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The framing of green innovations—a comparative topic modeling study on the public frames of the electric vehicle in Germany and UK

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ABSTRACT

In the innovation framing literature, scholars argue that green innovations are being challenged by legitimacy barriers associated with strong lock-in effects on the fossil-based economy. To break down barriers and create legitimacy, we stress the role of demarcation frames. Demarcation frames we argue are an important supplement to the established framing mechanisms that signal alignment and similarity with existing systems. Building on a machine-learning topic modeling approach, we investigate the development of the perception and meaning of the electric vehicle over a period of 27 years—i.e., its framing. By using public media data to undertake a systematic cross-country study in Germany and the UK, we show how and through which combinations of framing mechanisms the electric vehicle overcame the initial skepticism that was closely linked to the internal combustion vehicle. Hence, our research contributes to a better understanding of the framing processes around green innovations in the carbon-based economy. Firstly, we offer a novel analytical perspective focusing on the overarching public framing of green innovations. Secondly, we contribute to the literature by describing the theoretical implications and functionality of demarcation frames to overcome lock-ins. And thirdly, we discuss policy implications to support the dissemination of green innovations and propose future research avenues relevant for the green innovation and innovation framing field.

1. Introduction

This study focuses on the struggle for legitimacy of the electric vehicle (EV) in the public media debate over the course of 27 years in Germany and the UK. From the classical innovation literature, we know that innovations initially suffer from a lack of legitimacy, meaning that there is a perceived uncertainty about their function, market opportunities, and future viability. This is reflected in the variety of ambivalent frames and in specific critical frames that act as legitimacy barrier and question the usefulness of innovations (Aldrich and Fiol, 1994; Kaplan and Tripsas, 2008). Such critical frames are a serious barrier for innovations and especially for green innovations such as electric mobility, which have long been slow to spread despite their sustainability potential (IEA, 2018; Rietmann et al., 2020; Seto et al., 2016; Sovacool and Axsen, 2018). Recent literature about green innovations points to this ambivalence but also shows the variety of positive effects, including reducing pollution, saving energy, and gaining competitive advantage (Gohoungodji, N'Dri, Latulippe & Matos, 2020; Karimi Takalo, Sayyadi Tooranloo & Shahabaldini parizi, 2021). But the question remains of how the initial skepticism about the functionality and potential of green innovations can be reduced so that the positive effects be fully unleashed.

From the seminal work of Markard et al. (2016), as well as Kaplan and Tripsas (2008), we know that the reception of innovations and there subsequent success are reflected by the variety of associated frames (see also Liu et al., 2021). This means that there are multiple frames around an innovation pointing to different characteristics and describing technologies in very different ways—for instance, in more positive or more negative terms, as an innovative or immature technology, as an opportunity or a threat, or more abstractly, as being familiar or misaligned with the established system (Gurses and Ozcan, 2015). In our paper, we apply a similar perspective that underscores the plurality and overall framing of green innovations, because it enables us to capture the complexity of green innovations frames and thereby helps to identify legitimacy barriers and also alternative framing mechanisms that contribute to mitigating and overcoming these barriers. The

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development of such framing mechanisms is especially relevant in contexts with strong technological lock-in, as in the case of the mobility system and the fossil economy (Seto et al., 2016). Against this backdrop, we ask: How can green innovations overcome barriers and gain legitimacy in markets with strong lock-in effects and which framing mechanisms are associated with this process?

To answer these questions, we study the public framing of the electric vehicle within the automotive sector. This sector is an exemplary case of fossil lock-in, because it has been almost entirely dominated by the internal combustion vehicle (ICV) for decades (Urry, 2004). However, the extent of lock-in may vary in different contexts depending, for instance, on the importance of the domestic automotive industry (IEA, 2018). Therefore, we compare two different cases, the UK and Germany, which also opens up the possibility of gaining more generalized insights. To apply such a cross-country approach, we study the frames associated with the EV in the public media debate. The crucial advantage of media data is that they represent a time-authentic data source that includes a wide range of opinions and a diversity of actor groups and therefore speak to the ambiguity of technological frames (Bohn and Braun, 2021; Hielscher and Sovacool, 2018). To cover the critical years of EV establishment, we analyzed the public discourse between 1990 and 2017. Altogether, we collected 31,353 media articles from six national newspapers from both Germany and the UK. To systematically compare the cases, we chose topic modeling, an unsupervised machine-learning approach that is especially suitable for uncovering the variety of arguments in large text corpora (Hannigan et al., 2019). In this way, we were able to capture and contrast the frames related to the EV as well as the underlying mechanisms.

Our findings show the diversity and contradictory nature of the EV framing: there are more positive and more critical frames (promising for the future vs. unsustainable), frames that question the innovativeness of the EV and others that support it (low range vs. light and silent), and frames that point to barriers or signal alignment (risk or opportunity for the domestic industry). However, we found rather few frames that stressed the familiarity of EVs and ICVs as described in the literature (i.e., substitute and complementary frames). On the contrary, especially in the 1990s, the framing of the EV was characterized by the dominance of demarcation and devaluation frames and thus by a rather critical comparison of EVs and ICVs; this occurred to an even greater degree in Germany than in the UK. On the one hand, we find in our study that devaluation frames exhibit high persistence over time. On the other hand, we discuss the role of demarcation frames as an important framing mechanism that helps to promote the dissemination of green innovations. Additionally, we also show the more recent emergence of frames portraying the EV as a sustainable future technology that is politically supported and favorable both for society and the economy (political, social, and economic alignment).

With our study, we aim to make theoretical, methodological, and practical contributions to the innovation framing and sustainability literature. From a theoretical perspective, we contribute to innovation framing research by incorporating the birds' eye perspective of the dynamic public framing of a green innovation (Markard et al., 2016). Thereby, our exploratory study identifies demarcation frames as a barely described framing mechanism that point to the role of confrontation in order to dispel the barriers and lack of legitimacy of green innovations. In this regard, our study contributes to recent calls by policy, society, and academia to further investigate how green innovations can overcome barriers and gain legitimacy in the fossil-based economy (e.g. Gohoungodji et al., 2020; Karimi Takalo et al., 2021). Methodologically, we explore the potential of a machine-learning topic modeling approach, which is promising for the literature aiming to conduct comparative studies, either in different countries or on different green innovations. Our approach also offers practical insights, helping to develop supportive strategies for fossil-free technologies and thus having implications for policy actors.

