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System capacities and implementation challenges in Germany's electric vehicle policy mix: an actor-centered review of the policy mix

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ABSTRACT

Situated within the framework of sociotechnical transitions, this study analyzes the implementation of national e-mobility policy in Germany through the lens of actors operating across seven key fields. By integrating a policy mix analysis with empirical data from expert interviews, we explore how system challenges are perceived and negotiated. Using a sociotechnical transitions framework, we explore gaps in the current policy mix and advocate for a more integrated approach to address systemic deficiencies. The findings emphasize the role of intermediary actors in policy implementation and contribute to SDG 9 by identifying pathways to strengthen infrastructure and innovation in sustainable mobility.

1. Introduction

Electric vehicles (EVs) have developed into a critical technology for the decarbonization of road transport, which contributes to over 20 % of global energy-related emissions [1]. While road transport emissions are expected to decrease over time, the sector is expected to remain a key contributor to overall global emissions according to the European Environmental Agency [2]. At the European level, reducing carbon emissions from traffic significantly has become a key policy goal for the transport sector [3] and in consequence, electric vehicles have become part of the strategy to meet ends. As reported, electric vehicle registrations in Europe rose steadily in 2019, followed by an increase between 2020 and 2023 [4]. While technological advancements in range, model diversity, and performance are evident, questions persist about the state of innovation and the challenges surrounding its acceptance by industry, administration, and everyday users. This study, therefore, examines the challenges posed to the energy and mobility systems by the integration and distribution of these technologies.

Vehicles with an electric drive, either powered by battery or hydrogen play a crucial role in the transition to low-carbon transportation, and the adoption of electric vehicles (EVs) is a central element in destabilizing fossil-fuel-dependent automobility regimes or systems

[5]. Only a few accounts are provided in the transition literature on user perspectives of barriers and gaps to adoption [6,7]. This becomes more interesting considering the importance of actor-level decisions, that concern agency - the capacity and willingness to act in transition processes [8,9]. More specifically, while the motivation and behavior of actors strongly influence the adoption and deployment of emerging technologies, work on conceptual frameworks that connect micro and macro levels of analysis in transitions is arguably underdeveloped [10].

With this in mind, we focus on the analysis of challenges to the implementation of e-mobility policies, alongside actor-informed suggestions for strengthening institutional capacity, enhancing infrastructure development, and improving cross-level coordination. In particular, we focus on e-mobility policy implementation from an interpretative perspective, viewing policy implementation not as a simple transfer of national didact through to material change, but a process that involves interpretation, negotiation, and judgment [11]. As EV policy is multifaceted, we draw on the policy mix literature. In this way, we establish connections between the macro-level of policy (mix) and the micro-level of actor interpretation concerning e-mobility-specific topics as charging infrastructure. In contrast to our approach, previous studies e.g., Refs. [12,13] have focalized specific aspects of policy instruments, often overlooking their broader systemic interconnections and practical

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implementation dynamics. Similarly, Corradi et al. [14] have examined barriers to EV adoption with a focus on regime actors but without incorporating personal accounts or experiential perspectives, thus placing less emphasis on agency in policy implementation. Building on this, we summarize the main challenges related to charging infrastructure, as perceived by various actor groups, along with their proposals to enhance infrastructure development, institutional capacity, and policy integration. Building on expert interviews, we document how actors from selected fields contrast, contradict, and reveal unforeseen challenges with implications for their alignment with the national agenda on e-mobility. Aligned with SDG 9, this research explores how e-mobility governance and policy can foster innovation and sustainable infrastructure, supporting the global transition to low-carbon transport systems.

Our main research question concerns *how different types of actors (e.g. from administration, research, or energy provision) perceive and address challenges to implementing EV policy, particularly from their positions in the e-mobility system*. As said, our underlying premise is that policy implementation requires policy translation to practice and that understanding more about the obstacles to this, and associated implementation challenges, is useful for policy design. In the course of research, we found that some of the policy actors' recommendations could be categorized in terms of informal institutional forms, such as *technological, institutional, cultural-cognitive, and educational capacities* [15,16]. Thus, we adopt an additional transfer question, that involves the *recommendations actors offer for improving EV policy*. Working with a common definition by Geels [17] we frame actors according to the MLP as: *"social groups such as firms, policymakers, scientists, users, and societal groups that interact within sociotechnical systems, shaping and being shaped by the development and diffusion of innovations."* In terms of structure, the paper begins with an introduction to the diffusion process of EV technology, policy mix principles, and actor intermediation. Information on the research design, data collection, and methods or analysis is provided in the following method section. The analysis consists of two parts: a policy review of e-mobility in Germany and the results of the qualitative analysis. The results are taken up for discussion and all relevant points raised are summarized in the conclusion.

2. Literature discussion

Previous studies of e-mobility in the sociotechnical transitions literature have dealt with various issues: Some have focused on diffusion strategies [18], others on policy mechanisms to accelerate the adoption of EVs [19]; some have debated the role that social status may play in this process [20], and again others have sought to differentiate (segment) consumers' willingness to pay for electric vehicles and their charging applications [21]. Our literature review outlines key arguments on the diffusion of e-mobility as part of the shift toward low-carbon transport. This overview provides a framework for analyzing actors' perspectives on related challenges. We discuss concepts of EV diffusion (2.1), the design of policy mixes for e-mobility transitions (2.2), and the role of intermediary actors in implementing these instruments (2.3).

2.1. Factors affecting EV diffusion

In the first decade of the millennium, the 'electrification' of the transport sector has been viewed as a niche phenomenon, often subject to experimental studies [22,23]. A more recent approach frames transition processes in mobility as interlinked and part of the wider challenges within the landscape of energy and mobility [24]. In this way, the electric vehicle is viewed as representing more than a mere substitute for vehicles with internal combustion engines (ICEVs) using "cleaner, greener" sources for refueling. Most life cycle analyses demonstrate the climate efficiency of battery-electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) relative to fossil-fuelled propulsion, although

the production and disposal of batteries still raise questions about the raw materials supply and environmental and social impact [25,26]. Despite policy ambitions, the niche of e-mobility and the associated technology and social embedding has been slow-evolving when taking adoption and diffusion rates into account [27,28]. This is even more so when seen in the context of electric vehicles having been considered a promising technology at repeated intervals over the last century, yet failing to even develop as a niche product in the 20th century [29]. Since the turn of the millennium, the global discourse on climate change, enhanced by scientific reports [30] on climate change and its political corollaries has increased the landscape pressure on carbon-intensive practices and, consequently, forwarded the development of electric drive technology. Thus, the process of diffusion of electric vehicles and their challenges have mostly become the subject of study in the current and last decade [31–33].

