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Anticipatory climate policy mix pathways: a framework for ex-ante construction and assessment applied to the road transport sector

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ABSTRACT

Globally, climate policy implementation is failing to deliver on the ambitions outlined in the Paris Agreement and countries' Nationally Determined Contributions. We argue that a more strategic and anticipatory approach to policy mix design and implementation can help contribute to realizing these ambitions. Policy mixes need to co-evolve as energy transitions progress, in order to effectively target multiple transition challenges as these change over time. Accordingly, policy assessments need to both consider interactions between instruments and adopt a dynamic perspective, in terms of design logics and evaluative criteria. We highlight the need for a construction and assessment methodology for designing policy mix pathways which explicitly considers durability risks which could weaken support and lead to dismantling, and anticipatory design principles which can help mitigate these risks. Our paper addresses this gap by proposing and illustrating a novel framework for policy instrument mix pathway construction and ex-ante assessment. We identify generalizable durability challenges for effective anticipatory design: dynamic cost effectiveness, the distributive impacts and acceptance of pathways, along with fiscal and governance requirements for effective implementation. We demonstrate the value of the approach by application to the German light-duty vehicle sector transition. We construct and comparatively assess three illustrative pathways promising to deliver the German LDV sector 2030 GHG targets. The pathways differ in logic, and which of three main market dynamics driving a diffusion-stage transition they emphasize: battery electric vehicle (BEV) purchase, vehicle stock usage, and internal combustion engine (ICE) vehicle scrappage. Accordingly, the pathways utilize different instrument combinations, design features and calibrations. We also assess the illustrative pathways and discuss trade-offs. We argue that this approach can help improve climate policy planning and implementation processes, and increase the likelihood attaining ambitious mitigation targets.

Key Policy Insights

- Policy mix pathway design needs to consider instrument interactions and dynamic and inter-temporal durability challenges as they co-evolve with the stage of transition.
- Policy mix durability challenges increase risks of political backlash which may undermine support for the transition and lead to dismantling.
- Application of anticipatory design principles while constructing policy mixes,

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combined with reflexive assessment and recalibration can help mitigate potential durability risks.

- Supportive policy instruments can be combined with core instruments to reduce durability risks of the overall mix. This may include distributing resources and revenues to improve progressivity and increase acceptance.
- Our application to the German LDV sector highlights that a sequencing approach, initially focussing on stock turnover and shifting to usage over time, allows less accepted instruments (carbon pricing, vehicle-usage malus) to increase in stringency more gradually, reducing risks.

1. Introduction

Limiting global average temperature increase to significantly below 2°C requires unprecedented climate policy ambition (United Nations Environment Programme, 2021). The Paris Agreement and Nationally Determined Contributions (NDCs) have facilitated the establishment of national net zero emission goals and other mitigation targets. Yet, translating targets into action remains a significant challenge for policymakers (Fransen et al., 2023). This requires effectively constructing, implementing, sustaining, and adapting climate policy instrument mixes that are stringent enough to attain mitigation goals (IPPC, 2022). Accordingly, anticipatory climate policy instrument mix design and implementation is characterized by several key aspects.

First, no 'silver-bullet' policy instrument can drive multi-faceted transition processes (Gallagher et al., 2012). Climate policy design must focus upon identifying integrated policy mixes which can simultaneously address market and systemic failures (Rogge et al., 2020), and minimize trade-offs through synergistic instrument mix design (Rogge & Schleich, 2018). Policy mixes can seek to utilize both supply side and market pull-mechanisms, and dismantle supporting mechanisms for the current technological paradigm.

Second, anticipatory policy mix design needs to address multiple *durability challenges* simultaneously. Securing and maintaining sufficient political support to enable implementation is fundamental (Edmondson et al., 2019; Konc et al., 2022; Schmid et al., 2020). Minimizing distributional impacts, fiscal costs, and increasing dynamic cost effectiveness of transitions helps improve the political durability of pathways once implemented (Oberlander & Weaver, 2015), mitigating the potential for negative feedback mechanisms, political backlash, and retrenchment (Jordan & Moore, 2020).

Third, increasing the *credibility of policy commitments* (Victor et al., 2022) by establishing a viable strategy and trajectory, and providing clear and non-contradicting directionality of the transition are critical for reducing risk and accelerating the rate of change (Rogge & Dütschke, 2018). Still, significant uncertainty of technological, economic, social, and political conditions, necessitates balancing directionality, flexibility, and adaptation to changing conditions and unintended consequences.

Implementation requires effective *governance*, establishing and strengthening capacities for regular policy monitoring, evaluation, and updating of the policy mix pathway in a continuous, reflexive learning process. Furthermore, applied climate policy assessments may be challenged by limited availability of rigorous empirical ex-post evidence about the precise effects of interacting policy instruments.

Given these requirements, analysts and practitioners need to move towards dynamic policy assessment frameworks that account for and mitigate evolving uncertainties through anticipatory pathway design. Static policy assessments (Axsen et al., 2020) point out important features of policy mix design, but do not capture crucial temporal dynamics and interactions. The design of policy pathways and (related governance institutions) requires anticipating how instruments can balance challenges and attain mitigation targets through adjusting instrument stringencies and sequencing (Linsenmeier et al., 2022; Pahle et al., 2018), while incorporating enough flexibility to co-evolve over time with changing conditions and adapt to unexpected outcomes.

