16	18	18	
	Total sentences	55	55	55	55	122	694	584	826	904
	Fossil fuels									0

Center: La Republique en Marche	Nuclear									0
	Renewables									2
	Total statements									2
	Total sentences									724
United Kingdom										
	Years	1983	1987	1992	1997	2001	2005	2010	2015	2017
Centre-Left: Labour	Fossil fuels	8	2	5	1	3	1	3	5	3
	Nuclear	0	-1	-2	1	1	1	2	1	4
	Renewables	1	1	0	1	3	2	3	1	3
	Total statements	9	4	7	3	7	4	8	7	10
	Total sentences	1455	561	637	830	1494	1068	1133	1009	1328
Regional Party: SNP	Fossil fuels	-	-	1	5	0	-	-	2	3
	Nuclear	-	-	-2	-5	-2	-	-	0	3
	Renewables	-	-	2	3	1	-	-	6	11
	Total statements			5	13	3			8	17
	Total sentences			813	651	806			892	787
Centre-Right: Conservatives	Fossil fuels	5	3	7		0	0	3	5	10
	Nuclear	5	3	1		1	0	2	2	0
	Renewables	0	1	2		1	1	2	1	0
	Total statements	10	7	9		2	1	7	8	10
	Total sentences	774	1047	1686	1084	724	344	1112	1588	1496
Centre: Liberal Democrats	Fossil fuels	7	3	0	0	-1	0	1	5	-2
	Nuclear	4	6	-1	-3	-1	-2	-1	1	2
	Renewables	2	2	12	2	4	6	7	13	6
	Total statements	14	11	13	5	6	8	9	19	10
	Total sentences	741	960	837	842	1149	685	815	1917	1131

Table A.2: Frequencies of coded quasi-sentences on energy technologies per country, party, technology and year. Total sentences equals the total amount of quasi-sentences in a manifesto, including non-energy related topics. Positive or negative sign in front of numbers signifies support or opposition towards a given technology. In the rare case that a party has issued both positive and negative statements, the number indicates the net sum of these statements.

Paper 4: Electoral response to the decline of coal mining in the United States

Authors: Florian Egli*[1], Nicolas Schmid[1], and Tobias S. Schmidt[1]

* Corresponding author: florian.egli@gess.ethz.ch

[1] ETH Zurich, Department of Humanities, Social and Political Sciences, Energy Politics Group, Haldeneggsteig 4, CH-8092 Zurich, Switzerland

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Abstract:

Replacing coal with cleaner energy carriers is a crucial lever to reach many Sustainable Development Goals and the Paris climate targets. However, as coal decline results in local job loss, political backlash might arise, jeopardizing the clean energy transition. Yet, we lack evidence on whether such backlash exists. Here, we analyse the electoral response to coal mining job losses in the United States presidential elections from 2000 to 2016. For the main specification, our findings suggest that the local loss of coal jobs increased Republican vote shares by 5.4 percentage points (pp) in the 2016 elections (3.9 pp in 2012). The absolute effect on votes was more than six times larger than the number of jobs lost. Moreover, we find a spillover effect of 2.2 pp in 2016 into counties within 50 km of those affected by coal decline. These findings suggest that the electoral backlash exceeded job losses, which has important implications for coal phase-outs worldwide.

1. Introduction

Mitigating climate change, particulate air pollution, biodiversity loss and many other social and environmental costs related to the burning of coal require a replacement of coal with cleaner energy carriers (Burney 2020; Giam, Olden, and Simberloff 2018; Oberschelp et al. 2019; Le Quéré et al. 2018). Consequently, phasing out coal has a central role in almost all scenarios that are compatible with the Paris Agreement and the Sustainable Development Goals (SDGs) agenda (Edenhofer et al. 2018; Tong et al. 2018, 2019). While global coal production has strongly increased over the past decades, a trend towards reversal may have recently begun. In some areas, dramatic declines in coal mining can be observed. One prominent example is the US, where coal production has fallen massively since 2011, primarily driven by the rapid cost decreases of alternative energy carriers, such as shale gas and renewable electricity. Such transitions from old to new technologies affect value chains and jobs (Burke, Best, and Jotzo 2019; Carley et al. 2018; Mayfield et al. 2019) and, in turn, can provoke political backlash. As a result, this can slow down the transition to new, cleaner energy carriers, ultimately jeopardizing the SDGs and the Paris climate targets.

Political science literature shows that voters punish policymakers in charge for policies that directly impact their economic welfare or the socio-economic situation of their community (Broz, Frieden, and Weymouth 2019; Healy and Malhotra 2013; Lewis-Beck and Stegmaier 2000). Given the relevance of coal for reaching the SDGs and Paris targets and its prominence in political debates (Editorial 2019), very few – mostly qualitative – studies have investigated the political and societal effects of phase outs (Carley, Evans, and Konisky 2018; Vona 2019) and scholars call for more research on the topic (Jewell and Cherp 2020). Despite the often strong partisanship between political parties on whether and how to phase out coal, none of these studies has looked at electoral outcomes. Hence, there is no evidence on whether coal declines trigger an electoral response in favour of pro-coal political parties and how large such a response may be. This question is crucial to researchers and policymakers concerned about managing the transition away from coal towards less polluting and low-carbon energy carriers. Here, we address this gap and analyse the effects of coal mining decline on local voting outcomes in US presidential elections.

2. Coal decline and US presidential elections

We focus on the US, the third-largest coal producer worldwide in 2016, and analyse the effect of coal mining job losses on electoral outcomes in the presidential elections from 2000 to 2016. During this period, a remarkable trend reversal occurred. While coal mining jobs were on the rise until 2011, the US coal mining industry lost 39,650 jobs from 2011 to 2016, a 43% drop (Fig. 1), representing a loss of about 100 million annual labour hours. Production also fell by 33% (364 million short tons annually), and 697 coal mines closed, almost halving the number of active coal mines in the US (see Fig. S1 in the Supplementary Information, SI). Excluding Alaska and Hawaii, 24 of 49 US states reported coal mining jobs in 2011. Job losses were highly uneven across these 24 states. States with large (relative and absolute) coal job losses were concentrated in the eastern US with Alabama, Kentucky, Ohio, Tennessee, Virginia and West Virginia losing more than half of their coal mining work force from 2011 to 2016. Only three states (Louisiana, Mississippi and North Dakota) reported small increases in coal mining jobs (248 additional jobs in total). The variations were even stronger on the county-level as individual coal mines faced very different cost structures (e.g. output per worker was more than three times higher in coal mines west of the Mississippi River compared with those east of the river, see Fig. S2). As a result of this variation, the incidence of coal mining job losses depended on the local characteristics of coal mines and their productivity (Jordan, Lange, and Linn 2018) and was independent of federal and state policy (see Note S1). In this study, all subsequent analyses use county-level data and make use of this exogenous variation.

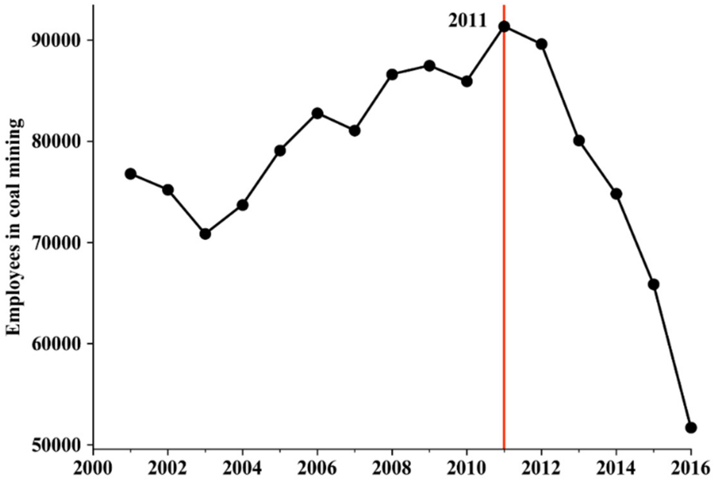

Figure 1: Employment in US coal mining.

Coal was a highly salient topic during the presidential campaigns of 2012 and, especially, 2016, with Republican and Democratic candidates holding completely opposing views on the issue (Brown and Sovacool 2017). On the one hand, the Republicans supported coal mining and framed the Obama administration's energy and climate policies (e.g. the Clean Power Plan of 2015) as a 'war on coal' (Eilperin 2013; Thurber 2019). On the other hand, the Democrats promised to accelerate the transition away from coal towards renewable energy carriers. In her 2016 campaign, Democratic candidate Hillary Clinton stated, 'We are going to put a lot of coal miners and coal companies out of business' (Pai and Zerriffi 2018). She would later call this statement her biggest regret of the campaign.

Here, we exploit the fact that the local incidence of coal mining job losses varies substantially amongst counties and is independent of federal policy. Coal mines were driven out of business by cheaper alternative energy carriers and international coal market prices (Kolstad 2017; Mendelevitch, Hauenstein, and Holz 2019a). While the alternatives were enabled by federal and state policies, these policies did not influence which mines lost coal mining jobs (see Note S1).

We use this quasi-experimental setting of rapid and locally concentrated coal mining decline combined with high political salience and employ a matched difference-in-difference (DiD) analysis to test whether the loss of coal mining jobs affected county-level (i.e., local) voting outcomes in the presidential elections from 2000 to 2016. Note that we use county-level data throughout this study, which is the most granular level on which sufficient data are available. We include all 3,142 counties in the US, excluding Alaska, Hawaii and overseas territories. Specifically, we investigate the voting outcomes of the counties that lost coal jobs between 2011 and 2016 (N = 163 'treated' counties) and compare those with the counterfactual development of most similar control counties. We use a propensity score 1:1 matching without replacement (see Methods for details) on six socio-economic variables and pretreatment outcomes in 2000 and 2008 (see Tables S1 and S2 for a description and summary statistics) to identify most similar control counties. Based on the economic voting literature (Margalit 2011; Stokes 2016), we choose the median household income, the unemployment rate, the share of manufacturing jobs, the share of white people in the population, the educational attainment and the population density as socio-economic control variables (see Note S2 for a detailed discussion of the literature and the theoretical considerations). Table S3 in the SI shows that, over the entire sample period, all socio-economic variables contributed significantly to explain Republican Party vote shares in the presidential elections (R^2 = 0.32). Specifically, counties with higher household incomes, unemployment levels, manufacturing employment shares, educational achievement and population density voted, on average, less for the Republican candidate in presidential elections from 2000 to 2016. Counties with a higher share of white people in the population voted, on average, more in favour of the Republican candidate. Hence, the choice of matching variables seems appropriate.

Fig. 2 shows treated and matched counties on a map and parallel pretreatment trends for matched samples for two main setups (see Methods). Treated counties are those that experienced a loss in coal jobs from 2011 to 2016. In the first setup, we let the matching algorithm choose control counties from all US states (Fig. 2a and c). In the second setup, we restrict the choice of control counties to states with at least one treated county (Fig. 2b and d). For both setups, the treated and control counties followed identical pre-treatment voting trends over 16 years from 1992 (Bill Clinton's first election) to 2008 (Barack Obama's first election). These trends changed from 2012 onward, satisfying the pre-treatment parallel trends assumption (see Methods) and indicating a voting outcome difference between treated and control counties in 2012 and 2016. A two-sided *t*-test confirms that all socio-economic variables for treated and control counties in 2000 and 2008 were statistically indifferent on a 5% significance level after the matching (see Methods and Table S2).