At issue here is how to design policy that takes account of the experience of those charged with its implementation, and those (often users, citizens, or consumers), who experience that implementation. Earlier work in that vein has, for example, illustrated the value of personal narratives for understanding actors' situated and conjunctural experience of the EV system [34]. Such narratives can help to indicate the complexes of attitudes, values, beliefs, and opinions of various actors, which in turn play a crucial role in determining the pace and level of acceptance of technological innovations, particularly concerning user adoption. Despite the importance of private user commitment in promoting the diffusion of e-mobility, Dalla Chiara et al. [35] emphasize that multiple factors influence the willingness of drivers to use electric traction. The literature has pointed to user concerns about higher acquisition costs, insufficient charging infrastructure, long charging periods, and relatively low range [36]. Additional factors, acting as social barriers to the adoption of electric vehicles include lack of consumer knowledge, limited EV model options, continuing range anxiety despite technological improvements, a prevailing automobility culture, and the durability of the overall technology including battery life [6]. These hindering factors are assumed to have slowed down the diffusion of electric vehicles by constraining demand. Despite this, electric vehicles run on low-maintenance motors, deliver high torque, and are experienced as significantly quieter than regular cars from a user's perspective [37].

2.2. Policy mix principles

The basic premise of policy mix theory is that multiple policy instruments need to be combined synergistically to address complex policy problems [38–40]. Policy mix rationales thus draw on interdisciplinary frameworks, to integrate different, key aspects of policy design [41]. In the context of e-mobility, a key challenge for policy implementation has been the entrenched incumbency and resistance of the conventional automotive sector [42]. The automotive industry is one of the most dominant industries in Germany and other industrialized countries, such as the U.S.A., Japan, and France [43]. To explain the complexity of cultural meanings associated with the durability of the automobility system, functional, symbolic, and societal frames have been developed [44]. In the context of our study, we view road vehicles as embedded in an extensive road, parking, and refueling infrastructure that facilitates established patterns of motorized, private transport [45,46]. Policy mixes are required to address the deep interconnectedness of the components of such a system. With the theory on policy mixes being developed quite well already, less investigation has been done on policy mixes under current implementation. It is therefore also our concern to study a real-world policy mix [47] in this case.

Conceptually it is first necessary to differentiate between different aspects of policy mix design. Rogge & Reichardt [41] refer to the building blocks of policy design as (i) policy elements, including strategy and instruments; (ii) policy process; and (iii) policy characteristics. These need to be applied to achieve integrated policy objectives and to

prevent mismatches, coherence, consistency, and congruence [48]. A single policy instrument may imply economic instruments, regulation, legal control, and specified directed information [41]. Some studies have focused on the analysis of single policy elements such as subsidies or incentives and their effects on the adoption of electric vehicles [49, 50]. In our case, we focus on the interplay of measures as perceived by actors at different points in the sociotechnical system, given our focus on the implementation process. The model of Rogge & Reichardt for policy mixes has been taken up and further developed in various contexts [51, 52]. For example, the extended concept of so-called transformative policy mixes integrates a long-term focus on policy-making and the concrete utilization of instrument mixes [53]. In addition, Kivimaa & Kern proposed a concept that integrates aspects of disruptiveness and the destabilization of established regimes into the policy mix [54]. The framework categorizes policy instruments as either supporting technical innovation and niche development (c-functions) or leading to the decline of carbon-intensive technologies (d-functions) and thus includes both reinforcing and disruptive impacts on the landscape and regime. In the subsequent sections, we use the standard model by Rogge & Reichardt to illustrate the instruments in place as part of the policy mix, as currently integrated into the national agenda for e-mobility in Germany. On that basis, we document and discuss the perspectives of actors in policy translation and contribute to the analysis of policy implementation with corresponding recommendations, promoting the diffusion of electric vehicles [55]. We do not aspire to analyze the policy mix and its instruments in-depth, as this would be outside the scope of the study undertaken and defeat the purpose of understanding the actors' perspective in the light of the regulatory framework.

2.3. Policy implementation as intermediary action

Policy implementation requires intermediary actors who transform abstract policy concepts and imperatives into practical strategies within specific contexts [56]. In the context of sustainability transitions, the roles and impacts of actors, specifically intermediaries, have gained increasing recognition [57]. Intermediary organizations play an influential role in navigating complex policy landscapes through the acceleration phase of transitions [58]. The understanding of the contributions to public policy, including a pivotal role in policy implementation has further developed in the literature. For example, Boon and Bakker (2016) examine how intermediaries in sustainability transitions interact with and influence public policy [59]. This adds depth to the understanding of intermediary actions, highlighting their importance in facilitating transitions and influencing policy agendas. What these studies have in common is that they highlight the dynamic nature of policy implementation and mediation and show the diverse roles that are mediated between the design tasks of sustainability transitions and public policy and administration. The sociotechnical transitions literature argues that intermediaries are key actors that can catalyze transitions by voicing new concepts [60], commencing novel policy or market procedures [61], and introducing new networks of actors [62]. In the policy process, actors taking the role of intermediaries can be characterized as a) bringing knowledge capacity into policy processes, b) advocating for new policy, and c) building consensus on policy proposals [63]. Intermediaries, though do not act as free agents but within institutional boundaries and arrangements [64]. Here, we connect conceptually to previous studies by drawing on the concepts of intermediaries and policy translation, particularly emphasizing the processes of agency, interpretation, negotiation, and the exercise of judgment.

In addition to the concept of intermediaries, elements of Scott's [65] institutional typology, as detailed further in section 3 are of further relevance to this study. Scott's perspective offers theoretical insight into the embedding of new social structures and hence has been applied in sociotechnical contexts [66]. Offering a framework for understanding the role of institutions in shaping organizational behavior, Scott's

approach defines three institutional pillars, each of which is reproduced by actors within organizations: regulative, normative, and cognitive. The interplay of these shapes organizational structure, practices, and strategies. As with policy implementation, actors necessarily mediate these processes, and their experience of this mediation tells us about the pressures that not only they face subjectively, but also about the pressures and tensions within the system. Thus subjective actor experience – the realm of micro-level sociology – has relevance for more structural accounts of social and sociotechnical life.

3. Method

The overall research design is an empirical case study aimed at exploring the diverse perspectives of actors involved in or connected to e-mobility policy and practice. While our study touches upon aspects of policy implementation processes, its primary focus is on exploring actors' perspectives within the e-mobility system, particularly emphasizing their roles and experiences in navigating challenges and opportunities for EVs in the sociotechnical system. To provide context for these perspectives, we begin with a review of the national policy landscape relevant to Germany. The review provided a knowledge base of the overall policy mix, including strategies, objectives, and specific instruments. In addition, we conducted actor interviews as field research. The two-fold approach established linkages between specific and detailed references by the interviewees and the policy elements, improving contextual and situational understanding of the system.