This article proposes a practical approach for anticipatory policy instrument mix construction and reflexive governance. We derive an assessment framework that helps guide the construction, implementation, and revision of ambitious climate policy pathways. By integrating evidence from multiple disciplinary perspectives,[1] and combining concepts of co-evolutionary design (Schmidt & Sewerin, 2017), policy feedback (Edmondson et al.,

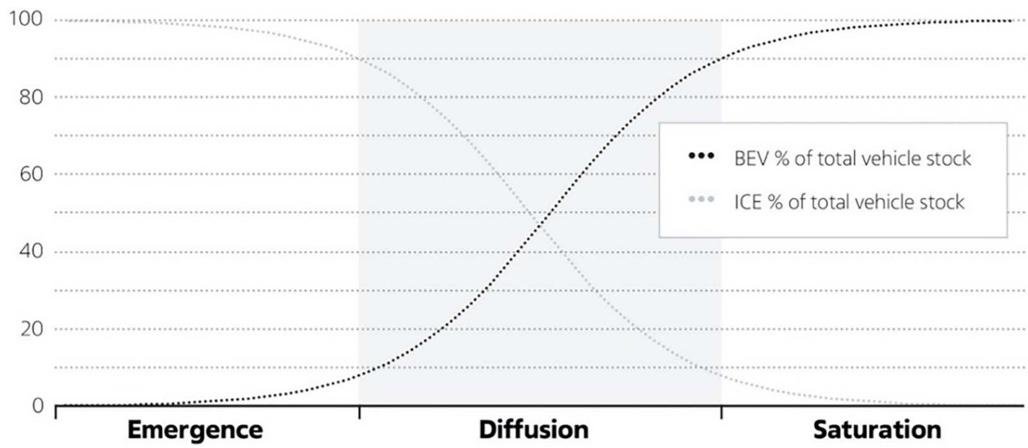


Figure 1. Stylized process of transition from internal combustion engine (ICE) to battery electric vehicle (BEV) fleet stock in the road transport transition to net zero emissions. Own illustration building on Markard et al. (2020) and Rogers (2003).

2019) and policy sequencing (Pahle et al., 2018), this framework offers guidance for crafting anticipatory pathways and thinking-through necessary reforms (Morrison, 2022). Many jurisdictions have established comprehensive climate policy planning, evaluation, and review processes (Dubash, 2021). Yet, an approach which combines ex-ante design principles, durability challenges and principles of reflexive governance, while also enabling practical and traceable guidance for implementation, is yet to be adopted. Application of our assessment framework might help further improve these procedures, helping identify areas of uncertainties and key risks and conceive strategic implementation trajectories. It also aims at stimulating further academic debate about rigorously constructing climate policy assessment frameworks that can inform applied climate policy analysis.

For this purpose, we demonstrate the main steps through application to the light-duty vehicle (LDV) sector in Germany. It is a particularly well-suited case, representing a maturing sectoral technological transition, breaking-through into broader market diffusion from its emergence stage (Rogge & Goedeking, 2024). This involves major changes in technological, economic, social, and political conditions, which requires anticipatory, co-evolving policy design. Our general approach can be tailored to other contexts and technologies, across sectors, regions, and time.

The paper proceeds by situating our approach at the forefront of sustainability transitions research (Section 2.1) and developing an analytical framework of durability risks and anticipatory design principles (Section 2.2). Three procedural steps for policy mix construction and assessment are outlined (Section 3), which are then demonstrated in the following sections through application to the German LDV sector. Section 4 reviews the state of transition, market dynamics and instrument selection. Section 5 assesses the status quo policy mix and derives incremental policy patches. Section 6 constructs, assesses, and compares alternative policy mix pathways, before section 7 draws conclusions and recommendations for further work.

2. Anticipatory policy mix design and durability challenges

2.1. Climate policy instrument mixes: design, diffusion, disruption, and durability

Transitions involve the emergence and diffusion of technological alternatives and new socio-technical configurations (Grin et al., 2010), which can either displace, or be integrated into the current paradigm (Geels & Schot, 2007) (stylized in Figure 1).

Typically, transition policies in the early-emergence phase help foster novel technologies in a protective space (Smith & Raven, 2012), accelerating development and demonstration through combinations of R&D

[1]Notably climate economics, political science, transport studies and sustainability transitions.

support, subsidies, regulations, economic, and systemic instruments (Borrás & Edquist, 2013). To drive the ongoing transition, policy makers can help establish a common vision that provides directionality and helps coordinate expectations of market actors (Jaakkola et al., 2023; Kanger et al., 2020). This can be achieved through establishing a strategy and a target (Quitzow, 2015; Reichardt & Rogge, 2016), which can be enshrined in legislation. Subsequently, policy instruments supporting acceleration need to be adopted (Nascimento & Höhne, 2023), and calibrated with design features and goals consistent with the target's objectives and other implemented instruments (Rogge & Reichardt, 2016). A key challenge is establishing policy instrument trajectories with enough credibility to guide directionality and drive the required rate of change (Rogge & Dütschke, 2018), while also allowing enough flexibility for adapting to unpredictable conditions (Jordan & Moore, 2022).

As the transition progresses into the early-diffusion stage (acceleration), the policy mix must co-evolve to address changing conditions (Edmondson et al., 2019) and focus on enabling market adoption (Hoppmann et al., 2014). Targeted interventions can reduce prevailing barriers to entry (Weber & Rohracher, 2012), including the potential lack of supportive infrastructure (Koch et al., 2022b). Policy mixes must focus not only on supporting the emergent socio-technical configuration, but also actively disrupting the existing paradigm (David, 2017; Rogge & Johnstone, 2017), including reforming rules and institutions which support the status quo (Kivimaa & Kern, 2016; Rosenbloom & Rinscheid, 2020). Interventions must change market conditions to favour the new emergent configuration while actively accelerating the phase-out of the incumbent polluting paradigm (Rosenbloom & Rinscheid, 2020; Trencher et al., 2023). This allows the emergent socio-technical paradigm to 'breakthrough' and displace the incumbent socio-technological regime (Kanger et al., 2020). As the existing paradigm shifts to organization around the emergent socio-technical configuration, enhancing just and equitable outcomes is essential (Wang & Lo, 2021). Anticipating and mitigating potential adverse societal effects requires explicit attention directed towards distributional impacts, access, and inclusion (McCauley & Heffron, 2018).