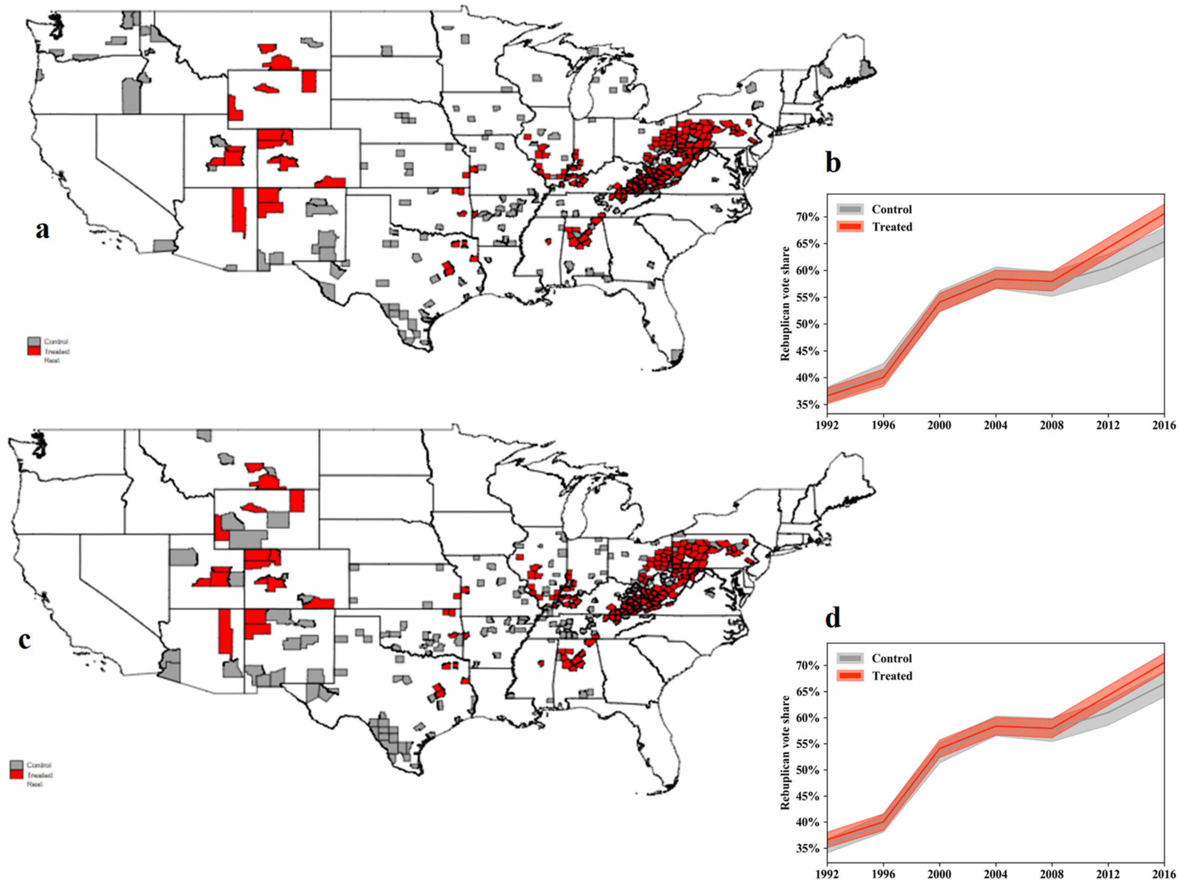

Figure 2: Treated (red, $N = 163$) and control counties (grey, $N = 163$) for two main setups. (**a**) Location of treated and control counties and (**b**) parallel pre-treatment trends since 1992 for all US states. (**c**) Location of treated and control counties and (**d**) parallel pre-treatment trends since 1992 for US states with at least one treated county.

In the following, we report the findings in three steps. First, we discuss effect sizes along a series of specifications, report according robustness checks and test our data against three placebo tests. Second, we investigate differences in treatment intensities. Third, we investigate geographic spillovers beyond counties with coal job losses.

3. Results

3.1. Magnitude of electoral response

For the estimation of the effect size, we report results along seven specifications with additional robustness checks provided in the SI. The specifications differ with regards to the matching and the inclusion of socio-economic control variables (see Note S2 for the choice of variables). Table 1 shows the results for the main specifications (specs. 1–2), a variation in the control county choice set (specs. 3–5) and a variation in the matching years (specs. 6–7). For each type of specification, Table 1 reports results with and without control variables in the final regression (see Methods). All specifications include county and year fixed effects; that is, besides the socio-economic variables, we control for all county-specific time invariant characteristics and for all county invariant and time varying characteristics. As a final robustness check, we use the specification restricted to states with at least one treated county to include state and year fixed effects interactions. In essence, this specification additionally controls for factors that vary by state and time, for example, state-specific time trends that are not captured by the socio-economic variables. In all specifications, the models explained a large share of the variance in Republican vote shares (R^2 = [0.49–0.76]). We discuss results at the 5% significance level, with almost all results being statistically significant at a 1% significance level (see Table 1).

In the main specification (1), we find Republican vote shares in counties with coal mining job losses were 3.9 pp higher compared with control counties in 2012. The effect increased to 5.4 pp in 2016. The effect sizes were relatively stable across all specifications ranging from 2.4 to 4.3 pp for 2012 and 2.8 to 5.6 pp for 2016. Across all but one specification (5), the 2016 effect was larger than the 2012 effect. Point estimates are statistically indifferent from zero for the years 2004 and 2008 except for a very small effect (0.8 pp) in specification (3), which disappears when adding socio-economic control variables (spec. 4). Finally, as a robustness check, we run the main specification for alternative treatment definitions. Fig. S3 in the SI shows parallel pre-treatment trends and the location of treated and control counties, where treatment is defined as the loss of coal labour hours from 2011 to 2016 instead of the loss of coal jobs. This specification includes more treated counties (N = 169) because counties where coal labour hours were reduced, but no layoffs occurred, are also included. Moreover, Fig. S4 reports results for yet another treatment definition: the closure of at least one coal mine from 2011 to 2016

(*N* = 131). The significance and the size of the 2012 and the 2016 effects remain very similar to specification (1).

Irrespective of the specification, the size of the effect is substantial when compared with average coal job losses in the treated counties (see Fig. S7b for the distribution of coal job losses). Job losses ranged from 1 to 3,218 per county, with an average of 265. The loss of 100 coal jobs translates to a 2.0 pp higher vote share for the Republican candidate in 2016 (1.5 pp in 2012), according to specification (1) in Table 1. Put differently, for each closed coal mine (see Fig. S7b for the distribution of coal mine closures), we find an increase in the Republican vote share of 0.9 pp in 2016 (0.75 pp in 2012). Importantly, these effect sizes suggest that it was not only affected coal miners who voted differently. In 2016, 5.07 million votes were cast in the treated counties. A difference of 5.4 pp represents 273,520 votes, which exceeds the 43,123 coal jobs lost in the treated counties by a factor of more than 6, and even the total 82,689 pre-treatment coal jobs by a factor of more than 3. In other words, while absolute job losses were small, the electoral response they triggered was large.

Table 1: Matched difference-in-difference results for different specifications. Main specification for matched to counties from all US states without (1) and with socio-economic controls (2). Coal state only specification without socio-economic controls (3), with socio-economic controls (4), and with state and year interacted fixed effects (5). Results for control counties matched in 2000 and 2004, instead of 2000 and 2008, without (6) and with socio-economic controls (7). All standard errors are clustered at county (or state for spec. 5) level.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VARIABLES	GOP	GOP	GOP	GOP	GOP	GOP	GOP
2004 effect	-0.000909	-0.000762	-0.00826**	-0.00512	0.00709	-0.00181	-0.00280
	(0.00361)	(0.00407)	(0.00373)	(0.00419)	(0.0137)	(0.00373)	(0.00408)
2008 effect	0.00605	0.00636	-0.00507	-0.00329	0.0203	0.0130	0.0115
	(0.00840)	(0.00830)	(0.00884)	(0.00867)	(0.0183)	(0.00864)	(0.00859)
2012 effect	0.0386***	0.0364***	0.0250**	0.0234**	0.0423**	0.0429***	0.0377***
	(0.0101)	(0.00986)	(0.0104)	(0.00993)	(0.0194)	(0.0102)	(0.00990)
2016 effect	0.0538***	0.0490***	0.0329**	0.0277**	0.0369**	0.0555***	0.0470***
	(0.0127)	(0.0122)	(0.0130)	(0.0121)	(0.0184)	(0.0128)	(0.0122)
Constant	0.542***	0.536***	0.537***	0.550***	omitted	0.542***	0.501***
	(0.00318)	(0.0584)	(0.00327)	(0.0687)		(0.00323)	(0.0738)
Specification							
Socio-economic controls	No	Yes	No	Yes	No	No	Yes
Coal states only	No	No	Yes	Yes	Yes	No	No
2000 & 2008 matching	Yes	Yes	Yes	Yes	Yes	No	No
2000 & 2004 matching	No	No	No	No	No	Yes	Yes

Fixed effects							
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County	Yes	Yes	Yes	Yes	No	Yes	Yes
State	No	No	No	No	Yes	No	No
State x year	No	No	No	No	Yes	No	No
Observations	1,630	1,630	1,630	1,630	1,630	1,630	1,630
R^2	0.500	0.523	0.512	0.543	0.759	0.493	0.518
Number of FIPS	326	326	326	326	326	326	326

Robust standard errors in parentheses

****** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$*

We test our data against three placebo tests. Fig. 3 first displays the results of specification (1) graphically (Fig. 3a) and then reports a series of placebo tests (Fig. 3b, see Methods for details)(Athey and Imbens 2017).

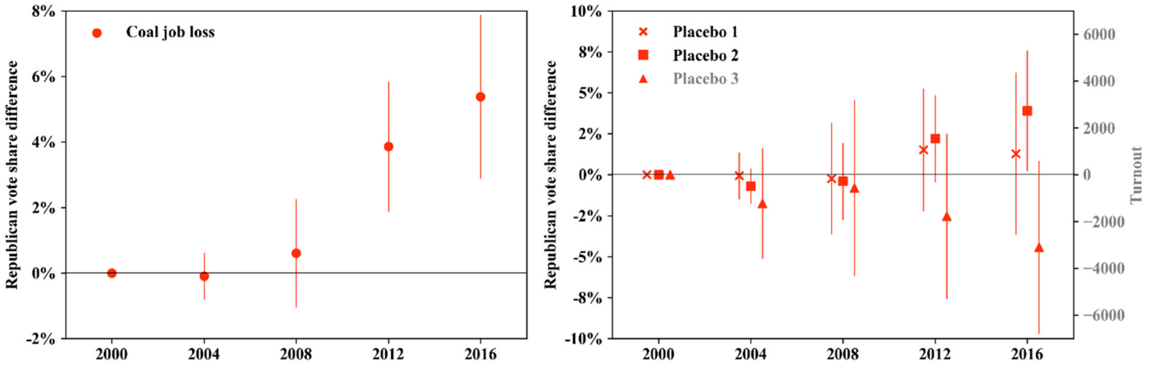

Figure 3: The effect of coal job losses on presidential elections: (a) effect size for presidential elections from 2004 to 2016 for the main specification (1); (b) and for three different placebo tests. Placebo 3 in grey is plotted on the secondary axis. The results (a) are robust when using the loss of coal mining labour hours or coal mine closure as treatment (Figs. S3 and S4) and are unaffected by third party vote shares (Fig. S6, Table S4). All treatment samples are matched individually. Displayed coefficients include a 95% confidence interval and are estimated with time and county fixed effects and standard errors clustered at county level.