To accomplish these goals, Section 2 provides an overview on the state of the research on the framing of innovation literature and summarizes different framing mechanisms. Section 3 outlines the methodological approach of the study, based on topic modeling and public media discourses. Section 4 presents the findings about the dynamic framing of the EV and the importance of demarcation and devaluation frames. Section 5 discusses our results against the background of the theory and offers policy implications. The final section summarizes the study and discusses limitations and future research areas.

2. State of research: the framing of innovations

The concept of framing has had a remarkable career in the innovation and sustainability literature (Kaplan, 2008; Lefsrud and Meyer, 2012; Markard et al., 2016; Rosenbloom et al., 2016). On the one hand, the framing approach is used to explain how actors strategically communicate about innovations in order to decrease or increase their legitimacy (e.g. Benner and Tripsas, 2012; Gurses and Ozcan, 2015; Rosenbloom et al., 2016). On the other hand, this research also emphasizes the general importance of frames as powerful structures that "guide people to select certain aspects of the environment" (Leonardi, 2011, p. 349) and thus have an essential role in technology change processes (Kaplan and Tripsas, 2008).

Goffman defines frames—in his seminal book about framing and frame analysis—as "schemata of interpretation" (Goffman, 1974, p. 21). Adapting this definition to address technology-oriented questions, Orlikowski and Gash (1994) define technological frames as containers for meaning "not only of the nature and role of the technology itself, but [also of] the specific conditions, applications and consequences of that technology in particular contexts." (1994, p. 178). In the context of innovations, frames reflect what is at the heart of novel technologies, what the key problems and questions are, and what the general role of the technology in solving problems or raising new questions is. Hence, frames point to very different and maybe opposing arguments and thus illustrate the ambivalent character of innovations (Leonardi, 2011). Consequently, the literature differentiates between frames that signal positive or negative meanings, for example, between biogas as a threat to conventional farming and food security and biogas as a sustainable future technology (Markard et al., 2016). As argued above, more positive interpretations point to the legitimacy of innovations and more negative ones de-legitimate them (Gurses and Ozcan, 2015; Rosenbloom et al., 2016).

One of the most frequently mentioned positive innovation frames in the literature is the pioneer framing, which is associated with terms like ground-breaking and future technology (Rosenbloom et al., 2016; Sovacool and Axsen, 2018) and points to the revolutionary character of an innovation (Gurses and Ozcan, 2015). However, such frames alone are not sufficient to demonstrate the novel functionality of innovations and to prevail against established technologies. Hargadon and Douglas (2001) used the example of Thomas Edison and the electric light to argue that, in order to overcome barriers and to establish an innovation in an existing technological system, it is necessary to present it as very similar to the established technology. Edison introduced the electric light as a functional substitute for the established gas lamp and so he "ensured his users would both recognize the purpose of his innovation at the outset and know without reflection how to use it in their everyday lives" (Hargadon and Douglas, 2001, p. 498).

Gurses and Ozcan (2015) challenged this assumption and argued in their study of the US cable TV market that a framing that presents a new technology as being a substitute may provoke strong resistance, because it may be interpreted as a threat by incumbents. Therefore, they suggest framing an innovation rather carefully, especially when there are strong incumbents and powerful regulations. In such cases, the authors suggest that it is useful to respond with a two-stage strategy. First, it is important to enter a market cautiously and to frame a new technology as being a complementary technology and therefore as something that does not threaten the established system. For instance, the introduction of cable

TV in the US "was aligned very carefully with the frame of the regulators and the interests of the incumbents" (Gurses and Ozcan, 2015). Secondly, after a certain degree of legitimacy has been achieved, cable TV was reframed by the proponents as being better TV and a revolutionary technology. Thus, in the second stage, they suggest using a combination of substitute and pioneering frames. By following this two-stage strategy, cable operators were not only able to erode the legitimacy advantage of the old technology but also to increase the spread of cable TV and further establish pay cable TV (Gurses and Ozcan, 2015). The merit of the approach adopted by Gurses and Ozcan (2015) is that it introduces a more processual perspective on framing that builds on alignment and complementary frames as well as substitute and pioneering frames. However, the cable TV market was highly regulated and the findings are therefore especially applicable in similar cases, like in the medical field. But to our knowledge, they have not yet been tested in a field where general technological openness exists at the regulatory level—as in the case of green innovations.

That brings us back to the automotive market. In an early study about electric vehicles, Cowan and Hultén (1996) critically reflected on the chances of the EV in the automotive sector. They argue that lock-in is omnipresent in this sector and interpret the ICV as an all-purpose vehicle—it is suitable for use in cities but also in rural areas—which hardly leaves room for a complementary innovation. In other words, the conventional interpretation of the car has blocked a new, more open and sustainable interpretation of the car (Canzler et al., 2008).

Thus, we learn from the literature that there are very different framing mechanisms related to innovations (Table 1). On the one hand, there are rather technological-focused mechanisms—like substitute, pioneer, and complementary frames—which address the relationship between novel and established technologies. On the other hand, there are alignment (and of course misalignment) frames that focus on conformity with social, political, and economic principles and institutions, like positive effects on health due to the introduction of the diesel particulate filter (Guérard et al., 2013).

Table 1
State of the art of innovation framing mechanism.

Framing mechanism	Explanation	Examples studies
Substitute	Pointing to familiarity with the existing technology	Electric light (Hargadon and Douglas, 2001), digital cameras (Benner and Tripsas, 2012)
Pioneer	Pointing to future associations, and the "revolutionary" and novel character of innovations	Solar power (Rosenbloom et al., 2016), alternative fuel vehicles, (Sovacool and Axsen, 2018), nanotechnology field (Granqvist and Laurila, 2011), cable TV (Gurses and Ozcan, 2015), mobility (Bergman, 2017), fracking (Nyberg et al., 2020), bioenergy (Kivimaa and Mickwitz, 2011)
Complementary	Pointing to familiarity with, and supplementing the existing technology	Cable TV (Gurses and Ozcan, 2015), mobility (Cowan and Hultén, 1996)
Alignment	Conformity to economic, social and political/ regulatory institutions	Diesel particulate filter (Guérard et al., 2013), bioenergy (Markard et al., 2016), solar power (Rosenbloom et al., 2016), digital cameras (Benner and Tripsas, 2012), fracking (Nyberg et al., 2020), cable TV (Gurses and Ozcan, 2015), electric light (Hargadon and Douglas, 2001)
Misalignment	Incongruent to economic, social and political/ regulatory institutions	Bioenergy (Markard et al., 2016)

However, the findings of recent studies draw somewhat different conclusions about the "optimal" framing of (green) innovations (see above, i.e., complementary or substitute frames). As argued above, this is especially relevant for the early phase of innovations, when green innovations are likely to encounter strong resistance from proponents of the conventional fossil system (Lefsrud and Meyer, 2012). In this regard, there is also a lack of knowledge that help to soften the resistance or end it altogether. Furthermore, we argue that while recent studies emphasize framing as an important mechanism, they mostly focus on specific actor groups like entrepreneurs, and rarely examine the overall public perspective, which is particularly relevant for sustainability issues and cases with strong lock-in (Seto et al., 2016). Given the importance of overcoming strong persistence and lock-ins in the case of sustainability and climate change, our goal is to uncover how green innovations like the EV can overcome barriers and gain legitimacy in the fossil-based economy. Thereby, our empirical approach focusing on public frames complements recent studies about green innovations that focus mainly on technical obstacles (Gohoungodji et al., 2020).