During the transition, the emergent paradigm can become self-reinforcing in a virtuous cycle (Edmondson et al., 2019). As market shares increase, firms' investment risks are reduced and yield greater returns, which strengthens networks of market actors and supportive coalitions (Hekkert & Negro, 2009). Yet, placing strong pressures on displacing the old paradigm without enabling the availability of viable and affordable alternatives, will likely incur negative feedback mechanisms from incumbents and opponents (Edmondson et al., 2020). Negative macro-economic impacts, regressive distributive effects, and social exclusion, increase the likelihood of societal and political resistance, which can undermine support for climate policies and lead to dismantling or termination (Gürtler et al., 2019). Rapidly ramping-up the stringency of policy instruments, such as introducing sudden restrictions through bans, increases the likelihood of acceptance issues and unintended consequences, which further increase the potential for resistance and backlash (Carattini et al., 2019). Accordingly, utilizing sequencing logic for increasing trajectories of more contested instruments (such as pricing) helps mitigate negative backlash against the new socio-technical paradigm (Meckling et al., 2017). This allows momentum to be generated and the policy mix to become more durable (Jordan & Matt, 2014) through strengthening networks and supportive coalitions (Gaikwad et al., 2022; Haelg et al., 2020), and changing societal norms and expectations (Upham et al., 2013). Even so, limiting the potential short-term costs and societal impacts of more ambitious mitigation policies must be balanced against the potential repercussions of low initial policy stringency (Köberle et al., 2021). Delayed ambition will result in targets being missed, incurring significant consequences for ecosystems and broader societal stability (Calvin et al., 2023). Consequently, balancing anticipated effectiveness in driving transition and GHG abatement with potential distributional impacts and backlash, through strategic combinations, timing and sequencing of instruments must be the explicit focus of policy mix design.

Many jurisdictions have adopted assessment processes for monitoring climate policy and sustainable transformation progress, including France (Ministère de la Transition écologique, 2024), Germany (BMWK, 2024), the Netherlands (Rijksoverheid, 2024), The UK (Climate Change Committee, 2024), and Sweden (Klimatpolitiska rådet, 2024). Such analyses measure the progress of sectoral decarbonization and/or the entire energy system, which help identify trends, rates of change, and potential bottlenecks. Even so, they are commonly less prescriptive about actionable steps to be taken to achieve objectives. Instead, the design and implementation of instrument mixes is relegated to respective appointed bureaucracies (for a particularly elaborate process, see the California scoping plan California Air Resources Board, 2022). Still, ambitious climate policy objectives have not been realized, and recent reports have called for increased attention to implementation (United Nations, 2023). Similarly, while scholars have started to address the implementation gap (Fransen et al., 2023), an approach which facilitates the construction and assessment of practical implementation strategies to achieve sectoral transformation, which simultaneously integrates anticipatory design principles, is still lacking. We contribute a construction and assessment methodology, which not only seeks to enable the attainment of mitigation objectives in terms of selection and calibration of *effective* instruments and synergistic interactions, but also explicitly considers *durability challenges* which may undermine political support for the policy mix over time.

2.2. Key policy mix durability challenges and anticipatory design principles

We develop a framework for anticipatory policy instrument mix pathway construction and assessment (Table 1). The framework combines insights from climate economics (Stern et al., 2022), policy design (Howlett, 2014), policy mixes for sustainability transitions (Rogge et al., 2017) and policy feedback theory (Beland, 2010). We propose key *durability challenges*, linking these to established feedback mechanisms (Edmondson et al., 2019; Oberlander & Weaver, 2015), and derive *anticipatory design principles* to be utilized by practitioners and analysts to help mitigate the risk of policy pathway failure.

2.2.1. Effects of policy mix design and implementation on population groups

Cost effectiveness refers to the economic costs of attaining transition and has both static and dynamic dimensions. From a societal standpoint, enhancing cost-effectiveness should aim to reduce both static (short-term) and dynamic (over time) inefficiencies. Economic analysis of climate policy often focusses on *static* cost effectiveness, targeting lowest cost GHG emission reductions across the economy in a restricted period of time (Fischer & Newell, 2008). Yet, focussing on static cost effectiveness can potentially promote incrementalism (Rosenbloom et al., 2020). From a dynamic perspective, the potential for investments to enable path-breaking changes and future cost savings should be taken into account. Increasing *dynamic cost effectiveness* (Stern et al., 2022) therefore requires targeting market and systemic failures hindering acceleration and diffusion, and reducing investment risks. Firms' behaviour is affected by trends in demand and consumer preferences (Mattauch et al., 2022), and the credibility and certainty of policy commitments (Rogge & Dütschke, 2018). Targeting market failures and providing clear and credible policy direction from government can directly address these challenges. Increasing policy certainty is particularly important for motivating private-sector expansion of infrastructure, which typically needs to be initially over-provided to support early-market diffusion (Funke et al., 2019). Doing so helps mobilize private sector finance, increase innovation, and scale-up production, which enable quicker cost-performance breakthroughs and reduce aggregate transition costs over time. These benefits of government intervention need to be weighed against risks of costs they might incur in case of error, or unpredictable changes in conditions. Policy instruments with flexibility mechanisms can help minimize trade-offs. In our case study, enhancing dynamic cost effectiveness may involve higher short-term costs of supporting BEV (Battery electric vehicle) diffusion and infrastructure development which only pay-off over time. In that respect, dynamic cost effectiveness may contradict static cost effectiveness considerations (Vogt-Schilb & Hallegatte, 2014).