We report three placebo tests for situations in which we expect to find a zero effect if both the underlying data and the empirical approach are valid. First, not all counties that reported coal jobs in 2011 experienced a subsequent decline in coal jobs. Hence, we check whether there is an effect if we define treated counties as those counties that experienced an increase in coal jobs from 2011 to 2016 (*N* = 40). We find a zero effect for these countries compared with most similar control counties in a matched DiD setting. Second, coal jobs in some counties followed an inverse U-shape from 2011 to 2016; that is, coal jobs continued to increase after 2011, peaked after 2012 and subsequently decreased. If the loss of coal jobs had an impact on the Republican vote share, we would expect these counties to show different effects in the 2012 and the 2016 elections. In this test, we therefore define those counties as placebo-treated, which experienced an increase in coal jobs from 2011 to 2014, followed by a decrease from 2014 to 2016 (*N* = 58). As expected, we find a zero effect for these counties in 2012 and a positive effect (3.9 pp) in 2016. However, this finding needs to be treated with caution for two reasons. First, there may be anticipation effects. If coal jobs were lost in many coal mining counties, there may have already been an electoral response in coal counties that were experiencing increases in coal jobs but feared future declines. Second, the zero-effect for 2012 only holds on a 5% significance level (or stricter), and the graphical evidence in Fig. 3b shows that there was a discernible change from 2008 to 2012, although not statistically significant. As a third and final placebo test, we check whether there was an effect on voter turnout. On the one hand, voter turnout is a variable that we do not expect to be affected from theory, and on the other hand, an effect of coal job loss on voter turnout would potentially confound our results. However, we find no effect on turnout in either election. Taken together, these results substantially strengthen the link between coal job loss and an increase in Republican vote shares in the 2012 and 2016 presidential elections.

3.2. Treatment intensity and regional differences

In the second step, we turn to treatment intensity. The intensity of coal job losses was highly uneven amongst counties (see Fig. S7). To account for this variation, we run two additional specifications (shown in Fig. 4a and b). First, we divide the sample into a weakly affected group with job losses below the median and a strongly affected group with job losses above the median. The sample of weakly affected counties (*N* = 81) includes all counties that lost from 1 to 94 coal jobs; the sample of strongly affected counties (*N* = 81) includes counties with more than 95 coal jobs lost. Fig. 4a shows that the total effect stemmed entirely from the counties with strong coal job losses. We observe an increase in Republican vote shares of 5.9 pp in counties with strong coal job losses in 2012 (6.2 pp in 2016). Residents of only weakly affected counties, however, did not vote statistically differently from the control counties (see Table S5 for regression coefficients). This result points to the importance of the magnitude of coal job losses for an electoral response.

Moreover, coal mining in the US varies substantially between the Montana mountain range in the west and Appalachia in the east (Kolstad 2017). Coal mines in the east are typically smaller and less productive than the western open-pit mines (see Fig. S2) and, therefore, more prone to closure. In the second specification, we thus allow for separate effects between eastern and western coal counties. Coal job losses above the median (strongly affected counties) are equally frequent among eastern and western counties (see Table S6), which means that, by splitting the sample geographically, we pick up variation that differs from the treatment intensity. The results are displayed in Fig. 4b and show that the loss of coal jobs in western counties (N = 28) did not affect voting outcomes. Whereas eastern counties with coal job losses (N = 135) showed an effect similar in magnitude to the estimated effect in the total sample (3.8 pp in 2012 and 5.1 pp in 2016; see Table S5). A note of caution applies when comparing eastern and western effect sizes, as they are based on different sample sizes.

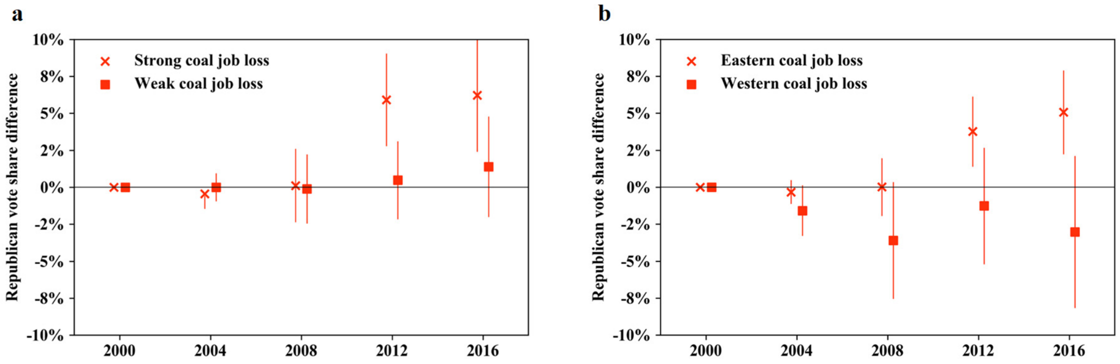

Figure 4: Effect sizes depending on treatment intensity and geographic location. (a) Effect size for strongly and weakly affected counties (demarked by the median decline in coal jobs); and (b) effect size for eastern and western coal counties (demarked by the Mississippi River). Parallel trends (Figs. S8 and S9) and coefficients (Table S5) are available in the SI. All treatment samples are matched individually. Displayed coefficients include a 95% confidence interval and are estimated with time and county fixed effects and standard errors clustered at county level.

3.3. Spillovers into neighbouring counties

Finally, in the third step, we investigate geographic spillovers. We expect such spillovers for two reasons. First, political science literature highlights the importance of social and cultural factors in explaining voting outcomes (Stokes 2016). We expect the cultural identity of coal communities to extend beyond county borders, into neighbouring counties without coal mines. Second, the 2017 American Community Survey shows that 24% of American workers worked outside their county of residence. Hence, coal miners may live and vote in counties without coal mines. To investigate spillover effects, we extend our analysis to counties that surround those with coal job losses, using three concentric perimeters of 50 km each. Fig. 5a displays the counties with coal job losses (dark red) and the counties without coal job losses in the three perimeters ranging from 50 km to 150 km (lighter red).

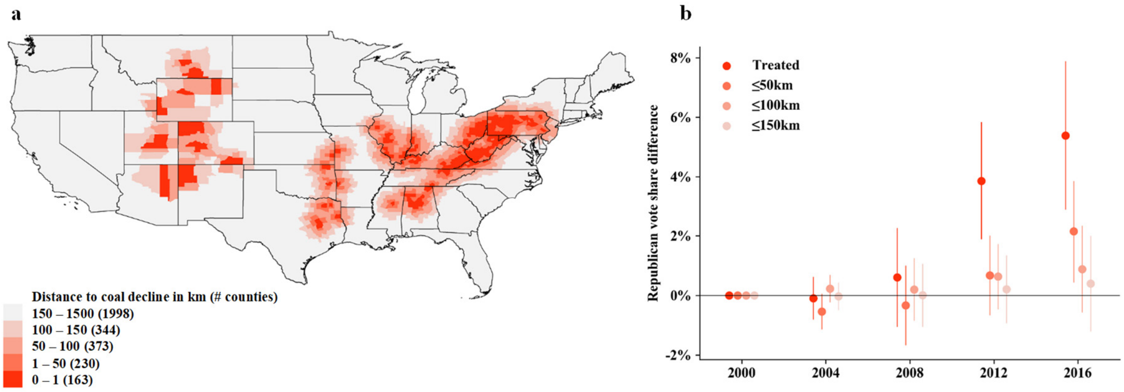

Figure 5: Effect spillover: (a) location of treated counties according to specification with perimeter distances measured between geometric county centres; (b) effect size for counties with coal job losses and counties in a 50 km, 100 km, and 150 km perimeter around those counties in US presidential elections from 2004 to 2016. All four treatment samples are matched individually (0 km perimeter corresponds to Fig. 3a).

Displayed coefficients include a 95% confidence interval and are estimated with time and county fixed effects and standard errors clustered at county level.

Whereas we find no spillover effect in the 2012 presidential elections, we identify spillovers in 2016 that extend up to 50 km around counties with coal job losses (Fig. 5b). The size of the spillovers is substantial. We find an increase in Republican vote shares of 2.2 pp in the 2016 election for counties without coal job losses that are within 50 km of a county with coal job losses. All other spillovers are statistically indifferent from zero (see Table S7 for regression coefficients). The existence of spillover effects is politically important because, in addition to the disproportionately strong backlash to coal job losses within affected counties, spillovers into neighbouring regions further increase the political cost of transitioning away from coal.

4. Discussion

Our analysis demonstrates that there was indeed an electoral response to the decline of coal mining jobs in 2012 and 2016 in the US: voters living in strongly affected coal counties were more likely to vote for the presidential candidates of the pro-coal Republican Party. The electoral response to coal decline was more than six times the number of coal jobs lost. We observe that the electoral response depended on the intensity of the coal decline and the location of the county: only counties with coal job losses above the median and counties east of the Mississippi river showed an electoral response. Lastly, we find that the effect spread beyond affected counties with spillovers into neighbouring counties within 50 km of the affected counties in the 2016 election.

The extent to which this electoral response to coal decline influenced the overall results of the 2012 and 2016 presidential elections remains unclear. On the one hand, West Virginia and Kentucky, the two states which lost the most coal mining jobs by a large margin (-12,310 and -

11,905, with third placed Pennsylvania at -2,899), were already Republican in 2008 and became more Republican with each election. On the other hand, four amongst the ten states that lost the most coal jobs are traditional swing states and two of these, Ohio and Pennsylvania, switched from a Democratic majority to a Republican one in 2016.

Moreover, it seems that President Trump’s pro-coal policies were unable to reverse the decline of coal (Mendelevitch, Hauenstein, and Holz 2019b). Coal jobs stabilized after 2016, but since 2016, seven of the ten largest private coal mining companies, representing 58% of total production, filed bankruptcy (Krauss 2019). Whether these trends dismantle the false promise of ‘bringing back coal’ and destroy its electoral appeal remains to be seen. Recent state elections may point in this direction. For instance, Democratic candidate Andy Beshear was elected Governor of Kentucky in late 2019, a state that the Republicans won by a margin of 31 pp in 2016 and which featured dramatic coal mining job losses.

While this paper establishes the existence of an electoral response and its size, future research should shed more light on the underlying mechanisms. For example, a remaining question is whether purely economic or also cultural factors trigger the electoral response and whether they need to be activated with an active political campaign. In case economic factors dominate, lump-sum transfers to and retraining programs of affected workers and communities might be the best option. For example, some scholars suggest that coal workers could transition to solar PV jobs and these opportunities would be quite large in Illinois, Indiana, Kentucky, Texas and Wyoming but low in North Dakota and Pennsylvania (Pai et al. 2020). If, however, the disruption of a cultural identity and a community fabric (Broz, Frieden, and Weymouth 2019) plays a major role, policy responses are more complicated and might (additionally) require managing the coal mining heritage. In either case, the recent wave of filed bankruptcies may complicate the issue as it has eroded the healthcare benefits of coal miners and pension plans of retirees (Krauss 2019).