When reviewing and documenting actors' situated assessments of the policy landscape, Germany's pivotal location within the European industrial economy should be borne in mind, as well as its deeply ingrained industrial framework, and its advocacy for environmental and sustainability issues [67,68]. Initially, we began our policy review by identifying the fundamental components of the German policy mix and its constitutive elements [69]. Our data sources for key strategy documents consisted of public reports released during the initial half of the decade following 2010 and updated in the 2020s. We followed a standard review procedure for policy analysis [70]: employing an initial scoping procedure, pertinent sections were marked within each report, and distinct features representative of policy elements were noted. This enabled the identification of policy elements and instruments. In addition, a legislative map for e-mobility was used for orientation [71]. Expert interviews were conducted with actors at different points in the electric vehicle (EV) sociotechnical system. The professional fields represented included public administration, commerce (SME), academic research, engineering, energy, and consumers. Participants were mostly drafted from the Lower Saxony areas and sought to represent each sector field illustratively, not statistically. As such, the interviewees' experience should be treated as illustrative of actor experience, not definitive, in the sense of representing all actors in similar positions. This trade-off between depth and numerical breadth is inherent to qualitative, case study work [72].

For our purposes, engineering refers to the technical arenas of electric drive technology, energy to all aspects related to the grid, and the provision of electricity. As said, the actors are not assumed to be necessarily representative of their roles, but rather illustrative: the issues that they raise are assumed to be within the larger set of issues that a larger group of such actors would raise. Detailed information about the content provided by each respondent and their grouping can be found in [Appendix B \(structure and content of the sample\)](#). Seven groups were formed, with two interviewees assigned to each group, enabling comparison across groups. We chose to sample actors primarily from one region to establish a case and improve comparability. The interview questions followed a protocol designed to encourage respondents to provide personal accounts of the policy process – i.e. accounts of their experience, from their standpoint within the EV system. For this reason, a semi-structured approach in the interviews was used, enabling a set of standard inquiries to be made, while allowing the conversation to build

and develop to explore new areas [37]. Semi-structured interviews are particularly useful when the research aims to understand actor perspectives of policy frameworks and underlying factors, which shape the viewpoints of the interviewed actors on policy instruments [73].

In this way, we explored the diverse roles and perspectives of actors in the e-mobility field, including their views on policy and its practical implications [11]. The selection of respondents followed a purposeful sampling approach rather than a random selection, with two interviewees chosen per subfield (part of the system). Additionally, snowballing techniques were utilized to identify potential participants and expand the network of interviewees [74]. All interviews were recorded with the written consent of participants and stored for a finite period on a secure server. Post transcription the material was cataloged using MAXQDA software.

Coding of the transcribed material sought to leverage the important aspects of the material related to our research questions [75]. Figure one summarises the two-round coding process, using high-level codes in the first round and sub-codes in the second round to explore various aspects of policy, including the actors' understanding of problems and challenges to the EV system, plus the institutional categories we explain in the following. Thus the analysis was conducted with a systematic approach while being sensitive to emerging themes. In the first round of coding, we employed concept-driven high-level coding to match individual accounts with policies relevant to their actor roles. For this purpose, we use the categorization provided by Hoffmann et al. [76]: resources, supply, and maintenance; infrastructure; technology and sociotechnical transitions; rules and regulations; cultural aspects; and user practices (further information: coding scheme in Appendix C). As part of the coding process, visual tools were used to review how the codes assigned spread across the sample. Special attention was paid to

policy conflicts in the areas of public service, infrastructure, political legislation, political administration, funding, market, and spatial planning. The analytic stage that followed included a selective application of Scott's theory of institutional types. Of particular relevance were normative orientations [65], which refer to the underlying values, beliefs, and norms that individuals or organizations hold and/or enact. Normative orientations help to shape behavior and decision-making within an institutional environment. In essence, they reflect moral and ethical principles, as well as preferred ways of doing things following societal and institutional norms. By categorizing actors based on their normative orientations, we can show how these affect their approaches to implementation, and how this influences their view of policy conflicts. In essence, Scott's theory of institutions facilitates a nuanced exploration of how different actors interact with and respond to both the policy imperatives and the sociotechnical system. While not a primary analytical focus, Scott's institutional typology provided a supplementary framing tool for understanding the pressures and tensions identified in the data, particularly the interplay of regulative, normative, and cognitive elements. In the third stage, we identified meta-themes highlighting structural challenges and points for policy intervention to improve implementation. The individual steps are not to be understood here as definitely distinct from one another but as phases with iterative transitions, which are illustrated more elaborately in Fig. 1.

4. Results of policy review

The first part of our results provides an overview of the policy landscape in which actors operate. We structure the policy agenda in Germany in terms of the conceptual model for policy mixes by Rogge & Reichhardt [41]. We identify fundamental components and constitutive

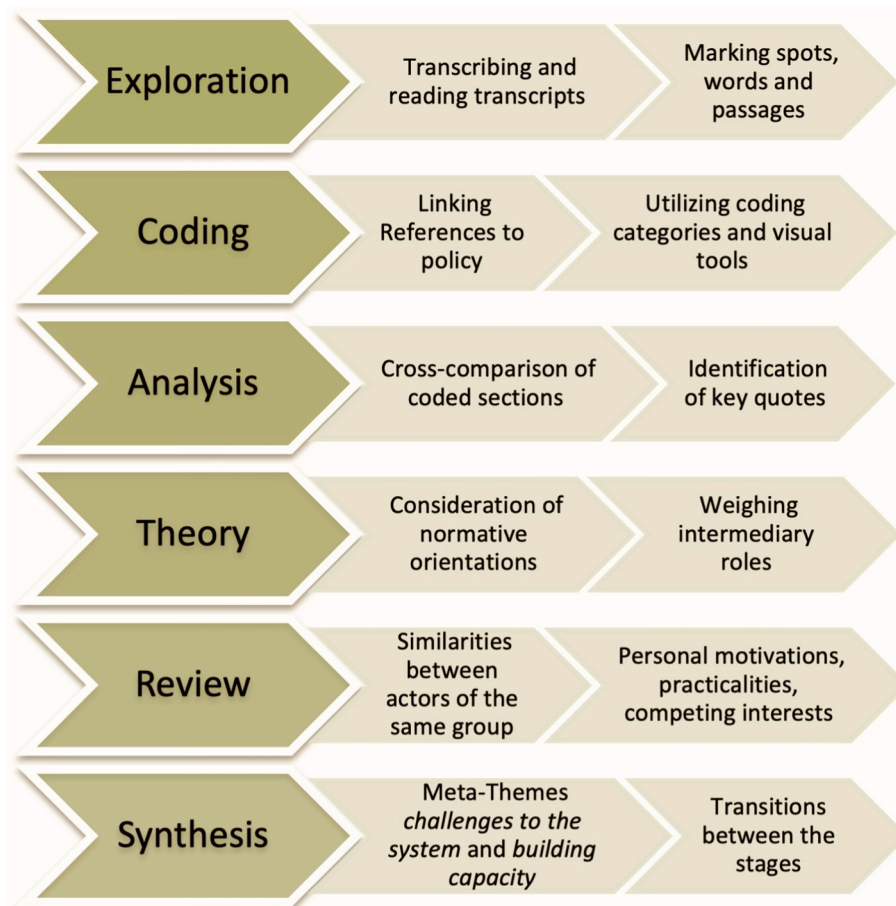


Fig. 1. Process of analysis.

elements [41,69] from data (strategy documents, governmental programs, public reports, laws, funding framework directives) and instruments of the policy mix. The policy landscape for e-mobility has evolved from tentative to comprehensive over the last two decades. The roman numbers indicate the policy documents we revised, listed in appendix C. One note on terminology: if not indicated otherwise, local refers to the level of municipalities and cities.