Distributional effects refer to adverse impacts among population groups and should be mitigated to avoid social exclusion and inequitable outcomes (Lucas et al., 2016). Distributional effects also relate closely to durability over time, since increasing inequality can undermine electoral support and more ambitious climate policy (Chandra et al., 2010). Perceptions of anticipated losses over time can mobilize interest groups, resulting in negative socio-political feedback mechanisms, increasing pressures to relax ambition, which may result in instruments being removed or suspended when significant opposition grows (or is anticipated) (Jenn et al., 2013). Progressivity of targeting can increase acceptance, whereas regressive outcomes are likely to undermine support (Mildenberger et al., 2022). Mechanisms to balance distributional effects include direct redistribution of revenues to citizens (e.g. income-and or/exposure-based per capita payments Dechezleprêtre et al., 2022) and earmarking funds for green infrastructure investments (Baldenius et al., 2021) which have indirect effects on

Table 1. Policy instrument mix durability challenges, potential feedback, and anticipatory design principles. Feedback mechanisms derived from (Edmondson et al., 2019; Oberlander & Weaver, 2015).

	Durability Challenge	Description and key dynamics	Potential negative feedback mechanism(s)	Core Components	Anticipatory design principles
Effects of Policy Mix Design and Implementation on Population Groups	**Cost Effectiveness**	Cost effectiveness of instrument mix in stimulating transition and achieving GHG abatement. Includes both static and dynamic dimensions of cost effectiveness. Dynamic cost effectiveness may contradict static dimensions.	**Socio-political Feedback:** Cognitive effects – Perception of widespread losses increases dissatisfaction in mass public. Concentrated and visible losses will likely result in significant opposition and mobilization of interest groups.	*Dynamic cost effectiveness*	- Addressing market and system failures hindering innovation, including consumer myopia, learning by doing spillovers, R&D spillovers, network externalities. - Supporting innovation through dynamic efficiency signals more long-term commitment. Increasing credibility helps avoid investment hold-ups by firms.
				Static efficiency	- Enhancing static efficiency can deliver short term mitigation (optimising) at lower aggregate costs. - Technology neutrality may reduce directionality of transition, thus increase investment risks.
	Distribution	Costs/benefits bestowed on target groups through policy instrument mix design. Target groups considered include socio-economic stratification of population groups and firms.	Interest group effects – Perception or anticipation of concentrated losses leads to development or strengthening of constituencies seeking policy change, and/or to fragmentation of existing supporting coalitions.	*Impacts on population groups*	- Minimizing regressive distribution of costs among population groups. - Implementation of redistributive mechanisms and design features.
				Impacts on firms	- Managing distribution of costs among firms and impacts on national competitiveness. - Introduction of rules and institutions which protect competitiveness (if permissible under local jurisdiction). Must be well-justified to prevent rent-seeking, special interests, and regressive distribution.
	Acceptance	Acceptance of mass public and firms associated with the mobilization of interest groups and constituencies. Acceptance in population groups linked to perceptions of fairness, and progressivity of distribution. Acceptance in firms linked to reduced risk of investment and retaining national competitiveness.	Agenda effects – Constituency and elite satisfaction with policy mix narrows agenda to incremental programme fixes, while dissatisfaction leads to more radical reform. These include replacement of core instruments, reduced ambition, or termination.	*Acceptance of population groups*	- Increasing acceptance among population groups/avoiding political backlash. - Sequencing of instruments by laying the foundations of effective instruments and increasing stringency over time. - Avoiding significant and sudden changes of personal autonomy (i.e. bans) and highly visible concentrated losses.
			Socio/political feedback may be generated for the policy mix as a whole, or towards particular instruments. Strategic policy mix design which helps balance benefits and losses across target groups can seek to reduce broad negative feedback against support for the transition.	*Acceptance of firms*	- Increasing acceptance/avoiding backlash among industry interest groups/ stakeholders. - Providing state fiscal support to promote national competitiveness can increase firms' acceptance. - Establishment of clear trajectory to reduce investment risk.

Budgetary and Capacity Requirements	**Fiscal Costs**	Incurred costs on fiscal budgets of supporting the policy instrument mix. Subsides incur direct fiscal costs, while regulations incur less visible administrative costs. Balancing policy instrument mix design to generate revenues can minimize aggregate fiscal costs.	**Fiscal Feedback:** High fiscal costs may result in negative fiscal feedback in times of crisis, where support for the policy mix is undermined through conflict with other budgetary priorities. Conversely, generating revenues may create political support and shielding for the policy instrument mix.	*Costs/revenues to state*	- Reducing fiscal costs mitigates disputes with other policy objectives, short-term decision making, or crises. - Increasing revenues generated from policy mix increases support from political elites. - Transparent investment and redistribution of revenues needed to increase acceptance.
	Governance	Capacities for recalibration, monitoring and enforcement needed to ensure effectiveness and mitigate evasion. All instruments have administrative and information requirements. Some instruments, and more complex combinations, incur higher administrative requirements and associated costs.	**Administrative Feedback:** If administrative failures recur frequently and grow in visibility or appear to get worse, the credibility of the policy mix is undermined. The reputation of the enacting governmental officials can be damaged and large or persistent governance failures may be reflected in electoral outcomes and reduced policy credibility.	*Administrative/ information requirements*	- Developing sufficient institutional capacities for reliable and timely monitoring and evaluation, enabling updating and recalibration over time. - Anticipating that complexity increases with more instruments, increasing interaction effects and likelihood of unintended consequences. - Ensuring development of state capacities required for ensuring policy instrument effectiveness (mitigating evasion).

progressivity. Policy instruments with design features which provide resources targeting disadvantaged socioeconomic groups can also be utilized to make climate policy more progressive, increase acceptance and reduce potential for backlash. Beneficiaries may mobilize to form supportive coalitions (Pierson, 1993b). Distributive impacts also relate to firms and industries, particularly if policies affect their international or domestic competitiveness (Meckling & Hughes, 2018).