3. Methods and case description

3.1. The automotive sector in Germany and the UK

The EV in the automotive sector is an ideal context for studying the framing of innovations and how green innovations could overcome lock-in. More than ninety-nine percent of cars worldwide are based on internal combustion engines fired by fossil fuels, which are responsible for around 20 percent of global greenhouse gas emissions (Worldbank, 2018). This is noteworthy because the automotive sector has made next to no contribution to reducing emissions over the last 25 years. Urry describes the lock-in in this sector by introducing the concept of the "steel-and-petroleum car" (2004, p. 27), which stands not only for a virtually "unlimited range and freedom" but also for the total domination and the fossil lock-in of the automotive industry. However, in the last three decades, climate change issues have become increasingly important. And the influential Californian clean air legislation in 1990 sparked off a technological innovation race between several different low carbon vehicle technologies. Attention has shifted from one alternative fuel technology (hybrid car, hydrogen car, etc.) to another in successive waves (Melton et al., 2016). After an early EV boom phase in the 1990s and its rapid end, the EV has become "the automotive industry's 'winner' in the low carbon vehicle technological innovation race" (Bergman et al., 2017, p. 166). However, it is still a niche market, with often less than a 1 percent market share in the main industrial countries (IEA, 2018).

Nevertheless, the EV is a technology that has received a great deal of attention and therefore lends itself particularly well to investigating framing processes. As argued above, we assume that lock-in varies in different contexts depending on the importance of the domestic automotive industry (Gurses and Ozcan, 2015). Therefore, we compare two different cases, the UK and Germany. Both contexts are comparable, as they were bounded by the same EU law and environmental policy targets until recently. By contrast, they vary considerably in the size of their domestic automotive industry. While the UK was one of the top 3 car manufacturers in the world until the 1960s, the industry has lost much of its importance in recent years (turnover of 77.5 billion pounds in 2017, BEIS, 2018). In contrast, one in six passenger vehicles worldwide was produced by German car manufacturers (Mazur et al., 2015, p. 90). The turnover of the German automotive industry in 2017 was EUR 426 billion and the whole industry, including suppliers, employed roughly 800,000 people (VDA, 2018). Another indication of lock-in strength is national policy. In recent years, both the UK and Germany have introduced several electromobility incentives, because the EV is seen as a technology that is contributing to reducing carbon dioxide emissions in the automotive sector (BEIS, 2018; UBA, 2016). The UK government was faster and established an EV grant scheme in 2011, whereas the

environmental bonus grant scheme in Germany was not introduced until five years later. Additionally, the UK government has announced a ban on the sale of petrol and diesel cars in the UK that will apply from 2040 (Energy_UK, 2018). In summary, we argue that both countries are characterized by strong inertia, yet in Germany, there is more pronounced lock-in than in the UK.

3.2. Data and topic modeling approach

Our methodological approach aims to capture and compare the frames connected with the electric car in Germany and the UK. In order to identify the frames, we relied on mass media texts because they are "ideal for studying long-term changes in attitudes" (Lupton, 2013, p. 22) and therefore frequently used in the framing literature (Meyer and Höllerer, 2010). We collected a longitudinal data set consisting of 31,353 articles from the most important national newspapers in terms of circulation. The newspapers have a variety of readership profiles in terms of political orientation (Table 2).

To select the newspaper articles for analysis, we conducted searches in public databases (Nexis, Factiva, WISO) using two groups of keywords: (1) "electric,'' "electro,'' or "electronic" and (2) "mobility,'' "car,'' or "vehicle'' and the respective German equivalents. The frequency of articles per year varied considerably, depending on the development phases of the EV (Fig. 1). Building on preceding analyses of society's attention to EVs (Melton et al., 2016), we differentiated the development between four temporal brackets: (1) the first EV heyday from 1990 to 1997, (2) the early end of the EV, from 1998 to 2004 (popularly described in the documentary "Who Killed the Electric Car?"), (3) the renewed interest starting around 2005 and lasting until 2011 (Dijk et al., 2013), and (4) a period of growing establishment, due to international legislative initiatives for EVs and to scandals involving diesel cars (2012–2017). We ended our analysis in 2017 because after that the diffusion rates increased significantly and the EV had in all likelihood overcome the initial barriers (IEA, 2018).

Due to the large amount of data, we chose a topic modeling approach. Topic modeling algorithms are statistical methods that compare the vocabulary of texts and thereby uncover latent patterns (Fig. 2). These patterns, known as topics, are represented as clusters of words that co-occur frequently throughout the corpus. The findings of a topic modeling analysis contain a number of topics, each described by a number of words of different weights. As each document is characterized by a number of topics (with specific weights), topic modeling also allows us to analyze the salience of topics over time.

Topic modeling is a relatively new method in innovation and management studies (Hannigan et al., 2019; Schmiedel, Müller & vom Brocke, 2019). However, its usefulness has been shown in recent studies, for example for mapping and analyzing frames (Fligstein et al., 2017), the content of patents (Kaplan and Vakili, 2015), or "simply" the general content of books (Blei, 2012). Topic modeling is an unsupervised machine-learning technique, meaning that all topics depend only on the co-occurrence of words within the documents and not on predetermined guidelines. One of the key features of topic modeling compared to

Table 2
Data basis, number of articles and political view.