The foundation for promoting electric mobility in Germany can be traced back to the *Integrated Energy and Climate Program (IEKP)* of 2007 (X). Concrete measures and discussions on electromobility began with the *National Strategy Conference on Electromobility* in late 2008 (IX). Germany’s political structure, organized as a federal republic, comprises national, federal state (Bundesländer), and municipal levels, each with distinct responsibilities. At the national level, the federal government sets overarching policies, legal frameworks, and funding programs for e-mobility. Federal states adapt these frameworks to regional contexts, implement state-level initiatives, and may introduce complementary measures. Municipalities are responsible for local infrastructure development, such as establishing charging networks and integrating e-mobility into urban planning. In line with these roles, the first national funding programs were launched in early 2009 as part of the *Fiscal Stimulus Package II* (VIII). In August 2009, the German government presented the *National Development Plan for Electromobility* (VII). To facilitate e-mobility efforts, the *Joint Federal Government Office (GGEMO)* was established in 2010 as a central point of contact [27]. Additionally, the *National Platform for Electromobility (NPE)*, formed in 2010, brought together representatives from various sectors to develop concrete proposals for achieving the goals of the *National Development Plan*. The NPE published its first interim report in November 2010 (VI). In the same year, following the release of the *Fiscal Stimulus Package II* (2009), a funding budget of approximately 500 million euros was allocated to several federal ministries, including those responsible for economics, transport, environment, education, and agriculture for e-mobility. Projects across fifteen thematic areas (V) included field trials of electromobility in passenger car traffic, the program model regions electromobility in Germany, and a proposed battery test center to improve European production [77].

That is while the first decade of the 21st century served to form policy strategy and principal plans, during the second decade instruments were further developed and legally refined. The developments resulted in a diversified policy mix as exemplified in Fig. II.

The political strategy for e-mobility includes building institutional, industrial and technological capacities, implementing measures to

increase the resilience of transport and mobility systems to energy and climate crises and providing economic drivers and incentives for the development of market structures (see Fig. 3). The principal plans are increasing renewable electricity production (Energy Industry Act, I), promoting the development of charging infrastructure (Masterplan Charging Infrastructure, II), and granting privileges for electric vehicles (E-Mobility Act, III). The instruments for implementation are described in the next section and illustrated by figure three. These initiatives reflect the national commitment to advancing industrial development and technological innovation in electromobility, focusing on improving batteries, charging infrastructure, and market uptake [78,79] Comparatively, limited efforts have been made to regulate and phase out vehicles with internal combustion engines. Germany’s initial resistance delayed the EU’s adoption of CO₂ fleet limits. However, a compromise was reached, allowing vehicles powered by e-fuels to be registered in the EU beyond 2035, provided they meet stringent climate neutrality criteria [80,81] In addition to national and EU-level legislation, academic advisors have proposed measures such as taxes and charges on combustion vehicles, urban tolls, and mobility management programs in companies and public institutions [82].

As visible in figure two the instruments in the national policy mix aim to promote sales and procurement of electric vehicles, provide tax incentives as benefits, promote the expansion of charging infrastructure and create privileges in traffic and parking. The concept of circular economy is supported through the battery law (BattG) and measures for climate mitigation are coordinated in the Federal Immission Control Act (BIMSchG). Building on our policy review, we identified a gap in the literature: a structured overview of the diverse regulatory instruments shaping the national e-mobility landscape was missing. To address this, we developed the model depicted in figure three.

By providing a systematic overview, the figure serves two purposes: first, it offers a framework to contextualize the diverse references made by stakeholders to existing regulations during our interviews. Second, it highlights the interconnections and thematic overlaps within the policy mix, and enables a comprehensive understanding. As no comparable visualization currently exists, this model aims to fill an important knowledge gap in the field and provide a tool for both academic analysis and practical policymaking. The instruments are incorporated in various legal documents: some in laws, some in directives or administrative regulations, and some in funding framework directives. Gustafson and Anderberg [83] provide an illustrative example of how policy measures at different levels of government affect a developing green technology. Similar to the legislative map of electromobility [71], this illustrates

Germany's E-Mobility Policy Mix

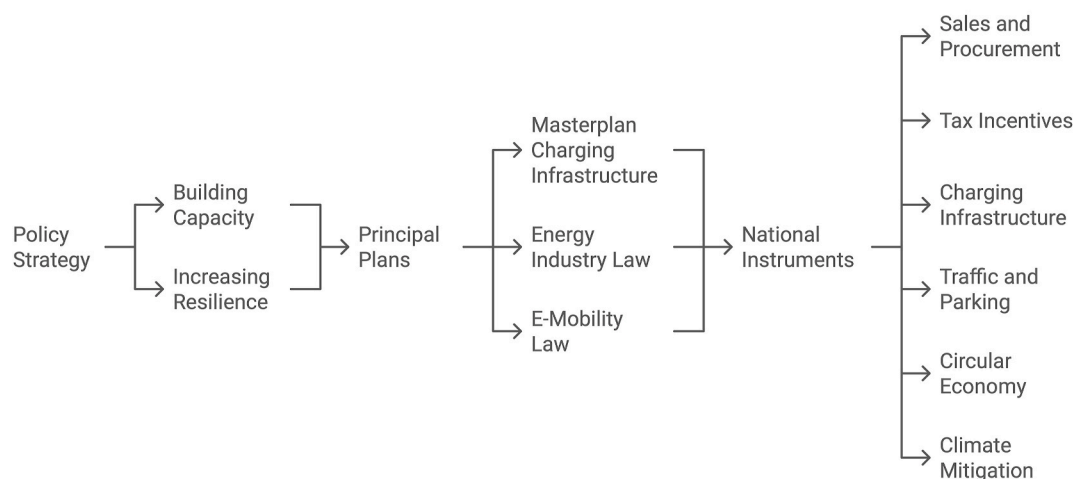


Fig. 2. Elements of the policy mix for e-mobility in Germany.