Acceptance relates to the receptivity of population groups to ambitious climate policies, considering governments have been penalized in elections for introducing unpopular policies (Stokes, 2016). The speed at which ambitious climate policy can be realized might thus be constrained by public opinion and/or electoral support (Levi et al., 2020). Acceptance of the new technology can also be increased through innovation, costs reductions, and reducing any practical disadvantages or network barriers which may favour the existing technology paradigm. For BEV, increased availability of high-capacity batteries and fast charging infrastructure has been shown to increase acceptance (Dijk et al., 2020). Instrument selection and design also relates to acceptance. Imposing sudden and visible restrictions will have low acceptance, posing a barrier to implementation (Jiang et al., 2020). Policy sequencing, and increasing to higher stringencies over time are effective strategies to enable the implementation of more contested instruments (Axsen et al., 2020; David, 2017). Some policy options may be strongly contested if inconsistent with cultural identities, norms, and ideologies. This particularly depends on how public opinion translates into political party platforms where political competition can also favour or exclude policy choices (Hughes & Urpelainen, 2015). Shifts in cognitions through shaping expectations, and increasing trust through enhanced transparency, pluralism and participation in governance institutions may also increase acceptance (Hardman et al., 2017). Population group acceptance of more controversial instruments, such as carbon pricing, is closely associated with perceptions of fairness (Tietge et al., 2016). Pricing mechanisms, which increase levelized costs of goods and services, can further exacerbate existing distributional inequalities within society if not managed effectively (Maestre-Andrés et al., 2019). Therefore, anticipatory policy mix design seeking to increase acceptance should not only minimize regressive distribution but also combine instruments and mechanisms to actively produce more progressive outcomes. As discussed, this may include revenue redistribution and provision of services for vulnerable groups (Dechezleprêtre et al., 2022). These benefits should be clearly and effectively communicated to increase visibility, and ensure the links between resource provision and climate policy are salient, enabling increased support for the transition (Edmondson et al., 2019).

Firms' acceptance and resistance are also important and linked to maintaining competitive market advantages and retaining existing assets. Utilization of industrial policy instrument options which can help protect national competitiveness, such as local content requirements, might help increase acceptance by firms. However, existing rules which exist nationally or internationally (including, in the EU, state aid rules) may restrict or prohibit the implementation of such mechanisms. In such cases, other forms of support which help support national industries such as R&D support or labour market support for supply chains may be utilized.

2.2.2. Budgetary and capacity requirements

Fiscal costs are state budgetary requirements for supporting the policy mix. Some policy instrument options incur direct costs on state budgets, while others incur indirect costs through increased administrative costs and governance requirements (Edmondson et al., 2019). Designing policy mixes with low fiscal burden shields from politicization (Oberlander & Weaver, 2015); helps resolve conflicts about trade-offs with other state investment opportunities; and increases durability when crises or short-term decision-making can reorientate support to other issues (Edmondson et al., 2020). Fiscal provision from the state should be balanced with the acceptance of the policy instrument mix. Allocation of resources to both population groups (e.g. direct subsidy, revenue redistribution), and firms (e.g. direct subsidy, rents, tax benefits) motives coalitions to support or oppose changes to the instrument mix (Pierson, 1993a). Therefore, while reducing fiscal costs might reduce resistance from budgetary guardians (finance ministry) (Oberlander & Weaver, 2015), it might increase opposition from political opponents, weaken advocacy coalitions, and undermine the political durability (Edmondson et al., 2020). Conversely, if policy instruments can generate revenues, they may be protected by budgetary guardians. Accordingly, anticipatory policy mix design should aim to reduce fiscal demands on the state by combining instrument types, where costs incurred by regulatory and subsidy instruments are balanced by price-based instruments which influence behavioural change while also generating revenues.

Governance relates to the substantial administrative and epistemic tasks such as preparing, monitoring, assessing, and updating policy mix pathways. Our focus is directed towards capacities needed for implementation and monitoring of instruments mixes (Mukherjee et al., 2021), and the variance in administrative and information requirements associated with instrument choices (Capano & Howlett, 2020). Sufficient capacities and structural institutions (Hodgson, 2006) are required to access and gather reliable information for monitoring and enforcement, to mitigate evasion and ensure effectiveness (Guy et al., 2023). Processes may be conducted internally by bureaucracies, delegated to public-private bodies or consultancies (Kuzemko, 2016), or convened through participatory approaches (Torfing, 2020). Information requirements may differ by instrument types, and reliability and access to data may be a critical factor for effective governance of some options (i.e. regulation) (Mukherjee et al., 2021). Adaptive governance requires (re)calibration of objectives and instruments over time (Folke et al., 2005). Anticipatory policy mix design should acknowledge uncertainties and design policy mixes with flexibility mechanisms to adapt and planned revision steps (Jordan & Moore, 2022). We assume that a higher number of interacting instruments in the mix tends to increase complexity, which can increase administrative costs, the risks of policy calibration errors, and unintended consequences (Howlett & Rayner, 2007). Visible failures result in negative administrative feedback, which damages the reputation of departments responsible for implementation (Oberlander & Weaver, 2015). In coalition government this can result in negative electoral outcomes for political parties with ministerial mandates to deliver on policy objectives, particularly if policy design choices have incurred losses for population groups, which are both visible and traceable enacting political parties (McConnell, 2010). Failures and negative administrative feedback become more likely if responsibilities are divided among multiple departments and institutions with conflicting organizational mandates and priorities (Adelle & Russel, 2013).