In sum, our results indicate that coal phase-outs worldwide required to meet the SDGs may be politically costly. Research has an important role to play in providing inputs and developing strategies for politically feasible and carefully managed coal phase-outs and the design of just transitions, for example, in ongoing transitions in Australia, Germany and South Africa, or in the context of the proposed Green New Deal in the US, or the Green Deal for the European Union.

5. Methods

We structure the methods in two parts. First, we introduce the used data, and second, we discuss the empirical approach.

5.1. Data

This study uses data on coal mining, electoral outcomes and socio-economic indicators on a county-level (details are available in Table S1 in the SI). The coal data include annual data on production, employees, labour hours and active coal mines for all US counties from 2001 to 2016, which was sourced from the US Energy Information Administration (EIA). The election data were purchased from David Leip's US election atlas (proprietary). The data set provides the vote counts for each candidate in each county for the presidential elections from 1992 to 2016. We select the Republican candidate for each presidential election and divide the votes cast for this candidate by the total number of cast votes for each county. Depending on the election year and the county, third party votes (e.g. independent candidates) may distort the calculation of Republican vote shares. The third party vote share was 19.5% in 1992 and dropped subsequently and stayed at 1% to 6% from 2000 to 2016 (Fig. S5a in the SI). Moreover, there is no difference in third party vote shares between treated and control counties (see parallel trends in Fig. S5b), and our results are robust to excluding counties with over 10% of third party votes, on average, from 2000 to 2016 as shown in Fig. S6 (N = 159, or 5% of all counties). Based on these findings, we conclude that using the Republican vote shares does not pose an issue for this analysis. The socio-economic indicators are available online from the US Census Bureau, with the exception of unemployment data, which is from the US Department of Labor (see Table S1 for the sources for each variable). The established data set covers all US mainland counties (N = 3,142), excluding counties in Alaska, Hawaii and overseas territories, and spans five presidential elections from 2000 to 2016. We are limited in going back in time to 2000 due to the availability of socio-economic variables on the county level (see above and Table S1). However, as county-level electoral data are available before 2000, we show parallel pre-treatment trends starting in 1992 in the main text (see Fig. 2).

5.2. Empirical approach

We employ a matched DiD approach implemented in Stata/SE 16.0 (StataCorp LLC, College Station, TX, USA). We first discuss the general properties and assumptions of matched DiD approaches and then provide the methodological background to the three empirical steps, which we reference accordingly in brackets. We use the DiD terminology and denote counties with a loss of coal mining jobs as *treated* and counties that we compare those with as *control* in what follows.

To study policy and political questions in social science, it is rarely possible to employ a fully randomized experimental setting. Hence, to study the effect of an intervention or an exogenous change, researchers use DiD approaches combined with pretreatment matching to ensure the control group provides a valid counterfactual (Angrist and Pischke 2009; Athey and Imbens 2017; Craig et al. 2017; Wing, Simon, and Bello-Gomez 2018). Matching treated counties with control counties prior to the treatment is more flexible compared with including control variables in DiD estimations because no functional form needs to be specified. Nonetheless, we combine both approaches and report estimates with and without controls (socio-economic variables) in Table 1 in the main text (step 1). Note that we do not include educational attainment in the regressions when including controls due to the lack of data availability (see Table S2). We implement the matching with the Stata package psmatch2 (Leuven and Sianesi 2018). Specifically, we use propensity score one-to-one matching without replacement, which means that each treated county is matched to one control county. A control county can only be used once. Thus, our samples always include equal numbers of treated and control counties. The selection of socio-economic matching and control variables is derived from the literature on economic voting (see Note S2). Prior to the matching, the treated counties exhibit lower median household income (2000 and 2008), lower educational attainment (2000), higher unemployment rates (2000), higher shares of whites in the population (2000 and 2008), and lower Republican vote shares (2000). These differences are all significant ($p \leq 0.001$), and some of them are substantial. For example, in the year 2000, households in treated counties earned almost $5,000 less compared with the others, had 3 pp lower rates of over 25 year of age with a bachelor's degree and had 1.1 pp higher unemployment rates. The matching ensures that the treated counties are no longer statistically different to the control counties on any socio-economic variables in 2000 and 2008 (see Table S2). To verify the robustness of the results, we vary two matching dimensions (step 1). In the main specification, we match on all socio-economic variables and pretreatment outcomes (i.e. Republican vote shares) in 2000 and 2008. In an alternative specification (6–7 in Table 1 in the main text), we match in 2000 and 2004 instead to ensure that the results hold when the last matching year is further away from the treatment year. We only use educational attainment in 2000 in the matching because the data are only available for a subset of counties in later years (see Table S2). In a second alternative specification, we restrict the matching algorithm to choose only control counties from US states with at least one treated county. The intuition behind this robustness check is to account for potential state differences that may bias the results if the control counties are chosen from structurally very different states compared with the states of the treated counties.

After the matching, we run a simple DiD regression with equal numbers of treated and control counties as indicated for each specification in the main text. Formally, we estimate Eq. (1) with varying treatment definitions and matching scopes as explained above and in the main text:

$$GOP_{it} = \alpha T_t + \gamma C_i + \lambda E_t + \delta (T_t \times E_i) + \varepsilon_{it} \,. \tag{1}$$

In Eq. (1), *GOP* denotes the Republican vote share in election *t* in county *i*. Depending on the specification, control variables are added. For simplicity, Eq. (1) does not show control variables. *T* denotes treatment (i.e. coal job loss from 2011 to 2016 in the main specification), *C* denotes the county fixed effect, and *E* denotes the election fixed effect. Note that a term including socio-economic control variables would have to be added to Eq. (1) to represent specifications 2, 4 and 7 in Table 1 in the main text, and county fixed effects would have to be replaced by state fixed effects and a state and year fixed effects interaction for specification 5 in Table 1 in the main text.

In the main text, we report estimates of δ graphically for each election year. Standard errors are always robust and clustered at county level. For the exemplary presidential election in 2016, the estimated δ is given by Eq. (2):

$$\hat{\delta} = (GOP_{T,2016} - GOP_{C,2016}) - (GOP_{T,2000} - GOP_{C,2000}) \,. \tag{2}$$

In Eq. (2), *GOP* denotes the across county average of Republican vote shares, *T* denotes treated counties and *C* denotes control counties. The equation shows that results are cleared for the level difference in 2000, which is 0.

In general, DiD estimators rely on three conditions to be valid. First, treatment needs to be independent of the outcome. In our case, this means that county-level outcomes in US presidential elections must not influence county-level variation in coal jobs. This is plausible for at least two reasons. First, US counties mostly function as state administrative arms, providing only services mandated by higher administrative levels (Farmer 2018). In other words, county-level decision-making is limited and – with respect to energy policy – irrelevant. Second, even federal policy did not have an effect on the local incidence of coal job loss. In fact, coal jobs were lost where coal mining was economically unviable. In addition to international coal market developments, which are independent of US electoral outcomes, federal (and foreign) policies induced the deployment of renewable energy and unconventional shale gas technologies (Betz et al. 2015; Kolstad 2017; Mendelevitch, Hauenstein, and Holz 2019b). These alternative energy sources put competitive pressure on the coal industry. As a result, lower productivity coal mines started to close down. These were typically situated in Appalachia, where labour productivity is lower and mines are smaller compared with the western open pit mines (Fig. S2). Hence, federal policy did not affect the local incidence of coal job losses. Second, treated and control groups need to show a parallel trend in the outcome variable prior to treatment. In other words, absent treatment, both groups would have continued to develop identically. We use the matching described previously to ensure the parallel trends assumption is met. To check for it, we extend our sample backwards and show that parallel trends hold for all presidential elections from 1992 throughout 2008. Third, the treatment effect needs to be identical across all treated units (stable unit treatment value assumption [SUTVA]). By definition, SUTVA assumes no spillovers – both amongst treated units and from treated to untreated (and potential control) units. In our case, we suspect that spillover effects across county borders may have been present due to worker mobility. We use two empirical strategies to address the issue (one to address different effect sizes amongst treated counties, and one to test for spillovers from treated to untreated counties). First, we allow for differences in treatment intensity (step 2) and show that, indeed, the effect is only visible for those counties, which experienced coal job losses larger than the median. Second, we explicitly test for spillovers from treated to untreated counties (step 3). We define three consecutive 50 km perimeters (0–50 km, 51–100 km and 101–150 km) around the centroid of treated counties and test whether there is an effect for those counties. A county is within the perimeter if its centroid is no further from the next possible treated county centroid than indicated in the perimeter. For each perimeter, we exclude treated counties and counties from lower perimeters from the set of potential control counties to choose from in the matching. Fig. 5 presents the findings and shows that there are no effects for counties surrounding treated counties with the exception of the lowest perimeter in the 2016 presidential election. The implications of this are discussed in the paper.

Finally, we use three placebo tests to verify the robustness of our results (part of step 1). Placebo tests are a common tool to verify the findings by replacing the outcome by a pseudo-outcome where the true value of the estimand is zero (Athey and Imbens 2017). There are neither theoretical foundations nor empirical standards for a certain type of placebo test (Athey and Imbens 2017). Rather, the choice of applicable placebo tests depends on the case and the studied phenomenon. Here, we conduct one placebo test in the strict sense of the definition (reported as the third test in the main text). We replace Republican vote shares with voter turnout as the outcome variable. Given our conceptual model and the literature, there is no reason to expect a non-zero effect of coal job losses on voter turnout. In addition, we vary the treatment definition to create two pseudo-setups. First, we analyse whether there is a zero (or positive) effect for counties, which experienced an increase in coal jobs from 2011 to 2016. Second, we analyse the effect for counties that experienced a decline in coal jobs after the 2012 election. While we look at the opposite of our treatment in the first specification, we vary the treatment group according to the timing in the second. In the main text, all three approaches are referred to as placebo tests.

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7. Annex

Note S1

This note describes the decline of US coal mining and identifies the drivers. It thereby establishes that market forces were the main driver of coal decline and hence the decline was exogenous to the outcome variable, county-level voting results.

The largest share of US coal mining production is used for domestic power generation (Culver and Hong 2016). For instance, in 2018, US mines produced about 756 million short tons of coal, out of which 636 million short tons were used for US coal-fired power generation, and 50 million short tons for industry such as coke plants (U.S. Energy Information Administration 2019). The remaining coal production is exported (Mendelevitch, Hauenstein, and Holz 2019). Hence, the fast decrease in US coal mining production and corresponding job losses can largely be explained with the decrease in coal-fired power generation (Schlissel, Sanzillo, and Feaster 2018). Between 2011 and 2016, 46.4 GW of coal fired power plants closed, and coal demand by electrical utilities dropped from 932 to 678 million short tons (U.S. Energy Information Administration 2019). This trend continued under the Trump administration, with an additional 19.7 GW closed in 2017 and 2018, and a further drop in demand to 637 million short tons. This decrease in demand had a huge impact on the coal mining companies, with over two dozen going bankrupt (Sussams and Grant 2015). The combined market capitalization of the four leading coal mining companies in the U.S. dropped from $44.6 billion in 2011 to just $45 million in 2016 (Mendelevitch, Hauenstein, and Holz 2019), a decrease of almost 99.9%. The decline in demand for US coal happened for three reasons.