National Implementation Instruments for E-Mobility Policy

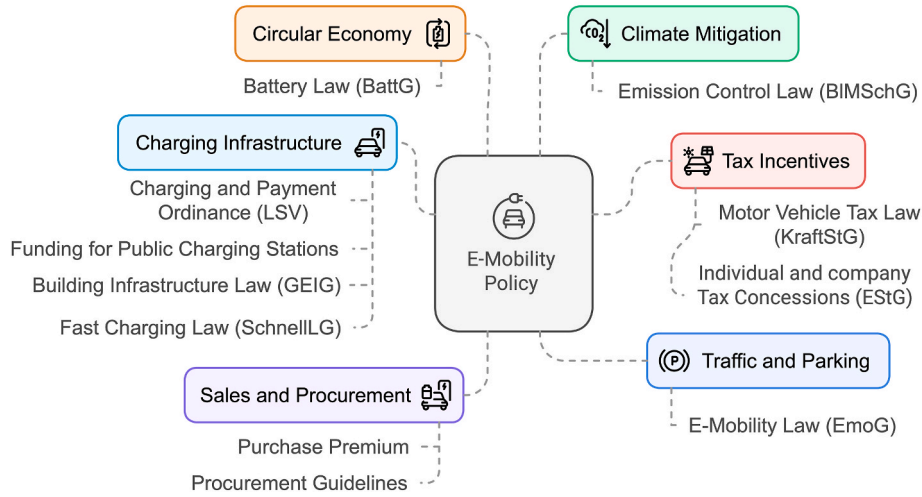


Fig. 3. Implementation instruments for e-mobility policy.

how different policy measures have an impact at different levels. As exemplified, certain legal instances are specifically formulated to facilitate cooperation in governance across levels. The directive on the Funding Framework for the deployment of public charging stations is enacted at the national level, while the responsibility for applying for funding for locally installed charging stations lies with the municipalities. Regarding higher-level European strategy papers, such as the Green New Deal European guidelines and national strategy papers define the objectives for corresponding legislation, such as the building electromobility infrastructure law (GEIG).

One note on governance and responsibilities: At the national level, laws and regulations primarily address overarching issues such as economic policy, energy regulation, and nationwide infrastructure, with a focus on the broader energy and mobility transition. At the level of the federal state (sometimes called regional), state-specific laws aim to implement national policies and address regional needs, particularly in energy policy and transportation systems. Municipalities, in turn, hold responsibility for local governance, including the development of urban transport plans, traffic management, and local charging infrastructure.

Most activities at the Lower Saxony level are aligned with federal funding programs, with municipalities primarily focused on practical measures such as parking regulations, charging infrastructure permits, and local incentives (e.g., free parking for electric vehicles). These measures vary widely and have seen notable reversals: for example, both Göttingen and Braunschweig recently discontinued free EV parking, citing the rising number of electric vehicles and a need to reallocate resources for charging infrastructure and parking management. Additionally, some local e-mobility policies are embedded in broader climate strategies or air quality plans, such as restrictions on combustion vehicles in city centers. What we seem is that municipalities hold a transformative potential within the boundaries of their realms of influence.

5. Implementation dynamics and capacity gaps: actor views

Having reviewed the policy landscape, we turn to our results on how actors engage in policy implementation. To understand this, we began by examining the overarching perspectives held by these actors on critical aspects of e-mobility development, encompassing infrastructure,

Table 1
Orientation and perceived challenges by different actor groups (charging infrastructure).

Field of Actor	Themes	Normative orientation	Identified challenges	Options for Policy Intervention
Rural retail, entrepreneurship	Availability of charging	Innovative focus, positive mindset towards shortcomings	Complexity and confusion associated with charging tariffs.	Streamlining payment service (legally)
Public-private partnership & non-profit organization	Charging Capacity	Focus on providing service, establishing effective partnerships, and fostering innovative solutions.	Internal limitations to further development, e.g., conflict of interests and administrative guidelines	Updating administrative guidelines and functions in ordinances (legally)
Municipal administration I and II	Procurement, scheduled drives and charging	Implementing policy, contributing to climate mitigation, providing service to the public	Flexible forms of service and small local solutions for charging spots; Identifying local hotspots for potential charging infrastructure	Adoption of municipal guidelines and concepts by the Council
Government agency	Featured programs, R&D funding, dialogue with public officials, infrastructure, governance	Creating linkages, promoting transfer of knowledge, fostering innovations	Dysfunctional charging spots (for various reasons), confusing references between the responsibilities of federal state and federal republic	Providing advice and mediation in ambiguous or unresolved legal areas, mandating providers to ensure functionality
Engineering	Upscaling and its limitations, charging options	Improving technology and efficiency, solving technological problems	Charging infrastructure in cities, insufficient options for private charging, capacity of the grid (connected load)	Further develop the existing legal basis for charging infrastructure in cities and the upgrading of the electricity grid
Private use	Charging on the road, Payment processing	Pioneering, supporting sustainable development, showcasing green mobility	Denser network of functioning charging stations, unified payment system	Streamlining payment service (legally), mandate providers to ensure functionality
Energy provision	Maps and navigation systems for charging spots	Promoting the e-transition, assisting through advice	Charging stations, unified payment system	Streamlining payment service (legally)

sociocultural factors, and resource availability. We especially explored the interplay between different actor groups and their normative frameworks - given Scott's emphasis on this, and the challenges that they perceive as part of the policy implementation process (Table 1). This actor-centric approach to transitions places greater emphasis on the social aspects of transitions, complementing the traditionally technology-oriented focus. It deepens our understanding of individual and collective behaviors as essential components of these transitions, as noted in prior research [9,10]. The accounts of the actors pointed to specific suggestions for strengthening institutional capacity, improving cross-level coordination, and advancing policy integration. In addition, many of these proposals focused on addressing challenges for the infrastructure development of the EV system. However, rather than reflecting abstract or generic notions, these accounts point to a situated, actor-driven process embedded in the e-mobility transition. This process involves adaptive engagement by formal institutions, intermediaries, and local stakeholders facing the concrete complexities of implementation.

We organized our findings into two sections. The first section (5.1) outlines the critical system challenges identified by the actors, while the second section (5.2) looks into their perspectives on the additional capacities needed in the sociotechnical system.

5.1. Challenges in the development of the EV system

From a sociotechnical systems perspective, system challenges are understood as complex and interconnected issues that arise from the interactions between social and technical elements within a system [84]. The sociotechnical systems approach recognizes that changes in one aspect of the system can have ripple effects on other components, leading to potential disruptions, conflicts, or unintended consequences. Addressing system challenges requires a holistic understanding of the sociotechnical context and the interdependencies between various elements to develop effective and sustainable solutions. Our actors viewed system challenges as an interplay between technological components, social practices, cultural norms, and institutional structures. Several actors voiced shortcomings and fundamental shortages for EV technology and the wider system in which it is embedded. These can also be framed as bottlenecks, systemic weaknesses, or initial positions for political intervention [85,86]. As such, what we present is more than a description of system-level challenges as perceived by the actors interviewed; it includes starting points for policy interventions, with a focus limited to charging infrastructure (Table 1). What we find is that the actors' perspectives of system challenges can also be understood as challenges to the institutionalization of EV system elements, which we refer to using Scott's term normative orientation [65]. While our interest was to map policy implementation processes as viewed by situated actors, charging infrastructure emerged as a key concern across actors, and we chose to focus on this aspect due to its centrality in the discussions. In the following table, the first and second columns link the field of the actor to emergent themes of problems in the socio-technical system. The third and fourth columns display the links between the perspective taken for problematization by the actors and their respective normative orientations. For instance, the following actor, serving as the director of a municipal service unit, emphasized quality in service provision:

And there are internal obstacles. Because as a general contractor, we are obligated to ensure traffic safety [...] And we have on-call services. In some cases, these still exclude electric vehicles. Because we must be on duty for longer periods, for example for winter services or unforeseeable events on the roads, accidents, and so on.