3. Procedure for construction and assessment of anticipatory instrument mix pathways

We now outline a methodological procedure for the construction and assessment of high-ambition climate mitigation instrument mix pathways. Our approach consists of three main steps: Reviewing states and trends of the transition, assessing the status quo policy mix, and constructing and assessing alternative anticipatory pathways (see Figure 2).

Throughout the next sections of the paper, we demonstrate the utility of the approach through application to the German LDV sector, building on previous work (Edmondson et al., 2022). We highlight key dimensions of the process here for illustrative purposes.

In our case study, we focus on the LDV transition to simplify analysis. The decarbonization of transport will also involve a modal shift in personal mobility beyond technological substitution of internal combustion engine vehicles (ICEs) with zero emission vehicles. Nevertheless, given LDVs make up the largest proportion of transportation emissions (~60%) and are likely to remain an important form of mobility, accelerating the transition to cleaner LDVs is essential.

To inform pathway construction and assessment, we reviewed existing LDV transition policy literatures and drew on policy analyses of the German LDV sector from think tanks, consultancies, and agencies. We compiled evidence relating to instrument characteristics, performance, and policy mix design challenges. There exists a broad base of (predominantly qualitative) evidence on mobility transitions. This literature has strengths in identifying system dynamics, and potential bottlenecks, but is less prescriptive on quantifying instrument stringencies and trajectories. In order to plan and implement policy trajectories in terms of magnitude and the rate of change required, we draw on the wider environmental transport literature and economic analysis of policy instruments. Single instruments, design features, and their impacts on challenges (such as acceptance, distribution, and cost effectiveness) are relatively well researched (Bhardwaj et al., 2022). However, quantitative evidence on the performance of policy mixes (including interactions, trade-offs, and synergies) is only more recently emerging in economic literatures (Koch et al., 2022a).

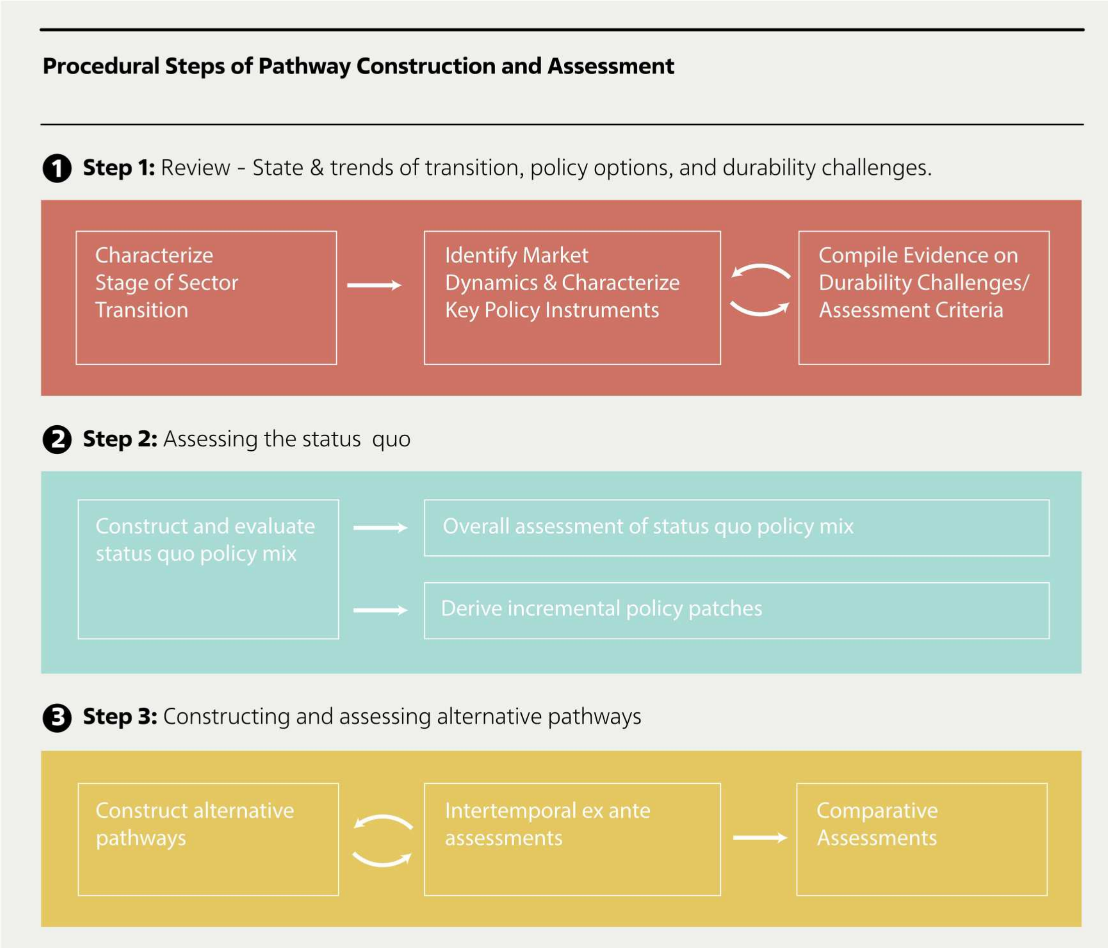


Figure 2. Three steps for ex-ante climate policy mix pathway design and assessment.