First, US electricity demand has been nearly flat, growing just 0.4% from 2008 to 2015 (Culver and Hong 2016; Houser, Bordoff, and Marsters 2017). At the same time, the global coal market shrank, due to a slow-down in Chinese coal demand, which depressed coal prices and reduced the market for US exports (Houser, Bordoff, and Marsters 2017). Second, during this time, electricity from other energy sources, such as natural gas, solar irradiation and wind, increasingly displaced coal-fired power generation (Sussams and Grant 2015; US Department of Energy 2017). Between 2007 and 2014, shale-gas production increased from 1.3 trillion cubic feet (TcF) to 13.4 TcF, and dropped to approximately half the price over the same period (Culver and Hong 2016). Natural gas, hence, became a competitor to coal-fired power production (Mayfield et al. 2019). For instance, between 2012 and 2016, Appalachian coal was outcompeted by natural gas prices in 43 of 49 months. Even cheaper coal fro Illinois and the Western basin was outcompeted in 28 of 49 months, over half of the time(Culver and Hong 2016). In 2016, natural gas was the largest source of electricity generation in the United States—overtaking coal for the first time (US Department of Energy 2017). At the same time, the levelized cost of electricity (LCOE) of solar and wind have become cost-competitive to coal (Culver and Hong 2016). Solar costs fell by 85% between 2008 and 2016 and wind costs fell 36% in the same period (Houser, Bordoff, and Marsters 2017). Third, federal and state policies played a role, however, rather in promoting these alternative energy carriers than in directly targeting coal-fired power generation or coal mining. While the Obama administration promulgated nine regulations directly addressing coal-fired power generation, only four took effect before 2016 (Mendelevitch, Hauenstein, and Holz 2019). For instance, the Obama administration introduced its key energy policy, the Clean Power Plan, in 2015 - four years after the start of the massive decline in coal mining. The introduction of another key policy targeting coal-fired power generation, the EPA’s Mercury and Air Toxics Standards (MATS), was delayed until 2016. Until the implementation of these policies, the EPA air-quality rules remained largely unchanged since 1990, which means that they predate the strong decline in coal after 2011 by almost two decades (Culver and Hong 2016). However, federal and state policies reinforced the development of alternative energy carriers discussed above (Stokes and Breetz 2018). Federal programs such as R&D funding or demonstration projects supported the uptake of cost-effective shale gas drilling. For instance, the Federal Energy Regulatory Committee partially funded the Gas Research Institute (GRI), an industry research consortium (Trembath et al. 2012). Further, three quarters of the states have renewable portfolio standards (RPS) or renewable portfolio goals, which have supported the growth of a renewable energy industry in the US(Carley et al. 2018). Besides RPS, federal tax credits and government research programs have supported the drop in wind and solar technology costs(US Department of Energy 2017).

The description above demonstrates that federal or state policy did not have an influence on the closure of *individual* coalmines, but influenced coal-mining production indirectly through supporting alternative energy carriers. These alternative energy carriers increasingly displaced coal-fired power generation, which reduced the demand for US coal. Two quantitative analyses support this argument. Coglianese et al. (2017) have shown that the decline in coal production from 2008 to 2016 is primarily caused by market forces, such as the declining price of natural gas relative to coal(Coglianese, Gerarden, and Stock 2017). The authors find that environmental regulations only played a small role. Hence, their findings suggest that the prospects for a rebound in coal production are slim, even in a more coal-friendly regulatory environment under the Trump administration. As more renewable and gas-fired generating capacity is added to the grid, coal faces increasing competition from these lower-cost alternatives(Schlissel, Sanzillo, and Feaster 2018). Evidence from Houser et al. (2017) supports these findings: They find that increased competition from natural gas is responsible for 49% of the decline in domestic US coal consumption, while the growth in renewables is responsible for 18%(Houser, Bordoff, and Marsters 2017). According to the authors, stable energy demand is responsible for 26%. Overall, these studies show that market forces were the main factor for US coal mining decline. To the extent it played a role, regulation promoted alternative energy carriers rather than targeting coal mining and power generation directly. The decline in US coal mining was therefore exogenous to local policy and consequently to local voting outcomes.

Note S2

We choose the county-level socio-economic variables based on established literature on economic voting (Margalit 2011; Stokes 2016), and the following theoretical considerations (we discuss the variables in the same order as they are listed in Table S1). We use median household income because extant literature has established differences in income as a major driver of voting choices: "pocketbook evaluations" are shown to influence vote choice (Healy, Persson, and Snowberg 2017). Based on this literature, we expect counties experiencing a decline in median household income to punish the incumbent political party. We expect a similar relationship between voting outcomes and the unemployment rate: Voting literature identified unemployment rates as a key indicator of vote choice (Grafstein 2005). Recent findings suggest that rising unemployment leads to negative evaluations of the economy and reduces the probability of supporting the incumbent government (Helgason and Mérola 2017). In addition, we include the share of manufacturing jobs to control for the potential influence of de-industrialization and re-location of traditional blue-collar jobs on voting outcomes (Inglehart and Norris 2016). For example, by matching on manufacturing shares, we ensure that we do not compare voting dynamics in coal counties with voting dynamics in "rust belt" counties (cf. Fig. 3a). Literature suggests that the industrial decline in rust belt counties partly explains shifts in votes towards the Republican Party (McQuarrie 2017). We expect counties with higher and/or declining manufacturing shares to punish the incumbent government. In the literature, shifts in voting outcomes are, however, not only explained as a purely economic phenomenon but as a result of social and cultural change (Inglehart 1990). Notably, progressive cultural change towards cosmopolitanism and post-materialism has triggered backlash among certain subsets of the population, especially white men and less educated citizens (Inglehart and Norris 2016). To account for these factors, we included two further socio-economic variables: the share of white population, and the level of education on county level. In line with theory, we expect counties with a higher share of white and less educated population to vote more in favor of the Republican Party. Finally, the rural-urban divide has received a lot of attention in literature on voting. We include population density to account for the impact of this divide (McKee 2008). We expect less densely populated counties to vote more in favor of the Republican Party than urban counties.

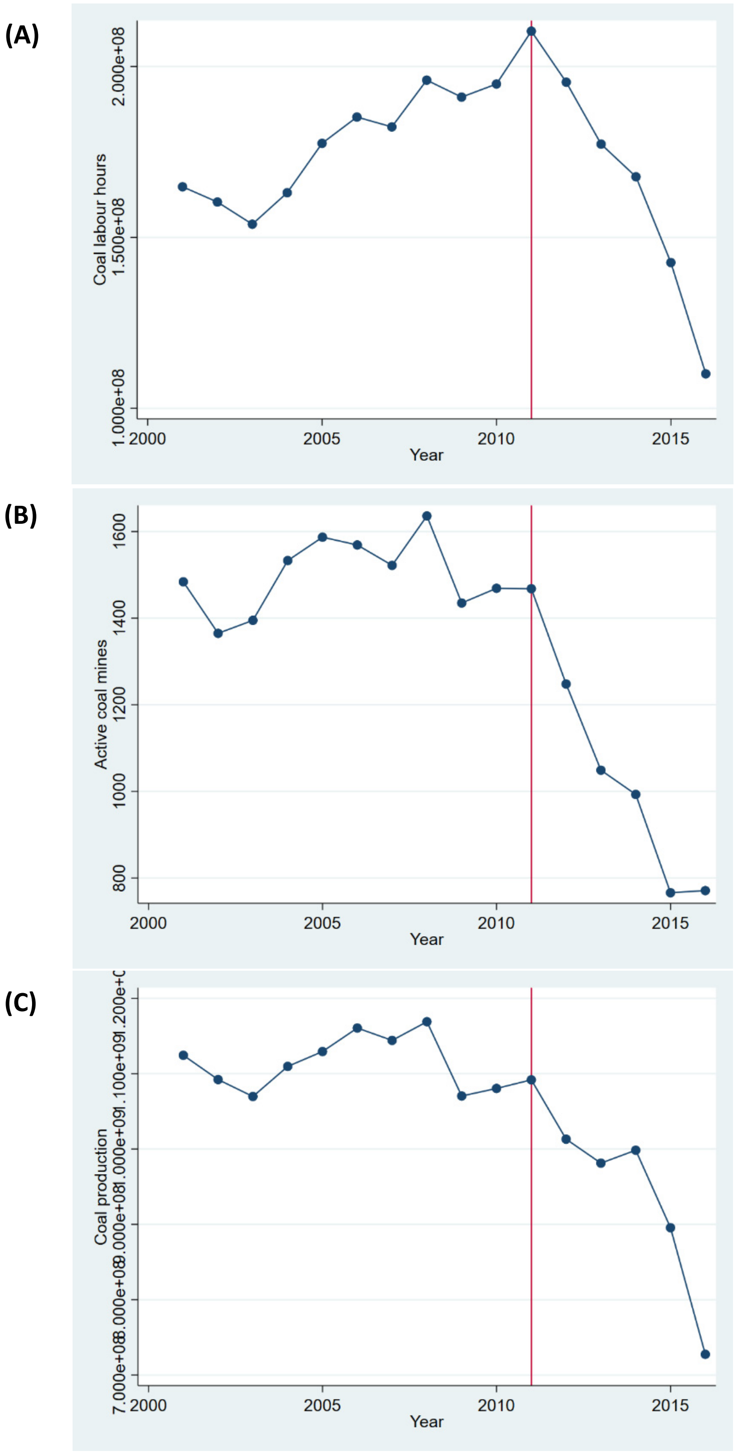


Figure S1: Evolution of the US coal industry from 2001 to 2016. (A) Labor hours in coal mining. (B) Number of active coal mines. (C) Coal production.

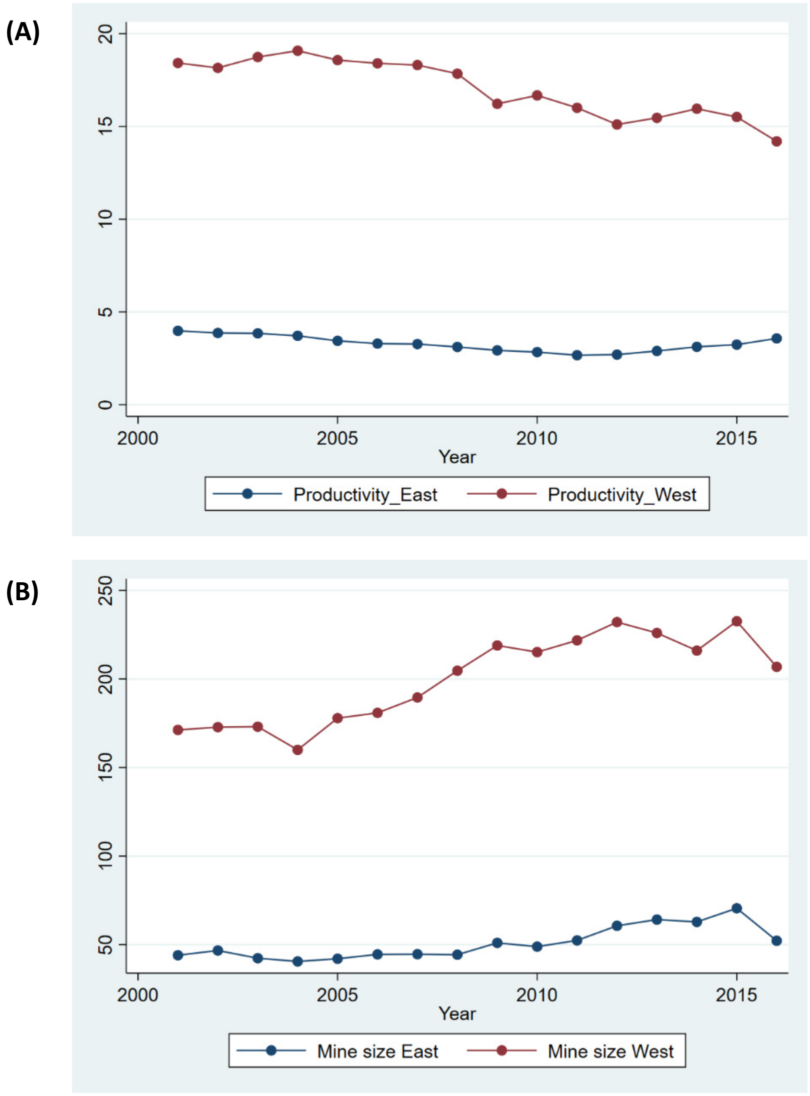


Figure S2: Differences between Eastern and Western coal industries. (A) Productivity measured in metric tons coal output per labor hour. (B) Mine size measured in employees per mine.