Country	Newspaper	Years covered	Political orientation	Number of articles
UK	The Times	1990–2017	Conservative-liberal	2051
UK	The Guardian	1990–2017	Left-liberal	2679
UK	Financial Times	1990–2017	Economic-liberal	3385
UK	The Daily Telegraph	2000–2017	Conservative-liberal	1527
UK	Daily Mail and Mail on Sunday	1992–2017	Conservative	899
UK	The Independent	1990–2017	Liberal	1792
Germany	Frankfurter Allgemeine Zeitung	1990–2017	Conservative-liberal	5981
Germany	Frankfurter Rundschau	1995–2017	Left-liberal	2661
Germany	Handelsblatt	1990–2017	Economic-liberal	3415
Germany	Süddeutsche Zeitung	1992–2017	Left-liberal	3562
Germany	die tageszeitung	1990–2017	Left	1195
Germany	Die Welt	1999–2017	Conservative	2206
Total				31,353

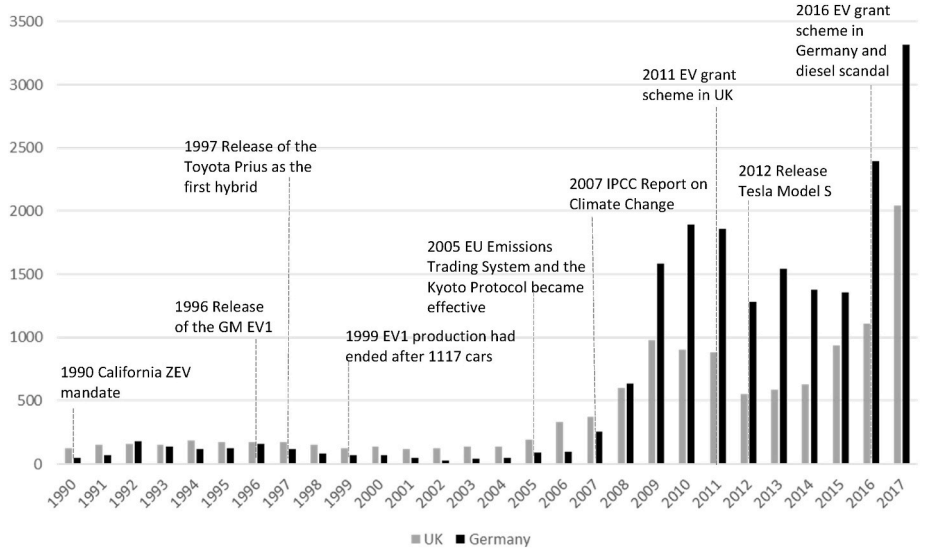

Fig. 1. Frequency of press articles on electric mobility (1990–2017, in Germany and the UK) and important international events.

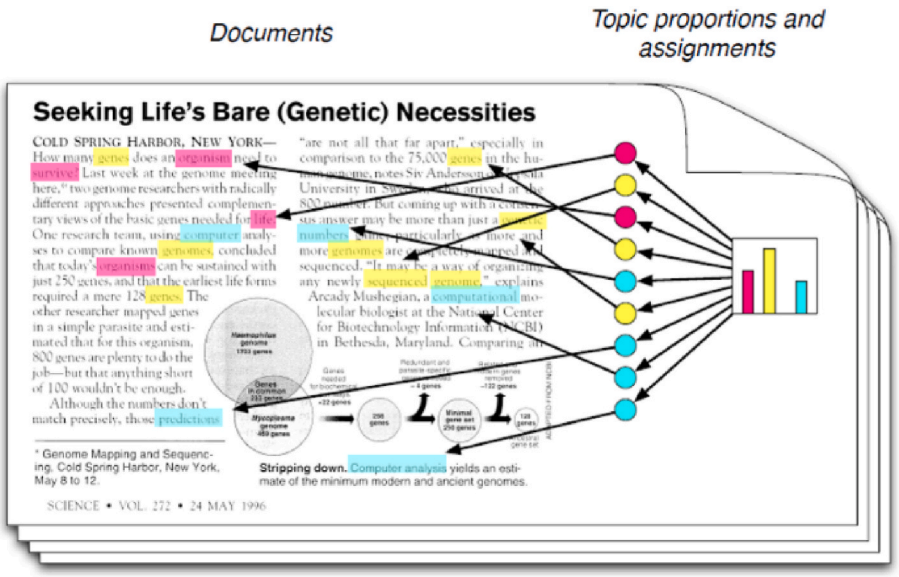

Fig. 2. Blei's figure (2012, p. 78) describes the idea behind topic modeling: the comparison of a large number of texts enables an automated analysis of which words frequently appear together (these words are grouped into topics).

classical frequency-based analyses is that the algorithm assumes that each word occurs in several topics. This makes it possible to capture different meaning structures connected with one word—for example, the positive and negative connotations of a term. We describe the detailed rendering and preprocessing steps for the topic modeling analysis in the online appendix. The appendix also contains tables showing the topic interpretation (see table A1 and A2).

We used the distribution of topics over documents and analyzed the average salience of frames and framing mechanisms per year, creating several time plots and tables (e.g., Tables 3 and 4 summarize the top frames for each country and each period). The following table summarizes our topic modeling findings and visualizes all frames and the

Table 3
Top 15 frames in Germany between 1990 and 2017 (average values in percentages, critical frames are grey shaded).

1990–1997		1998–2004		2005–2011		2012–2017	
Greener car	15.8	Greener car	12.6	New industry	14.5	New industry	12.2
Short range	13.1	Better alternative	12.5	Greener car	10.0	Greener car	8.2
Reality check	7.4	Short range	12.4	Short range	8.6	Incentives	7.4
Bad energy mix	6.5	Charging problems	6.7	Future tech	6.1	Short range	6.0
New industry	6.3	Urban mobility	6.1	Industry targets	6.0	Infrastructure prob.	5.7
Urban mobility	6.3	New industry	5.8	Better alternative	5.3	Functioning EV	5.5
Charging problems	5.6	Light & silent	4.9	Incentives	4.6	Future tech	5.0
Better alternative	5.4	Future tech	4.8	Energy transition	4.6	Industry targets	4.9
Future tech	5.1	Infrastructure prob.	3.5	Public Investment	4.2	Solution ICV problems	4.7
Light & silent	3.2	High costs	3.1	Infrastructure	4.1	Urban mobility	4.1
Infrastructure prob	3.1	Incentives	3.0	Risk car industry	3.9	Better alternative	3.8
Energy transition	2.9	Bad energy mix	3.0	Urban mobility	3.8	Energy transition	3.8
High costs	2.7	Reality check	2.8	Light & silent	3.7	High costs	3.4
Incentives	2.3	Energy transition	2.8	High costs	3.6	Risk car industry	3.3
Heating prob.	2.0	Functioning EV	2.8	Functioning EV	2.2	Linked to future tech	3.2

Table 4
Top 15 frames in the UK between 1990 and 2017 (average values in percentages, critical frames are grey shaded).