We ensure that instrument goals and ambition levels are consistent with those enshrined in the codified mitigation targets in Germany, and instrument interactions are synergistic. We draw on policy mixes for sustainability transitions (Rogge & Reichardt, 2016) and policy mix design (Howlett & Rayner, 2007) literatures in our construction procedure (Step 3), to make informed choices about instrument interactions. We focus on the instrument mix design, and thus do not adopt an extended policy mix conceptualization and all characteristics proposed by Rogge and Reichardt (Rogge & Reichardt, 2016). Crucially, in all reviewed disciplines, ex-post evidence on instrument and policy mix performance at the breakthrough stage of the transition (accelerated market diffusion) remains relatively limited. Acknowledging this limitation, there are inherent uncertainties in some evaluative criteria, such as acceptance of currently unprecedented high-stringency instruments. In defining our pathways, we drew on technological trends and cost projections (BloombergNEF, 2021), and modelling analyses (Luderer et al., 2021). Pathways and assessments were constructed through an iterative process among author team members, consisting of sectoral experts with interdisciplinary backgrounds in economics, political science, sustainability transitions, innovation studies, and psychology. We conducted the analysis, construction and assessment processes throughout 2022, hence the enactment stage for our illustrative pathways begins in 2023 (section 6). For further application of our approach, we suggest integration with energy systems modelling (Rogge et al., 2020; Süsser et al., 2021; Wachsmuth et al., 2023).

4. Step 1 – reviewing the German LDV transition: stage, market dynamics and instrument options

4.1. State of transition

The initial stage of instrument pathway construction involves assessing and characterizing the state of the sectoral transition unfolding in the locality of analysis (country, region etc.). We draw on established frameworks of technological change for indicative metrics (Table 2).

We reduce our metrics to codifiable indicators, therefore excluding informal indicators including cognitive and normative attitudes as well as cultural rules and institutions which also affect the rate of transition. We also exclude extended indicators for functions of an innovation system (Hekkert et al., 2020), since: (i) current globalized markets for technologies and supply chains are not nationally determined, thus in jurisdictions which

Table 2. Indicators, metrics, data, and application to the German LDV sector.

Indicator	Metrics	Data	Application to German LDV
Technologies	Viable technology alternatives. Rate of innovation of the technology including components. Includes costs/performance trends and projections.	**Performance of technological alternatives:** relative to existing technology. - Emission reduction potential - Total production and market costs. - Trends over time. - Projections. - Component trends/costs.	**Viability assessment of technological substitute**: Costs/performance/ availability of main technology options in debate. - PHEV; EV; E-fuels (hydrogen). - Total cost of ownership; current/ projected. - Lifecyle GHG emissions; current/ projected. - **Components:** (i.e. battery technology) - Costs; availabilities; projections.
Diffusion	The current magnitude, rate, and scale of diffusion of the new technologies, and decline of existing technology. Current technology usage per capita and trends in usage/ownership.	**Purchase:** - Current sales; Market shares. **Stock:** - Total stock; aggregate diffusion as % of stock. **Targets:** - Target diffusion by milestone. - Diffusion rate required.	**Purchase and stock data** - PHEV and EV - Sales; aggregate; total LDV stock. - LDV usage per capita. **Proxy targets** - Government sales targets; market shares and diffusion rate required to attain.
Infrastructure	Infrastructure requirements; current provision; state/private sector; price/performance projections.	**Infrastructure diffusion:** - Annual. - Aggregate. **Price/performance:** - Technology options. - Costs/trends/projections.	**Diffusion of charging stations** - Aggregate and rate. - Estimated/modelled charging requirements for Germany. - State/private provision. **Proxy targets for charging stations** - Government deployment targets; required diffusion rate to attain.
Actors/ Networks	Market actors; market share of national actors; trade body; lobby/interests.	**Market data:** - Market share of national firms. - Firm roadmaps. - Investment in R&D. - Firm/trade body press releases.	**Market data:** - Market shares of EV sales from German firms. - Investment data. - Roadmaps for EV production. - Supply chains of EV manufacture. - Public statements from firms/trade bodies on EVs.