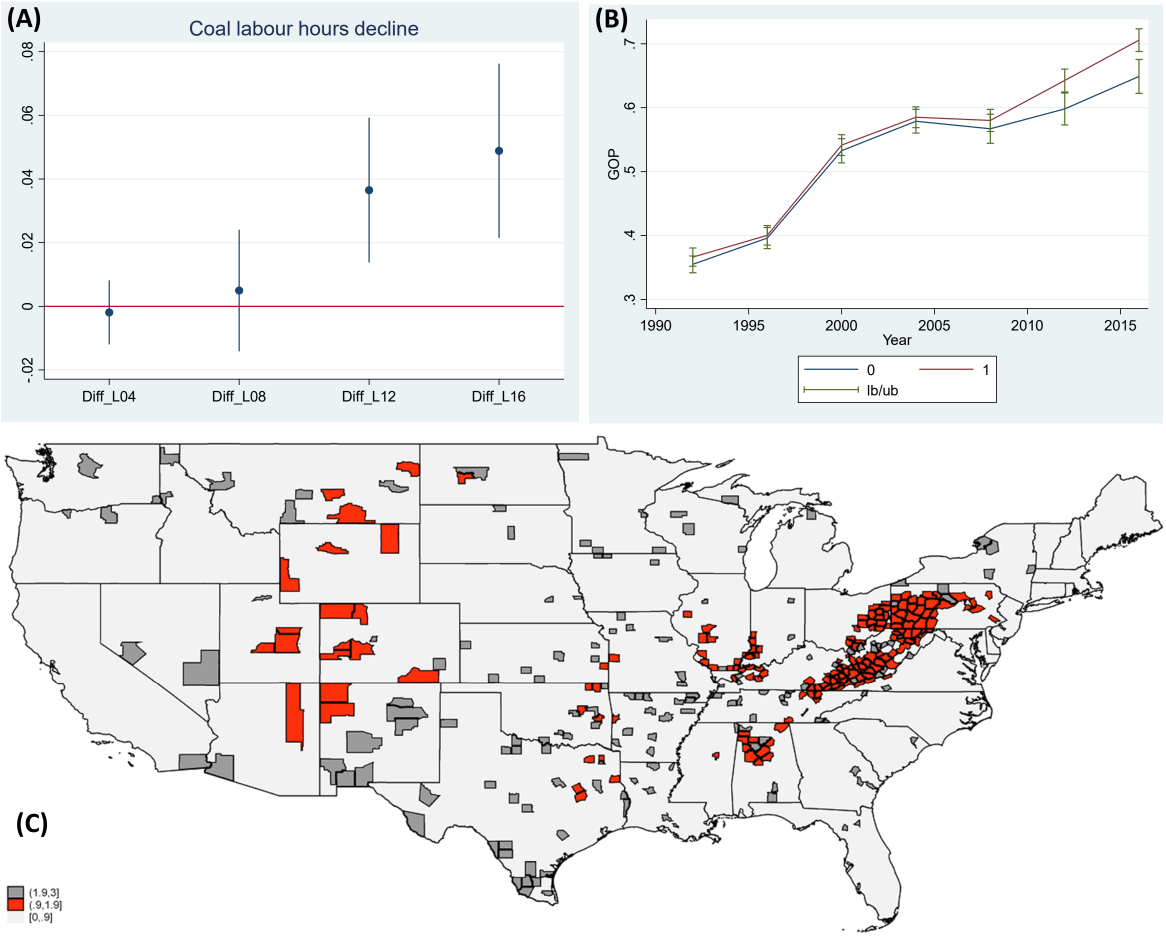


Figure S3: Effect size for counties with labor hours loss between 2011 and 2016. (A) Effect of coal labor hours loss on presidential elections from 2004 to 2016. (B) Parallel trend in presidential election vote shares from 1992 to 2016. 0 = control, 1 = treated, bars denote 95% confidence intervals. (C) Geographic location of treated and control counties. Treated counties are in red (N =169), control in dark grey (N = 169). Displayed coefficients include a 95% confidence interval and are estimated including time and county fixed effects and standard errors clustered at county level.

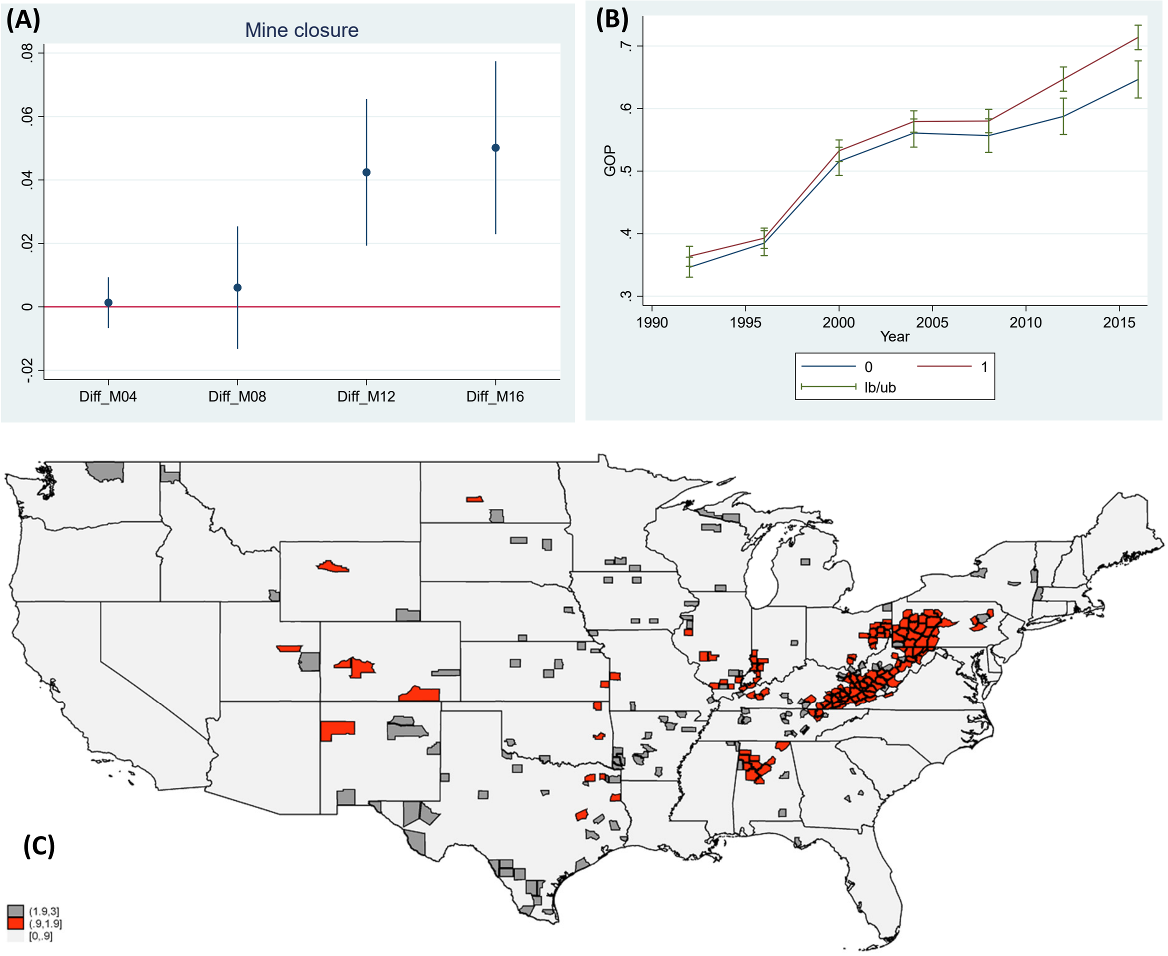


Figure S4: Effect size for counties with coalmine closure between 2011 and 2016. (A) Effect of coalmine closure on presidential elections from 2004 to 2016. (B) Parallel trend in presidential election vote shares from 1992 to 2016. 0 = control, 1 = treated, bars denote 95% confidence intervals. (C) Geographic location of treated and control counties. Treated counties are in red (N =131), control in dark grey (N = 131). Displayed coefficients include a 95% confidence interval and are estimated including time and county fixed effects and standard errors clustered at county level.