1990–1997		1998–2004		2005–2011		2012–2017	
Greener car	14.0	Better alternative	17.2	New industry	12.6	New industry	13.0
Short range	13.1	Greener car	10.2	Better alternative	10.2	Greener car	9.1
Better alternative	8.9	Urban mobility	8.9	Incentives	9.3	Incentives	8.3
Air pollution sol.	7.9	Incentives	7.9	Greener car	8.5	Functioning EV	7.7
New industry	6.9	Short range	6.7	Emission targets	7.7	Emission targets	5.8
Urban mobility	6.8	Emission targets	6.3	Short range	6.1	Better alternative	5.5
Bad energy mix	6.7	Fast and green	4.5	Bad energy mix	5.9	Short range	5.4
Incentives	5.3	Bad energy mix	4.5	Urban mobility	5.1	Rare earths	5.3
Future tech	5.0	New industry	4.5	Future tech	5.0	Infrastructure p.	5.0
Emission targets	3.2	Future tech	4.3	Infrastructure p.	4.5	Urban mobility	4.5
Infrastructure p.	2.9	Infrastructure p.	4.0	Public Investment	4.5	Bad energy mix	4.5
Fast and green	2.8	Functioning EV	2.5	Functioning EV	3.7	Air pollution sol.	4.0
High costs	2.6	Charging problems	2.4	Energy transition	2.7	Future tech	3.8
Functioning EV	2.5	Energy transition	2.1	Charging problems	2.5	Public Investment	3.1
Light & silent	2.0	Air pollution sol	2.1	Rare earths	2.3	Charging problems	2.4

related framing mechanism (Fig. 3). This allowed us to identify the central patterns and predominant frames describing the essence of the EV.

4. Results

In the following, we describe the predominant frames for each time period in Germany and the UK (for a complete list of all frames and topics, see the online appendix). Afterward, we compare the cases and further describe the development of the overarching framing mechanisms.

4.1. EV framing in Germany

In the first period, between 1990 and 1997, the most salient frame in favor of the EV was *greener car*, which covered 15.8% of all frames (Table 3). This frame points to the environmental advantages of the EV, which involve the notable reduction in carbon dioxide emissions. At the same time, this frame emphasizes the disadvantages of the existing technology and therefore demarcates the EV from the ICV. What is very striking in the German context, however, is the overall rather critical public framing of the EV connected to frames like *short range* (13.1%), the *reality check* (7.4%), the *bad energy mix* (6.5%), the long *charging* duration (5.6%), *better alternatives* (5.4%), *infrastructure problems* (3.1%), *high costs* (2.7%), and *heating* problems (2.0%). All these critical frames served as a serious barrier for the EV diffusion.

> "[Renault] had set the goal of reducing the price of EVs to the level of a well-equipped ICV in the same class. (…) In addition to the expensive acquisition costs, problems include the heavy weight, the short range of around 100 km and the service time of at least 6 hours during the charging process … " (FAZ, 1995; ID 50195)

Frames like *short range* and *charging duration*, which we describe as devaluation frames, compare the innovation critically with the features of the existing technology. Additionally, frames like *bad energy mix* also contradict the link of EVs to sustainability and thus signal misalignment. The reality check frame referring to the "Rugia EV test" was a special issue in Germany that linked all the critical points associated with the EV. Between 1992 and 1997 several German car manufactures, including BMW, Mercedes, and VW, tested EVs on the island of Rugia in the Baltic Sea. The test found that EVs were an immature technology with a poor carbon dioxide balance since the German electricity mix at that time was based mainly on coal power plants (see also Bohn and Braun, 2021). Accordingly, the first period was characterized by an overall critical framing of the EV, especially based on the comparison with the conventional features of the "steel-and-petrol car."

In the second period from 1998 to 2004, the overall attention given to EVs plummeted and what was left of the debate was dominated by competing fuel technologies. This is manifested in the *better alternative* framing, which signaled the openness of the technological innovation race and reflected the argument that alternatives like natural gas, hydrogen fuel cells, or the combination of internal combustion engines with an electric motor (hybrid) may be more promising than battery-powered EVs, especially in terms of sustainability. Overall, the share of misalignment frames increased in the second period, and critical frames continued to dominate the public debate about the EV. In contrast, more positive frames like the substitute and pioneering frames were used relatively rarely; together, they made up just 10% (see also Fig. 4).

In the next period, between 2005 and 2011, the framing of electromobility changed significantly. The once-dominant frames decreased in relevance (e.g., *greener car* 10.0%; *short range* 8.6%) and there were several newly emerging frames that pointed to the potential of the technology to enable the government to reach the set of sustainability goals (*energy transition* 4.6%) and provide an opportunity for the German automotive industry (*new industry* 14.5%). Besides *new industry*, which was the top frame in this period, the high degree of alignment frames is especially based on policy activities. For example, in this period, the German government introduced a plan to become the lead market and lead supplier of EVs, which is consistent with frames about the government's aim of fostering EV development (*industry targets* 6.0%), the funding of research, development activities, and infrastructure investments (*public investment,* 4.2%), and the debate around a grant scheme to accelerate the sale of electric cars (*incentives* 4.6%). The associated opportunities for the economy also entailed risks, for instance, job cuts in the automotive industry (*risk car industry* 3.9%). However, such critical frames were less salient and the period was simultaneously characterized by an increase in economic and political alignment.

In the last period, between 2012 and 2017, this development continued, the *new industry* frame again topped the list (12.2%), and the critical comparison with conventional features frames continued to lose relevance with only three frames in the top 15 list (*short range, infrastructure problems, high costs*). Additionally, the more positive pioneering, substitute, and alignment frames dominated the public reception of the EV.

Summarizing the whole observation period in Germany, the framing of the EV changed considerably and developed from characterizing EVs as an intensely criticized "immature" technology—which was a serious barrier for the EV—to a positive viewed technology that had the potential to boost the German economy. The framing of the EV developed so that it portrayed EVs as a politically supported, greener technology, connected to cutting-edge technologies like autonomous driving and digitalization and with similar features to the ICV.