(Entrepreneur A2, pos. 19)

The referenced actor identified internal limitations, such as conflicts between development goals and administrative guidelines, as a key challenge. This phenomenon was observed among multiple actors. Table one illustrates the challenges perceived within the actor's field

and their associated normative orientations, which often appear to conflict with these challenges. To maintain a clear focus, we highlight one thematic arena common to all actors: charging infrastructure. However, the same analytical framework can also be applied to other areas examined, such as policy, regulation, and technological development.

Different actors in the e-mobility field face unique challenges but also have specific goals. For example, rural retailers struggle with confusing charging tariffs, while public-private partnerships deal with internal conflicts and unclear rules. In the field of administration, tension may arise between normative orientations and implementation practice, exemplified in the quote following. A senior executive at a federal innovation agency linked to car manufacturers and suppliers in the region is primarily tasked with coordinating funding programs and associated projects, as well as promoting dialogue between public and private structures. Normative orientations point to: improvement of cooperative collaboration, promotion of knowledge transfer and further development of innovations. The manager problematises confusing administrative responsibilities:

1 How can you bring regenerative energy into the vehicle and make it usable for electric driving? Whether that is a passenger car, an e-bike, or an e-vehicle, that can then certainly become enforced. You can always do a lot, but it's a question of what kind of understanding you have of what the state's mission and responsibility is in this context [...]. And I think that this current [...] situation shows very clearly, if you want to create incentives there, that there's always somebody who says, 'No.' (Manager C2 A, Item 23).

Despite the officer mentioning the often confusing formal accountabilities, which several respondents raised as an issue, he also emphasizes the lack of a 'progressive' attitude towards innovation and highlights the problem of malfunctioning charging spots not being repaired promptly by the provider. A third example demonstrates the comprehensive considerations that can take place in the background of decision-making processes, even if neglected in direct decision-making.

A municipal officer entrusted with climate protection matters described his thoughts on the question of a potential failure in the context of EVs, the following way:

2 Where do we build charging infrastructure? And what energy is generated at the same time as the charging demand arises? Do we want everyone to charge at home in their single-family [...] home and we get huge peaks in electricity demand from 5 to 7 pm? Can we get business models that offer flexible electricity tariffs? Can local energy suppliers already do this? What are the follow-up costs? Or wouldn't we prefer employers to be supported in setting up charging infrastructure that charges much more slowly, that charges at the midday peak, when the sun can provide the energy for three-quarters of the year? So there are a lot of technical and organisational questions that offer many opportunities, but you have to recognize them at first. And that is often not the case in reality. Instead, there is a very acute, implementation-oriented focus on what we need to do now and urgently. And then misallocations and wrong decisions are often made because there are no concepts that really look at the future: what do we need by 2030?' (Public Officer B1, pos 132).

In the broader policy landscape, municipal administrations reported difficulties in implementing policy effectively, particularly in adapting national-level strategies to local conditions. Actors from engineering fields emphasized the need for technical support in upgrading the grid and expanding charging infrastructure. Similarly, representatives of public-private partnerships stressed the importance of accessible and flexible administrative frameworks to facilitate collaboration. Rural retailers pointed to challenges in charging tariffs and payment systems, highlighting the need for simplification to support broader accessibility.

In sum, the examples highlight the complex interdependencies between social practices, cultural norms, institutional structures, and technological systems within the e-mobility landscape. The normative orientations of the actors often revealed tensions between their intentions and the systemic barriers they encountered. These contradictions point not only to persistent structural challenges but also to entry points for targeted policy intervention, as outlined in Table 1. Interviewees frequently emphasized the need to improve institutional capacity, ensure more effective cross-level coordination, and accelerate infrastructure development—particularly in addressing the widespread issues surrounding charging infrastructure.

5.2. Supporting systemic capacities for sustainable policy and governance

Recent discussions in sustainability transitions research have moved beyond conventional notions of capacity-building, embracing more multidimensional frameworks such as *transformative capacity* [87], *systemic innovation capacities* [88], and the *functions of innovation systems* [89]. These concepts emphasize that capacities essential for enabling and accelerating socio-technical transitions extend beyond technical domains to include institutional, educational, cultural-cognitive, and infrastructural dimensions. In the context of electric mobility, actor insights pointed to a range of capacity-related challenges that connect

Table 2
Measures to advance capacities in the sociotechnical system.

Field of capacity	Objectives	Suggested improvements	Policy Options
Technological	Expand and improve the charging station network	<ul style="list-style-type: none"> - Increase public charging spots - Enhance accessibility - Ensure compatibility - Install fast chargers - Set up charging facilities for larger utility vehicles - Streamline maintenance and payment service of charging spots - Improve technical reliability - Create virtual connectivity with software 	Further promote development of charging infrastructure according to masterplan, legally mandate technical reliability including sanctions, and promote research for the integration with vehicle-to-grid systems.
	Further develop the technology required for low-carbon electric vehicles	<ul style="list-style-type: none"> - Expand the range of vehicle models - Adapt available technology to larger utility vehicles - Increase battery range - Optimize thermal management - Propel research, development, and innovation - Enable integration into vehicle-to-grid systems 	
Institutional	Advance effective policy-mix	<ul style="list-style-type: none"> - Balance incentives and regulations. - Support the integration of evolving technology into the landscape. - Administer programs for the diffusion of socio-technical solutions. - Coordinate public invitations to tender. - Endeavor synchronization of collaboration among stakeholders. - Refine public procurement guidelines. - Foster public or public-private collaboration. - Enable the electrification of public transport. 	Continue the political work for a balanced policy mix that combines incentives and regulations, supports stakeholder collaboration, and integrates evolving technologies into public procurement and public transport systems.
Cultural-cognitive	Advocate a shift in mobility conceptions	<ul style="list-style-type: none"> - Cultivate a shift in attitudes, norms, and beliefs toward e-mobility - Heighten awareness about electric vehicle advantages - Dispel and clarify misconceptions - Foster a culture supportive of eco-conscious, localized solutions. - Address mobility behavior to align with vehicle capabilities - Embrace the challenge trio: digitization, electrification, and connectivity - Consider novel usage patterns, emergent business models and innovative mobility services - Foster an overarching transformation in mobility paradigms. 	Investing in awareness-raising campaigns social perception and behavior towards e-mobility (such as <i>Schaufenster E-mobilität</i>), offering consulting options through funded intermediaries to clarify misconceptions and continue to promote a culture of environmentally conscious mobility, e.g. through municipal offices for climate protection and appointed climate protection managers/officers.
Educational	Strengthen skills and competencies in the field	<ul style="list-style-type: none"> - Offer trainings to stakeholders in the field - Increase awareness about electric mobility - Disseminate knowledge about the latest developments in the field. - Provide qualifications through training for experts in the field 	Support capacity building through co-funding specialized training programs, and encourage transfer of knowledge and training initiatives for stakeholders and professionals in the field.