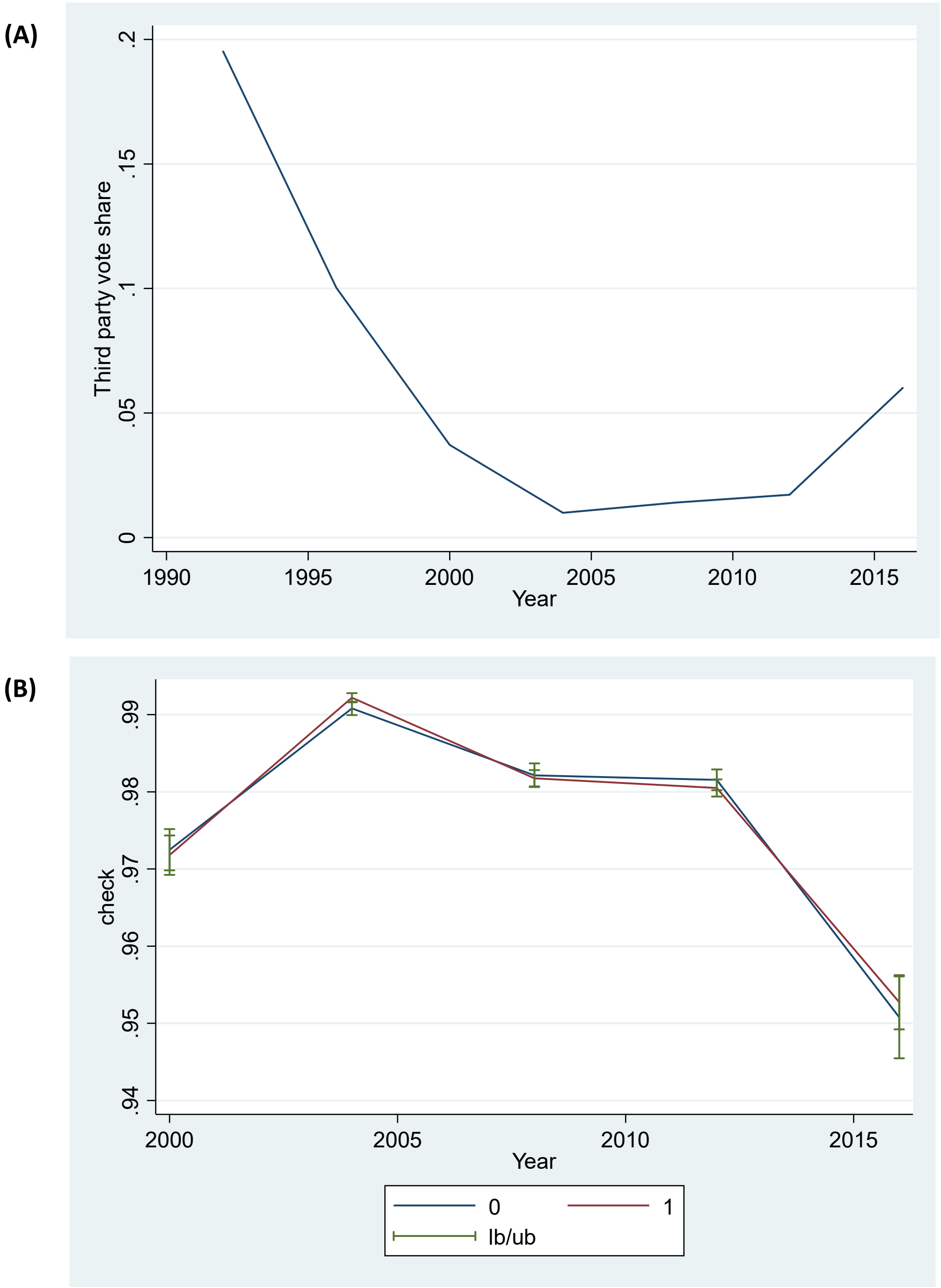
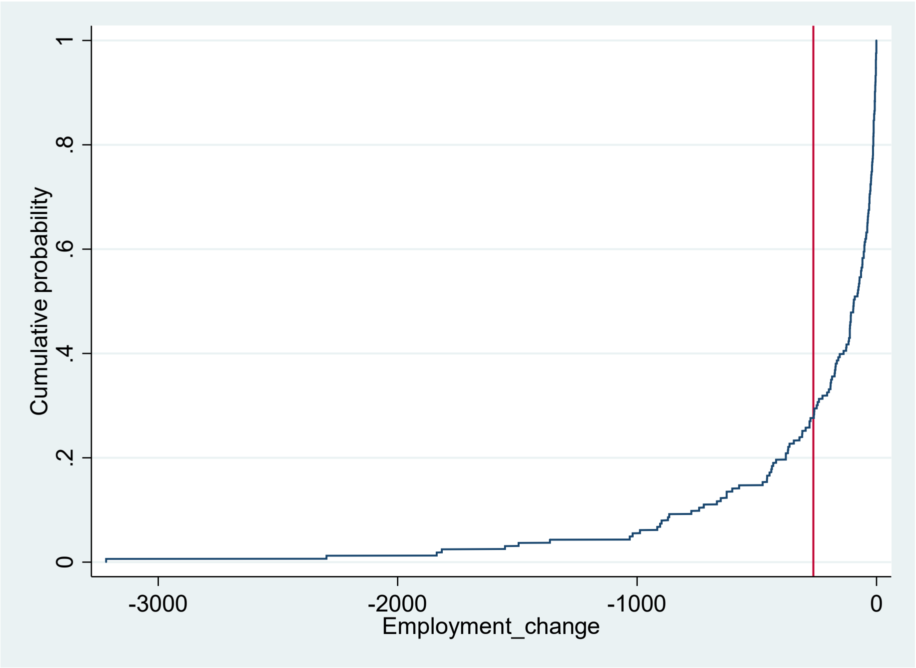


Figure S5: Third party vote shares. (A) Evolution of third party vote share from 1992 to 2016. (B) Difference of combined Democrat and Republican vote share between treated and control counties (main specification) from 2000 to 2016. 0 = control, 1 = treated, bars denote 95% confidence intervals.

Figure S6: Effect size for the main specification when excluding third party vote counties (see main text).

(A)



(B)

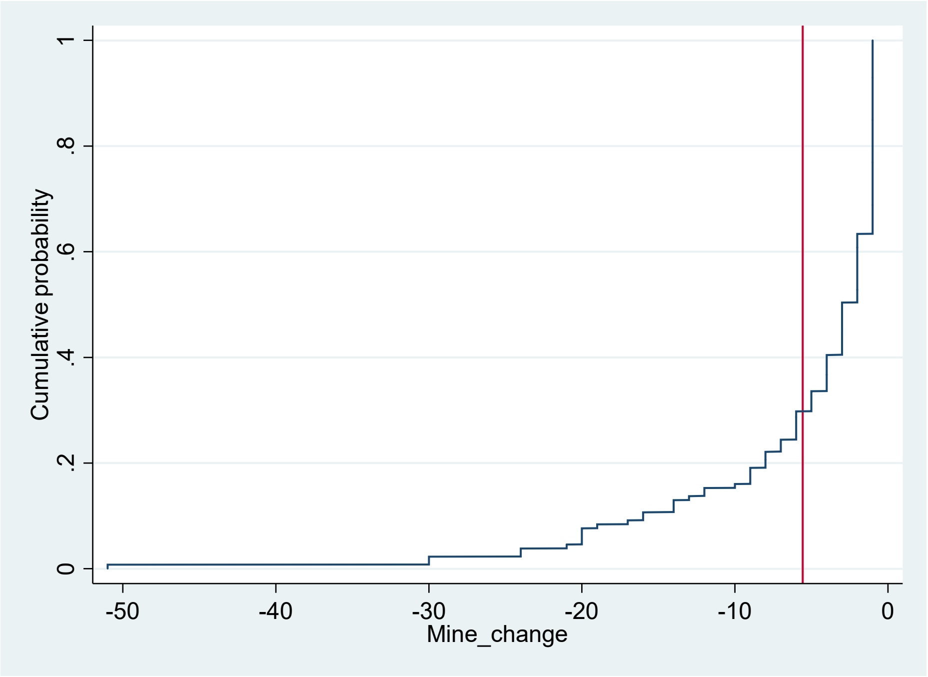


Figure S7: Treatment intensity. (A) Distribution and mean (red line at -265) of coal job losses for affected counties. (B) Distribution and mean (red line at -5.6) of coalmine closures for affected counties.

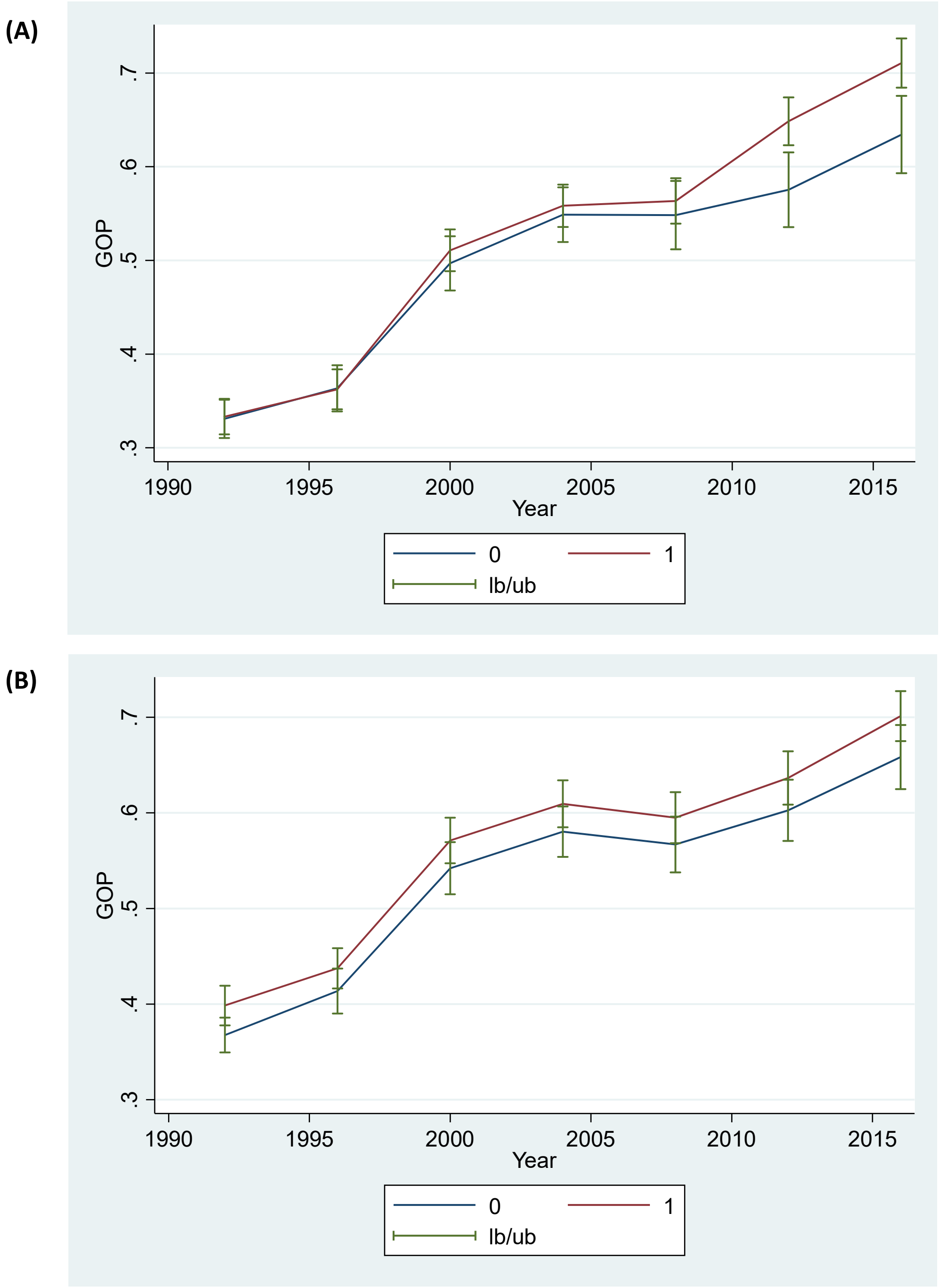


Figure S8: Parallel trends from 1992 to 2016. (A) Counties with a strong (>p50) coal job loss (strongly treated). (B) Counties with a weak (<p50) coal job loss (weakly treated). 0 = control, 1 = treated, bars denote 95% confidence intervals.