4.2. EV framing in the UK

In contrast to Germany, positive frames were more salient in the UK from the beginning. In the first phase, the most salient frames that portrayed the EV positively were *greener car* with 14.0% of word assignments (Table 4), followed by another sustainability issue relating to the new technology's role in reducing *air pollution* (7.9%), then the *new industry* (6.9%), and the *urban mobility* frame (6.8%).

> "… recharging electric cars overnight using off-peak surplus electricity, and developing ever more efficient versions, would cut pollution drastically. Electric cars with ranges of 100 miles between recharges and speeds of up to 100mph would soon be able to compete with petrol and diesel cars …" (The Independent, 1990; ID 8594)

The *greener car* frame, which was the most dominant frame, clearly signaled the demarcation. Demarcation framing is about the differences and advantages of the EV compared with the ICV. However, as in Germany, there were also critical frames pointing to problems for the EV, such as *short range* (13.1%), *better alternatives* for sustainable cars (8.9%), and a *bad energy mix* (6.7%). Despite this criticism, the majority of frames in the media were positive. The EV was presented as a new technology that could potentially contribute to societal and political goals such as emission targets. Furthermore, even though the technology was not yet fully developed, it was framed as a complementary technology that could be used in cities (*urban mobility*), where people usually only need to cover short distances. There were various small cars in the UK such as the G-Wiz and, even before that, the Enfield 8000, Sinclair C5, and a long tradition of other small electric vehicles like milk floats, for example (see also Cowan and Hultén, 1996). Another UK-specific frame was the *fast and green* frame, containing attempts to break speed records with electric vehicles. This frame points to the potential of the technology as a substitute for and functional equivalent to the ICV, reaching similar speeds or even faster but with a greener character. Although there were a number of critical arguments in the UK of the 1990s, unlike in Germany, most of the frames were positive.

However, just like in Germany, the second period (between 1998 and

Illustrative topic vocabularies (top 10 words)	Frames	Frame category	Frame mechanism
G_108: driving car trip fast driver car good speed hour keep	Functioning EV (draw on and take-over central car features)	Functionality frames (showing functionality of EV similar to ICV and incorporate central features)	Substitute
UK_73: record speed world land set first wales break attempt bluebird	Fast and green		
G_135: public city transport car local-transport mobility train bus good new	Urban mobility	Niche frames (& areas of application for short driving distances)	Complementary
UK_80: milk float something think first good lead last delivery motor	Delivery car		
UK_2: future: business vision big build line believe promise many mass	Future technologies	Future frames (position the EV as a pioneer over the old "steel-and-petrol car")	Pioneer
G_167: car new google drive apple autonomous digitalization tesla industry future	Linked to future tech (like autonomous driving, sharing & digitalization)		
G_66: car driving hear silent good driver street small motor inaudible	Light & silent	Superiority frames (point to core characteristics different from the established "steel-and-petrol car")	Demarcation
UK_169: emission carbon produce dioxide co2 less cent emit kilometer cut	Greener car (e.g. less emissions, sustainable, vehicle-to-grid)		
G_93: euro cost price battery kilowatt hour kilometer expensive range decline	High price	Immature technology frames (points to EV disadvantages compared with the ICV)	Devaluation
UK_168: range battery cost limited infrastructure price technology high recharge remain	Short range		
G_11: charge mile range drive battery able recharge travel need hour	Charging duration		
UK_67: charge point people public infrastructure travel buy question need many	Infrastructure		
G_160: Battery grad high problem winter temperature air technology system water	Heating problem		
UK_11: air pollution city emission diesel clean quality reduce health government	Addresses air pollution and health problems	Sustainability frames (point to overarching issues like climate change, air pollution and energiewende/energy transition)	Alignment (Social)
G_38: energiewende money new climate_protection expansion government fond country support euro	Energy transition		
UK_131: emission climate change target government carbon energy new transport cut	Emission targets		
UK_115: industry technology market new face come manufacturer big potential challenge	New industry (increasing market, joint ventures, new jobs)	Economic chance frames (emphasizes the economic importance of the new technology)	(Economic)
G_107: alternativ time diesel müller motor germany drive change internal_combustion foreseeable	Solution for the ICV problems (system change, shift from ICV)		
UK_198: grant government subsidy price scheme nissan leaf cost uk new	Incentives (grant scheme, tax incentives)	Governmental support frames (show the political support and the connection to political aims)	(Political)
G_110: euro million billion development research government invest support fund earning	Public Investment (including Public R'n'D investment)		
G_109: 1_million aim street government germany reach drive roll car lead_market	Industry targets		
UK_18: petrol diesel plan sale ban new announce government France move	Regulation (standards, diesel ban)		
G_35: earths rare raw_material metal battery china lithium copper require percent	Rare earths	Non-sustainability frames (question & deny the sustainable character of the EV)	Misalignment (Social)
UK_33 power electricity energy emission fuel station generate coal carbon fossil	Bad energy mix		
UK_89: hydrogen fuel cell toyota technology hybrid biofuels power alternative future	Better alternatives for sustainable car (e.g. hybrid, hydro and gas)		
UK_97: problem cause concern fire safety battery big risk issue people	Safety issues battery and autonomous driving	Technical hazard frames	
G_79: germany china us japan development competition france car_manufacturers international automobile_sector	Risk car industry, (job loss, challenge for the automotive industry)	Economic risk frames	(Economic)

Fig. 3. Data structure (see online appendix for the complete list of topics and frames).

2004), was characterized by a rather critical view of the EV. As argued above, this period marked the end of the EV boom for the time being and the misalignment frames related to sustainability issues increased considerably. This was particularly evident in the discussion that gas-powered vehicles, hybrids, and hydrogen fuel cells are the *better alternatives* for sustainable mobility (17.2%). With the exception of fuel cells, all these technologies are based on fossil fuels and therefore follow the traditional fossil path.