policy alignment with the dynamics of the sociotechnical system. Strengthening these capacities is not only critical for enhancing system resilience and upscaling but also for enabling actors to effectively navigate transition processes. Interviewees highlighted deficits and needs across multiple domains, stressing that the success of the transition depends on coordinated efforts to address these systemic weaknesses. In addition, the capacity to navigate transition processes can decisively determine their success [90]. The following categorization (Table 2) synthesizes the main capacity types referenced by the actors—technological, institutional, cultural-cognitive, and educational—and situates them within the broader discussion on building governance capabilities for sustainability transitions.

What we can see regarding technological capacity is a two-fold challenge. Research, development, and innovation are viewed to address both charging and vehicle technology, including battery, drive, and thermal management. Hence actors underscore the durability and longevity of the technology (Entrepreneur, Engineer, Researcher), and its commendable power delivery and acceleration (engineer, user, energy provider) as main potentials already developed, but. Still, also note that electrification needs to address larger utility vehicles (Public-Private Entrepreneur). In addition, the grid needs to incorporate mobile power storage units to apply the vehicle-to-grid concept (Engineer, Energy Provider), and various improvements are required to expand and improve the charging station network. A particular request voiced by several actors was streamlining payment services (Entrepreneur, Manager, User, Energy Provider). Lacking transparency in payment processes for charging increases the uncertainty associated with the technology for potential users. All of these factors contribute to building technological capacity for a large-scale transition to e-mobility. A further developed drive and battery technology, that serves different types of vehicles and interacts smartly with the grid would provide all additional functions to the mobility system (Administrative, Entrepreneur, Energy Provider). From an institutional perspective, the main objective of building capacity is to advance an effective policy mix and strengthen capability and competence within the administration and public service agencies, to progress policy, regulation, and governance. The entities involved need to be equipped with appropriate legal authority to enforce the statutes that are in place. This includes incentivizing the adoption of electric vehicles, creating operational structures, and synchronizing collaborative efforts among relevant stakeholders. It is particularly important to promote cooperation between municipalities and local companies (public-private, public-public, and private-private), as exemplified by several actors (public-private entrepreneur, public officer, manager, energy provider). An officer stresses that a trio of present challenges - digitization, electrification, and connectivity - need to be addressed by municipalities. This involves a spectrum of novel usage patterns, emergent business models, innovative mobility services, and an overarching transformation in mobility paradigms as part of strengthening cultural-cognitive capacity. Cultural-cognitive capacity here involves cultivating a societal shift in attitudes, norms, and beliefs to embrace electric mobility. Among the arguments raised within this category was heightening awareness of the advantages of electric vehicles in everyday-life contexts, and dispelling misconceptions, e.g., about range (both Users, Car-sharing Director, both Researchers and Energy Provider). Another partial but essential capacity addressed multiple times is the educational capacity generated by educating professionals, and providing training to strengthen skills and competencies. Building educational capacity can involve programs such as the “*showcase Lower Saxony*” described by a public-private innovation manager. The program seeks to enhance public dialogue and promotes test drives, but also increases the visibility of other electric vehicles such as buses and bicycles. It also includes specific training for professionals already in the field, but not yet familiar with electric drive technology, such as mechanics who need a specific certificate to operate on high voltages. This particular aspect was also raised as a recommendation by engineers and the operator of a local car workshop.

One not on policy process and approach, that leads us to further discussion of the results: In our study, actors primarily focus on identifying what needs to be addressed within their own institutional boundaries, which aligns with the concept of a “policy approach.” This emphasis on institutional priorities reflects a limited ability or inclination to engage with the broader “policy process,” which involves the interplay between multiple institutions. This observation is critical because it highlights the fragmented nature of policy discourse, where actors may not fully consider the interconnected dynamics inherent in sociotechnical transitions. The absence of substantial discussion on the policy process among actors can be attributed to two key factors. First, understanding the institutional capacities and constraints of other organizations involved in the process requires a broader systems perspective that many actors may lack. Second, actors tend to focus on their immediate institutional goals and roles, making it challenging to “think outside the box” of their organization. This insularity limits the ability to address challenges to the sociotechnical system collaboratively.

6. Discussion

The study raises issues relating to the complexity of policy implementation processes as viewed by different actors intermediating in the field. In particular, it indicates a need to achieve a shared understanding of the challenges and opportunities inherent in the transition, albeit with distinct perspectives shaped by their respective roles, expertise, and normative orientations. These differences highlight the importance of actor-centered analytical perspectives in understanding policy implementation processes, particularly in the context of e-mobility. Scott’s institutional typology provides a valuable lens for framing these dynamics, as it highlights how regulative, normative, and cognitive pillars influence the behavior of organizations and individuals and stresses the role of institutional capacity. Some actors emphasized the importance of institutional capacity-building, fostering collaborations, and overcoming regulatory barriers (normative and regulative aspects). Other actors stressed the relevance of technical readiness and innovation, such as improved charging infrastructure or vehicle-to-grid integration (regulative and cognitive aspects). By considering how actors’ experiences and normative orientations interact with these institutional pillars, this study offers a more comprehensive view of how policy is enacted and interpreted across different sectors.

Both actor interviews and policy review examined in this study reflect the complexity of the e-mobility transition. Across accounts, actors articulated distinct, field-specific challenges in navigating the e-mobility transition. Their perspectives underscore the need for improvements in institutional capacity, infrastructure development, and cross-sector collaboration through more coherent legal and procedural integration [91]. In line with broader understandings of capacity-building as the development of competencies, resources, and practices that enable collective action and strategic direction, our findings suggest that such capacities emerge across multiple, interrelated dimensions of the electric vehicle (EV) system. This aligns with existing research on transition management, which emphasizes the importance of strengthening systemic capacities—particularly across governance levels—to effectively steer sociotechnical change. [92,93]. Strengthening technological capacity involves not only advancing EV infrastructure—such as charging networks and grid integration—but also supporting continuous innovation in vehicle technology. Institutional capacity, by contrast, depends on improving governance structures and fostering effective cross-level coordination and policy integration. While cultural-cognitive capacity was addressed less frequently, it remains essential for shaping societal norms, user practices, and public acceptance of electric mobility. Educational capacity, meanwhile, is critical for developing a skilled workforce capable of supporting the technical and operational demands of the transition. The interplay of these capacities, when aligned with efforts to resolve the policy challenges

identified in this study, forms the basis for a targeted policy design and future research. Ultimately, the long-term success of the e-mobility transition will depend not only on technological progress but also on the establishment of a coherent policy framework that enables inclusive actor engagement and mobilizes expertise across sectors.