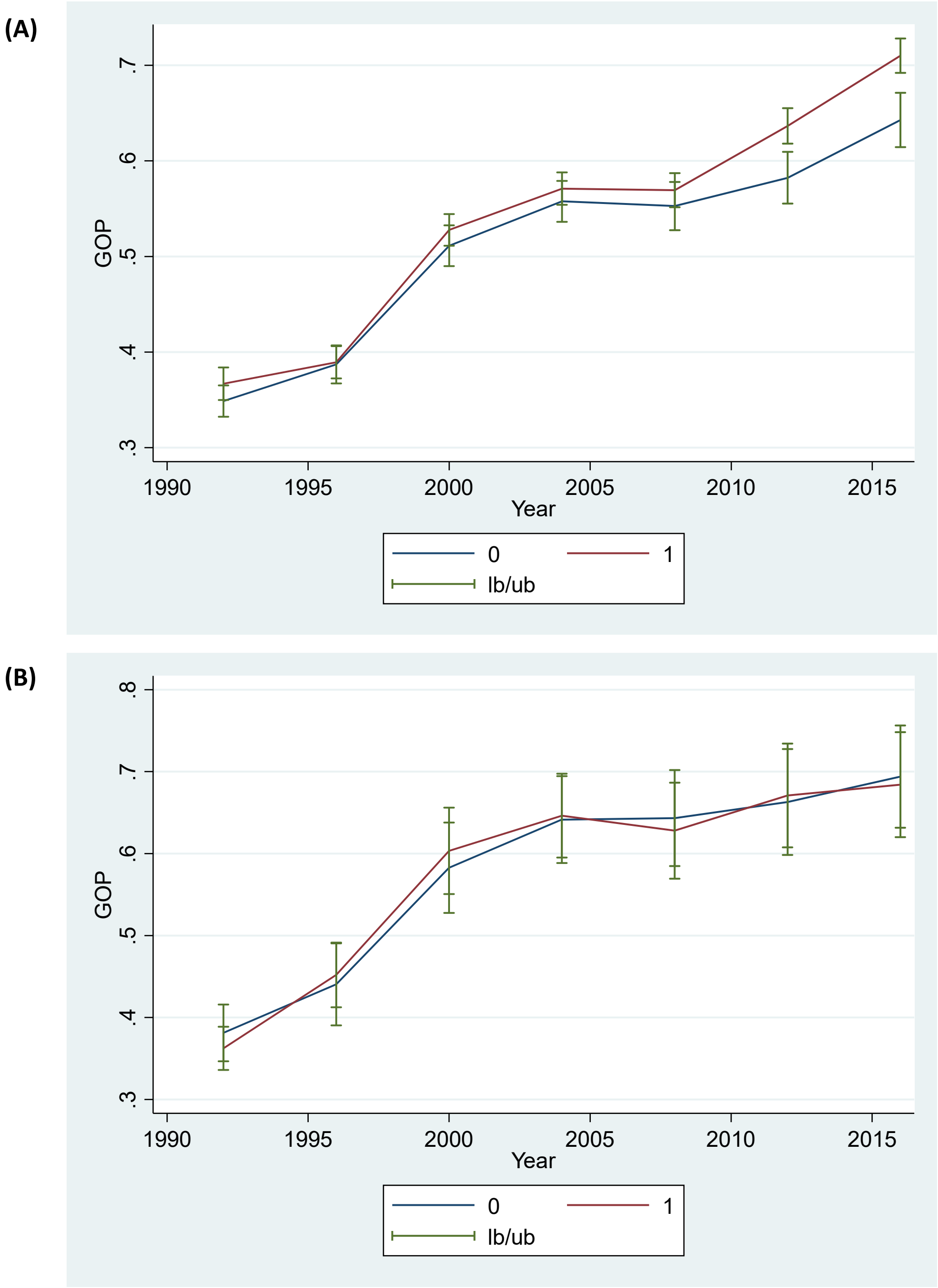


Figure S9: Parallel trends from 1992 to 2016. (A) Counties with coal job loss located in the East. (B) Counties with coal job loss located in the West. 0 = control, 1 = treated, bars denote 95% confidence intervals.

Table S1: Variable descriptions. All variables are on the county level.

	Variable name	**Description**	**Time range**	**Source**
Coal variables	Coal production	Total annual production of coal in short tons	2001 - 2016	The U.S. Energy Information Administration (EIA) and the U.S. Mine Safety and Health Administration
	Coal employees	Total number of employees in coal mines	2001 - 2016	
	Coal labor hours	Total labor hours in coal mines	2001 - 2016	
	Active coal mines	Number of active coal mines	2001 - 2016	
Election variable	GOP share	Republican party's presidential candidate election share (Republican votes divided by total cast votes per county).	1992 - 2016	David Leip's US election atlas
Socio-economic variables	Median household income	Income of all members in the household in the past 12 Months. The median income is based on the distribution of the total number of households including those with no income.	2000, 2008	U.S. Census Bureau: Small Area Income and Poverty Estimates (SAIPE) Program
	Unemployment rate	Labor force data annual average; Unemployed population divided by total number of employees	2000, 2008	The U.S. Department of Labor
	Manufacturing share	Total number of employees in the Manufacturing Sector (NAICS codes 31-33) divided by total number of employees	2000, 2008	U.S. Census Bureau: Quarterly Census of Employment and Wages
	White population	Share of white population (in % of total population)	2000, 2008	U.S. Census Bureau: Intercensal Datasets
	Educational level	Share of population of age 25 or higher that has achieved a bachelor or a higher degree (in % of total population)	2000, 2008	U.S. Census Bureau: Census and American Community Survey
	Population density	Total of population divided by county area in square miles	2000, 2008	U.S. Census Bureau

Table S2: Summary statistics for socioeconomic variables. Columns (1-5) provide the summary statistics for each variable across the entire sample. Columns (6-7) provide the p-values of a two-sided t-test before and after matching. The t-test indicates the statistical significance of the difference between treated and control counties for each matching variable.

	(1) Obs	(2) Mean	(3) Std. Dev.	(4) Min	(5) Max	(6) T-test pre-match	(7) T-test post-match
Income 2000	3071	36278.97	8933.405	15231	91210	0.000	0.795
Income 2008	3072	44026.3	11313.29	19182	111582	0.000	0.812
Education 2000	3070	.1642941	.0768845	.049	.605	0.000	0.883
Education 2008	770	.2605143	.0979567	.0797967	.69571	n/a	n/a
Pop. density 2000	3073	221.4033	1664.876	.0971701	67479.06	0.396	0.847
Pop. density 2008	3073	232.446	1699.081	.0911904	69514.76	0.361	0.957
Unemployment 2000	3073	.0436105	.0165999	.014	.175	0.000	0.239
Unemployment 2008	3073	.0580631	.0204767	.013	.226	0.092	0.272
White share 2000	3073	.8768477	.1550463	.1182913	1	0.000	0.475
White share 2008	3073	.8665028	.1558794	.0938383	.9968254	0.000	0.477
Manu. share 2000	3071	.1568301	.1279322	0	.7043269	0.317	0.990
Manu. share 2008	3072	.1243025	.1033554	0	.6801096	0.238	0.967
Rep. vote share 2000	3106	.5696694	.119414	.0895173	.9246935	0.001	0.908
Rep. vote share 2008	3107	.5685513	.1378352	.0653256	.9263804	0.390	0.761

Table S3: Socioeconomic variables as predictors of Presidential election vote shares. Specification (2) includes less observations because education data is only available for a subset of counties. Standard errors are clustered at county level.

VARIABLES	(1) GOP	(2) GOP
Income	-1.59e-06***	-1.68e-06***
	(2.17e-07)	(2.46e-07)
Pop_density	-9.81e-05***	-8.59e-05***
	(2.64e-05)	(2.60e-05)
Unemployment	-0.183***	-0.0929*
	(0.0448)	(0.0519)
White_share	0.440***	0.463***
	(0.0771)	(0.0774)
Manu_share	-0.0864***	-0.0862***
	(0.0173)	(0.0215)
Education		-0.290***
		(0.0437)
Year fixed effects	Yes	Yes
County fixed effects	Yes	Yes
Observations	15,378	9,998
R-squared	0.303	0.320
Number of FIPS	3,076	3,076

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table S4: Effect size excluding counties with more than 10% third party shares on average between 1992 and 2016. The dependent variable (GOP) is the local Republican vote share in the Presidential elections from 2004 to 2016. Effect sizes are the interaction of the year and treatment dummies.

	(1)
VARIABLES	GOP
2004 effect	-0.00228
	(0.00362)
2008 effect	0.00433
	(0.00855)
2012 effect	0.0372***
	(0.0103)
2016 effect	0.0521***
	(0.0126)
Constant	0.540***
	(0.00321)
Year fixed effects	Yes
County fixed effects	Yes
Observations	1,565
R-squared	0.525
Number of FIPS	313

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table S5: Effect size for four specifications; (1) strongly treated counties, (2) weakly treated counties, (3) Eastern treated counties, (4) Western treated counties. The dependent variable (GOP) is always the local Republican vote share in the Presidential elections from 2004 to 2016. Effect sizes are the interaction of the year and treatment dummies.

	(1)	(2)	(3)	(4)
VARIABLES	GOP	GOP	GOP	GOP
2004 effect	-0.00440	6.81e-05	-0.00326	-0.0158*
	(0.00510)	(0.00481)	(0.00409)	(0.00855)
2008 effect	0.00120	-0.00105	0.000129	-0.0359*
	(0.0126)	(0.0118)	(0.00997)	(0.0197)
2012 effect	0.0591***	0.00481	0.0377***	-0.0126
	(0.0158)	(0.0134)	(0.0120)	(0.0197)
2016 effect	0.0623***	0.0139	0.0507***	-0.0303
	(0.0194)	(0.0172)	(0.0144)	(0.0256)
Constant	0.504***	0.557***	0.519***	0.593***
	(0.00485)	(0.00435)	(0.00375)	(0.00683)
Year fixed effects	Yes	Yes	Yes	Yes
County fixed effects	Yes	Yes	Yes	Yes
Observations	810	810	1,350	280
R-squared	0.566	0.463	0.543	0.415
Number of FIPS	162	162	270	56

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table S6: Number of strongly and weakly affected counties and their geographic location for job losses and mine closure. Note that in splitting up the sample into strongly and weakly affected counties from job losses, we drop one county with job losses precisely at the median in order to have equal sample sizes to compare to each other.

	East	**West**	**Total**
Job losses	135	28	163
Strong	67	14	81
Weak	67	14	81
Mine closure	116	15	131
Strong	65	1	66
Weak	51	14	65

Table S7: Effect size into neighboring counties; (1) baseline (main specification), (2) 50 km perimeter, (3) 100 km perimeter, (4) 150 km perimeter. The dependent variable (GOP) is always the local Republican vote share in the Presidential elections from 2004 to 2016. Effect sizes are the interaction of the year and treatment dummies.

	(1)	(2)	(3)	(4)
VARIABLES	GOP	GOP	GOP	GOP
2004 effect	-0.000909	-0.00541	0.00231	-0.000322
	(0.00361)	(0.00306)	(0.00234)	(0.00237)
2008 effect	0.00605	-0.00333	0.00199	0.0000568
	(0.00840)	(0.00679)	(0.00533)	(0.00537)
2012 effect	0.0386***	0.00676	0.00630	0.00206
	(0.0101)	(0.00681)	(0.00557)	(0.00577)
2016 effect	0.0538***	0.0215*	0.00885	0.00400
	(0.0127)	(0.00871)	(0.00742)	(0.00815)
Constant	0.542***	0.566***	0.572***	0.561***
	(0.00318)	(0.00230)	(0.00192)	(0.00201)
Year fixed effects	Yes	Yes	Yes	Yes
County fixed effects	Yes	Yes	Yes	Yes
Observations	1630	2320	3750	3420
R-squared	0.500	0.502	0.329	0.189
Number of FIPS	362	464	750	684

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

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