As in Germany, the framing of the EV changed rapidly from 2005 onwards. Sustainability-related frames like the UK emission targets then appeared in the top five frames and the government introduced several incentives to foster the development of the EV (e.g., by granting subsidies as well as establishing the plug-in grant scheme). Just as in Germany, but to a smaller degree, the new industry framing was the most salient frame in the third and fourth period. This framing reflects the argument that the EV would provide a new opportunity for stimulating the UK-based automotive industry as exemplified by the Nissan plant in Sunderland, which began to manufacture EVs at the time. Overall, the

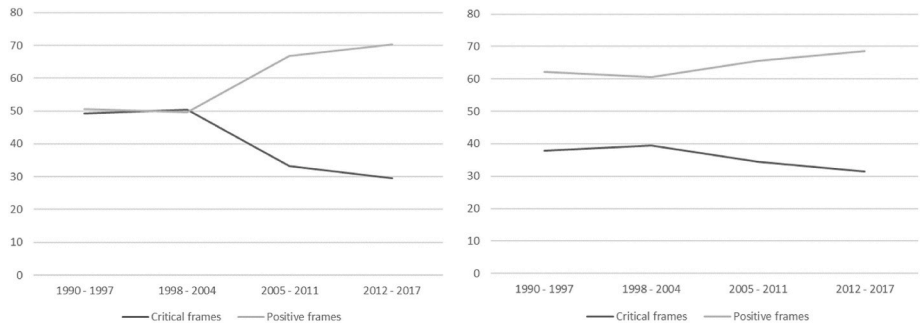

Fig. 4. Distribution of critical and positive frames in Germany (left) and the UK (right).

societal, political, and economic level of alignment was high in this period. And by the end of our observation period, the new EV was mostly framed as a functional substitute for the ICV (*functioning EV*) that was fitted with a politically supported (*incentives*) green technology and could help the government reach environmental goals (*emission targets*) while simultaneously boosting the UK automotive industry (*new industry*). Nevertheless, the EV was still not fully established, as the critical frames that have been leveled for 20 years were still salient (e.g., devaluation frames like *short range, or rare earths*).

4.3. Comparative consideration

Considering the similarities and differences in the UK and Germany, we first note that the overall framing of the EV has become more positive over the years. In both countries, there were notably fewer critical frames, but especially in Germany where, in the first two periods, critical frames contributed to around 50% of the discourse around EVs (Fig. 4).

One reason for this development was that, from the middle of the 2000s, the climate change debate gained worldwide attention (IPCC, 2007), and the governments in the UK and in Germany launched several climate protection programs in which electric mobility was mentioned as one of the cornerstones for reducing carbon dioxide emissions in the transportation sector. This had the effect of once again igniting debates about the potential of EVs as a future mode of mobility. One of the most noticeable changes in both countries in the third period was the increase of frames that signal political, economic, and societal alignment. In comparison, the number of misalignment frames and the polarizing demarcation and devaluation frames decreased in salience over time (Figs. 5 and 6).

What is remarkable, however, is that, in the first two periods, demarcation and devaluation were the most apparent innovation framing mechanisms. Frames pointing to similarity (complementary and substitute) and the future (pioneer) were much less salient. We conclude that the first two phases were characterized by an intensive struggle about the nature of the EV. And this process is not yet over. Especially in Germany, devaluation frames are still an important mechanism, which suggests that the lock-in of the "steel-and-petrol car" is a crucial hurdle for the EV.

5. Discussion

In our paper, we argue that framing is a key concept when seeking to understand the success or failure of green innovations. We chose a comparative topic modeling approach focusing on the public frames of the EV in order to show the ambivalence and dynamics of EV frames over time. In the process, we follow recent calls to study legitimacy barriers of green innovations beyond technical obstacles by "analyzing the influence of the social and political environment" (Gohoungodji et al., 2020, p. 9). In what follows, we discuss the theoretical, methodological, and policy contributions and make suggestions for future research.

5.1. Theoretical implications

Our study shows how green innovations can overcome initial skepticism and legitimacy barriers. However, they also suggest that legitimacy barriers—i.e., devaluation frames like immature technology—have persisted over long periods of time. Devaluation frames such as the *short range* and *high price* frames critically compare the EV with the established "steel-and-petrol" car and generally question the sense, purpose, and innovative character of the EV. In other words, the established system has blocked the innovation. Urry puts it in a nutshell and concludes that "[a]utomobility is a Frankenstein-created monster, extending the individual into realms of freedom and flexibility […] The car is the literal 'iron cage' of modernity, motorized, moving and domestic." (Urry, 2004, p. 28).

However, our study also highlights the role of another framing mechanism which is demarcation. Demarcation frames are different from devaluation frames in that they refer to the disadvantages and negative consequences of the existing system, for example the higher emissions of ICVs. Similar to substitute and complementary frames, demarcation frames also stress the relationship between the innovation

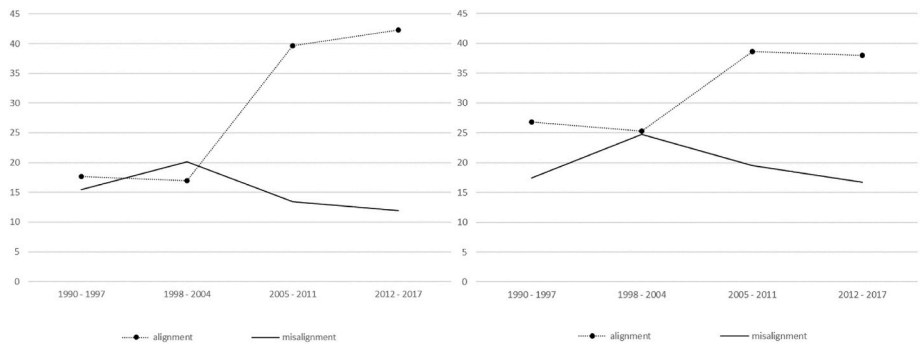

Fig. 5. Distribution of alignment and misalignment frames in Germany (left) and the UK (right).

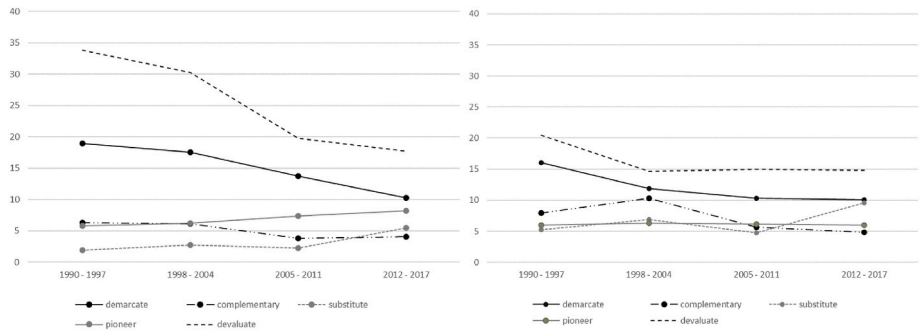

Fig. 6. Distribution of technological-comparative framing mechanism in Germany (left) and the UK (right).

and existing technologies. Whereas there is an intense debate in the literature on whether either substitute (Benner and Tripsas, 2012; Hargadon and Douglas, 2001; Pan, Li, Chen & T., 2019) or complementary frames (Gurses and Ozcan, 2015) are the main factor for overcoming legitimacy barriers, we found that both may be of secondary importance in contexts with strong lock-in such as in the fossil-based economy. Instead, we have shown that demarcation was the dominant framing mechanism. Demarcation frames suggest that the electric vehicle is not a matter of supplementing the internal combustion engine or substituting it with something else but of establishing a new system that does not only seek to replace the engine but brings about a new kind of mobility including new infrastructure, digitalization, autonomous driving, and sharing.