Drawing from the results we see a need for improved coordination, specifically in and between three fields: (i) Technically between research, manufacturing; and (ii) user experiences, infrastructure-wise, between grid operators, municipalities, and user representatives; and (iii) socially between experienced users, potential users, and public organizations. In terms of challenges to the EV sociotechnical system, we described how actors expressed concern about shortcomings and fundamental shortages for EV technology and the system. These can also be framed as bottlenecks or initial positions for political intervention [85]. What we found particularly is that actor perspectives of system challenges are also implied as challenges to the institutionalization of EV system elements. Moreover, the differing commitments of the actors stood out – that is, their differing roles, as expected, shaped their views of policy implementation problems and how they interpreted policy.

In terms of the relationship between actors' normative orientations and the problems identified in the sociotechnical system, however, a repetitive pattern was identified. The pro-EV normative orientations of actors contradict and contrast with the challenges and problems they regard as most disturbing and pressing to the transition of the system, i. e., the system deficits prevent their pro-EV stance from being realized in practice, and that tension also tends to catalyze engagement for change and transition. At the same time, analytically normative policy orientations are shaping the tasks they undertake and their impact on the system's overall functioning. Essentially, as hypothesized, actors' beliefs and policy perspectives interact with challenges to the sociotechnical system and their organizational roles which shape their actions and contributions to the transition to e-mobility. It is noteworthy that, within our set of interviewees, key actors, including administrative officials, project managers, researchers, coordinators, and representatives of lobby organizations, often played dual roles as users. They actively participated in the testing and evaluation of electric vehicle technology on a personal level in parallel with their strategic actions at a professional level. This dual function creates a self-reinforcing process where insights from both their professional and private roles enrich each other, contributing to further developments in the field. From the inferred recommendations for policy and capacity-building, we can infer a willingness on the part of each actor to contribute to the transition toward e-mobility as a whole. In many cases, their narrative content appears to be testimony to innovative and creative problem-solving accounts, particularly when taking the narrow limits of implementation into account.

Methodologically, we employ three foundational concepts to underpin our research: (i) the model for policy mix elements developed by Rogge & Reichhardt [41]; (ii) the dimensions of the automobility regime within the context of a multi-level governance framework presented by Hoffmann et al. [76] and (iii) Scott's model comprising the pillars of institutions [65]. Thus our research also contributes to the analytical discourse of sociotechnical transitions studies by demonstrating the practical utility of these conceptual frameworks per se and when brought together to outline a systematic approach for transferring expert knowledge. Arguably the compilation of instruments in the policy mix merits further research in-depth in transitions studies, focusing on the policy implementation part of the policy cycle, with a view to understanding the intricate and interrelated mechanisms and instruments at play in policy mixes.

Furthermore, there is room for future research to explore additional aspects, including the alignment of strategy with specific instruments, the effectiveness of various instrument types such as the purchase premium, and the evaluation of policy coherence when taking all governmental programs into account. When considering the broader sociotechnical system, assessing causality in transition processes is a

formidable task due to their complexity and multidimensionality [84]. This complexity also extends to the analysis of policy implementation processes, which are influenced by the actions of intermediaries. Even with a wealth of data, attributing successes and failures to specific factors in the policy process remains challenging and requires additional methods and data sources such as regression analysis with quantitative data. As a consequence, the question arises as to whether a more transparent legal framework would lead to a denser network of charging stations or whether more funding for programs to promote public awareness and visibility of the technology would lead to higher sales of e-vehicles. Adapted quantitative research method could allow a reliable statement to be made in this regard. Given the exploratory nature of our research and the tentative nature of evidence in a single case study region, further investigations into the effectiveness of policy implementation are necessary. These would ideally take the complexity of policy implementation processes influenced by intermediaries into account and would use systematic assessment, data triangulation, and consultation of policy experts in a similar way.

7. Conclusion

This study has explored the perspectives of diverse actors involved in the e-mobility system in Lower Saxony, Germany, examining how they perceive and navigate challenges within the broader sociotechnical landscape of e-mobility. Based on interview data with actors from seven fields of action within the e-mobility system, and a review of the policy context, the analysis reveals problematic issues in several sub-areas of the sociotechnical system: resources, supply, and maintenance; infrastructure; technology and sociotechnical transitions; rules and regulations; cultural aspects; and user practices. We interpreted our results in terms of a need for a more comprehensive and integrated policy approach that addresses current deficiencies and shortcomings. By highlighting challenges related to infrastructure requirements and usage patterns of electric vehicles from the perspective of key actors we describe conditions, that need to be transformed for a continuing diffusion of electric vehicles. As a result of our analysis, we identified several system challenges to the implementation of e-mobility policies, including the availability and capacity of charging infrastructure, complexity, and confusion associated with charging tariffs, limitations in technological development and upscaling, and conflicts of interest and administrative guidelines within organizations. While these issues are widely recognized, our main contribution lies in emphasizing the need to consider the practical experiences and perspectives of diverse actors within the e-mobility system, who encounter and navigate these challenges in their intermediary roles. Yet, from a top-down perspective, a coordinated approach of adapted and orchestrated policy instruments can add to the improvement of e-mobility governance. Looking from a bottom-up angle the insights of expert knowledge provided specific and applicable recommendations to enhance capacities in the EV system. These include improving technological capacity through research, development, and innovation in EV technology, strengthening institutional capacity through policy coordination and collaboration between stakeholders, enhancing cultural-cognitive capacity by promoting awareness and dispelling misconceptions about electric vehicles, and building educational capacity through training and skill development.

Thus, in short, the research presented here highlights the need for a comprehensive and integrated policy approach, coordinated among the political levels. As shown, policymakers need to address the challenges and deficiencies to improve the adoption and diffusion rates on a pathway to sustainable mobility patterns. In addition to this, our analysis led to further information on the options available to enhance the current policy mix as a basis for future recommendations. Here we aligned with SDG 9 by addressing the development of sustainable and innovative mobility systems. By identifying policy and actor-driven strategies for e-mobility, the study contributes to building resilient infrastructure and promoting inclusive, sustainable industrialization,

key targets of SDG 9.

CRedit authorship contribution statement

Lea Gathen: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Paul Upham:** Conceptualization, Writing – review & editing, Supervision. **Jens Newig:** Software, Resources, Writing – review & editing, Supervision.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DEEPL in order to improve the linguistic accuracy and correctness of the terms used. Chat GTP was employed to enhance readability and assist in the structural refinement of arguments by providing alternative formulations and suggestions for conceptual consistency. In particular, the tool was used iteratively during the revision process to align terminology and improve coherence across sections. All AI-generated suggestions were critically reviewed, adapted, and edited by the authors, who take full responsibility for the final content of the publication.

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.rser.2025.115787>.

Data availability

The authors do not have permission to share data.

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