While demarcation frames point to core characteristics that differ from those of the conventional system, they have a dual function. First, demarcation frames signal the innovative character of the novel technology (e.g., lower emissions, silent). And second, they point to the disadvantages of the conventional technology (e.g., not sustainable, not silent). Hence, demarcation opens up the possibility of questioning the established system. Over time, this may lead to small shifts in the understanding of the conventional technology. Thus, demarcation frames are—in addition to substitute and complementary frames—an alternative mechanism for weakening the legitimacy advantage of an established system. We argue that the specific mix of the different framing mechanisms may be crucial. Whereas in some domains it might be more promising to emphasize substitute frames (e.g., everyday issues like range), in other domains it might be more promising to place emphasis on demarcation (e.g., more sustainable).

However, as argued above, strong demarcation might go hand in hand with strong resistance. Incumbents may perceive an innovation as being a potential threat and lobby against it (Gurses and Ozcan, 2015). Consequently, demarcation has two sides, meaning that besides having the potential to dissipate the legitimacy gap, it could also prolong resistance. To compensate for the possible negative consequences of demarcation frames, our study shows that framing mechanisms are potentially interrelated and work in combination. In particular, the resistance triggered by demarcation frames can be ameliorated by alignment frames (e.g., the EV as a chance for the domestic industry). While demarcation frames are central for challenging the dominant conventional technology and constructing an alternative, alignment frames are important to show the innovation's conformity with the economic, political and social system (Benner and Tripsas, 2012; Gurses and Ozcan, 2015; Hargadon and Douglas, 2001). In other words, in order to break up the legitimacy advantages of the conventional technology, it may be necessary to balance demarcation and alignment, which is even more important in contexts involving strong inertia as in the fossil-based economy.

5.2. Policy and managerial implications

Our study also has important policy and practical implications. We especially argue that the big data approach we used allows us to both capture and quantify critical frames and thus identify the dominant legitimacy barriers for the EV. For example, we have shown that the salience of very critical devaluation frames has decreased over time, but they still exist to a certain degree, especially the *short range*, *infrastructure problems*, and *rare earth* frames (Tables 3 and 4). On the one hand, such frames can be regarded as concrete instructions for entrepreneurial and policy action on what issues they should focus on, for example, government support for the development of the charging infrastructure or for the establishment of a battery industry. On the other hand, our findings also point to the persistence of issues that were once critically reflected upon—even though there has been technical progress (e.g., most of the recent EV models have a range of more than 300 km and, since 2012, the Tesla models have even been able to drive up to 600 km). The case relating to renewable energies is similar—critics continue to frame it as too expensive, although the marginal costs per kilowatt-hour have significantly decreased and lower than those of fossil power plants (Sensfuβ et al., 2008). Thus, political actors have a significant task in supporting green innovations and reducing prejudices not only by grant programs or laws but also by supporting them with an adapted framing strategy. Our study can help political actors to develop such strategies, because knowing which critical frames exist and how strong they are will make it easier to develop better target-group-specific response to reduce stereotypes. For example, our study points to the importance of demarcation frames in overcoming legitimacy barriers because they stress the disadvantages and negative consequences of the existing system.

Specifically, our results suggest that a successful framing strategy should combine demarcation and alignment frames in order to develop an efficient response to critical frames. By adopting such strategies, policy actors would be able to challenge conventional technologies by constructing a desirable alternative i.e., a more sustainable, autonomous-driving-based mobility system that also promotes the digital sector. Furthermore, we want to stress that policy actors and especially its staff units may use topic modeling to capture public discourses in real time, which goes well beyond previous media studies (Hielscher and Sovacool, 2018). In addition to traditional success measures, this would allow them to capture the impact of policy initiatives on a communicative level. As topic modeling is a comparative method, it is useful to systematically compare different countries with each other, for example when an EU-wide funding program is to be examined for its effects in the different member countries. In this respect, aside from our results, the methods our paper uses are of high relevance for political actors seeking to promote green technologies.

From a managerial perspective, the comparison between the UK and Germany also revealed that entrepreneurs should be aware that great resistance is to be expected, especially if a strong domestic industry is involved. But, based on our findings, entrepreneurs can also learn which combinations of framing mechanisms can potentially evoke less resistance. Framing an innovation with demarcation and substitute frames provokes the greatest resistance, whereas demarcation and

complementary framing reduce it (see also; Gurses and Ozcan, 2015).

6. Conclusion, limitations, and outlook

To sum up, from an empirical perspective, we have studied the dynamic meaning of the EV from 1990 to 2017 and thereby compared the more and less successful years of this green innovation. In this way, we described the main legitimacy barriers and how the EV has overcome the initial skepticism. Recently, the EV has come to be viewed as a technology that will be able to contribute to a significant reduction in CO_2 emissions if the energy mix changes (Mazur et al., 2015; Rietmann et al., 2020), and—as we conclude—it is seem as being able to diminish the dominance of the ICV. We also described the dynamics of this process and the development of the EV framing, from an anti-sustainable and immature technology to a sustainable and future-oriented functional equivalent to the internal combustion engine vehicle.

Besides the potential of our topic modeling approach on public media data, our paper has also limitations. We have shown that the framing of the EV has become more and more positive, but this does not enable us to make specific predictions about tangible long-term effects, for example, in terms of sales numbers or industrial growth. This would require a survey of the industry that addresses both the corporations and all other stakeholders. In addition, our paper does not fully exhaust the potential of the method for comparative framing studies because of the focus on only two countries. When studying the breakup of established technological paths, it would be promising to compare more countries and especially very different cases in order to further generalize the findings. In the case of the EV, for example, it would be inspiring to compare the leading car-producing countries—Japan, China, the United States, and Germany—and the leading EV countries—like Norway, Sweden or the Netherlands. In this way, our study can be seen as a source of inspiration for further research that uses the promising character of topic modeling to compare processes of green innovation framing in very different contexts.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.132499.

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