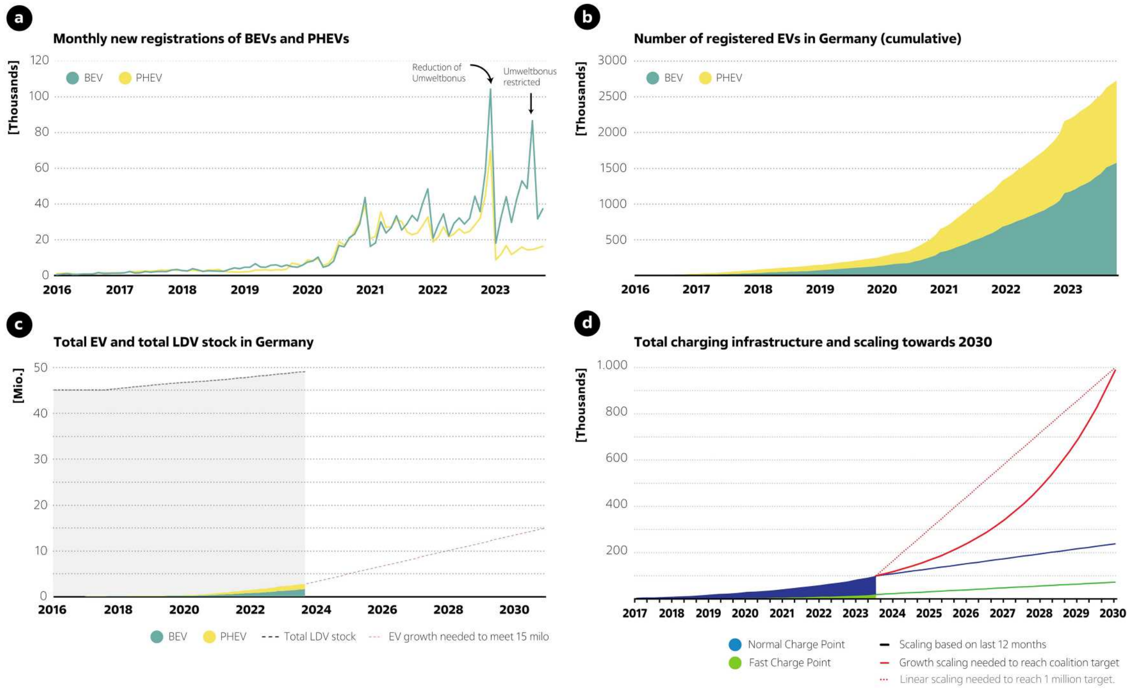


Figure 3. Characterizing the state of LDV transition in Germany: (a) Monthly registrations of BEVs and plug-in hybrid electric vehicles (PHEV), (b) cumulative registrations, (c) total number of EVs as a proportion of total stock, and (d) Infrastructure deployment/trends. In (c) and (d) the dashed trend lines illustrate linear scaling needed to reach the German coalition targets of 15 million EVs and 1 million charging points by 2030, respectively. In (d) the solid straight lines display linear scaling of deployment rates from the past 12 months, for both fast and normal public charging infrastructure. The curved line shows the rate of deployment needed to reach the coalition target, indicating that current infrastructure deployment rates are significantly lagging behind requirements.

import technologies and do not have established national industries, such indicators are redundant; (ii) there remains a lack of consensus as to what extent the management of innovation or transition processes is the role of the state or the private sector, and we aim at the generation of an approach which has broad applicability.

The German LDV sector transition is currently shifting from the emergence stage to early-diffusion (acceleration). Battery electric vehicles (BEVs) are the dominant design technological substitute for ICEs, due to observed and projected trends in cost/performance and technological potential. Alternative technologies (i.e. e-fuels) are not expected to be practically (scale of production) or commercially viable to deliver 2030 mitigation targets (Mock & Dornoff, 2022). BEV sales have increased significantly in Germany since 2020 (Figure 3(a–c)). As of late 2023, BEV sales made up 17% of total new registrations, while BEV and PHEV collectively made up 24.5%. However, BEVs remain less competitive than ICEs without policy support due to currently higher purchase costs and greater depreciation (Agora Verkehrswende, 2022). This results in higher total costs of ownership in absence of supporting policies (Suttakul et al., 2022). There also remain practical and convenience-based disadvantages associated with the limited range of current battery technologies and the limited availability of public charging infrastructure (Figure 3(d)). There is a large manufacturing sector for ICE-based LDV in Germany. Some industry actors (e.g. VW) are more supportive of a transition to EVs and are positioned to gain competitive market advantage by more ambitious production schedules for their EV models. However, the cost trajectories are largely dependent on innovation in battery technologies and global supply chains for critical materials, which is largely exogenously determined.

4.2. Market dynamics of diffusion and key policy instruments

Our focus is on accelerating a transition at the early-diffusion stage, utilizing levers which drive technology break-through into the existing market. This involves selecting instruments and designing interactions which combine phase-in of new technology (purchase and use), and phase-out of the old technology (scrappage and use). To conduct this stage of the analysis involves review of existing evidence for instrument effectiveness and interactions with other instruments. We conducted an extensive review of the existing transport sector climate policy literature (included in the SI). This also served the purpose of compiling evidence on durability challenges and anticipatory design principles, which we drew on for constructing and assessing the status quo policy mix and the alternative pathways.

GHG emissions of LDVs can be abated by (i) reducing the use of existing ICE stock, and (ii) shifting stock composition towards zero-emission vehicles, achieved through increasing BEV purchase and scrappage of ICEs. We consider key policy instruments (based on observed and anticipated effectiveness) that target these mechanisms to advance the transition and to address potential market failures (Figure 4). Increasing the operational *usage* costs of ICE through high carbon prices on fuels incentivizes ICE vehicle owners to drive less, and/or to switch to BEVs or other modes of transport (Axsen et al., 2020). However, in the early-diffusion phase consumers may still undervalue the potential economic advantages of BEVs due to bounded rationality and myopia (Gillingham & Munk-Nielsen, 2019), which can slow BEV diffusion in a competitive market, especially in the short-term. Similarly, manufacturers with vested interests in maintaining their competitive advantages may be reluctant to embrace the new technology paradigm (Meckling & Nahm, 2018). Coordination failures may delay adaptation of supply chains. Supply focussed instruments can incentivize higher short-term investment to BEV supply chains (reducing BEV costs) to address these barriers and market failures (Fox et al., 2017).

Policies focussing on *purchases* (Bonus-Malus Habibi et al., 2019; ZEV mandate Sykes & Axsen, 2017) can directly target consumer myopia (Wolfram et al., 2021) and producer learning-by-doing. Network externalities

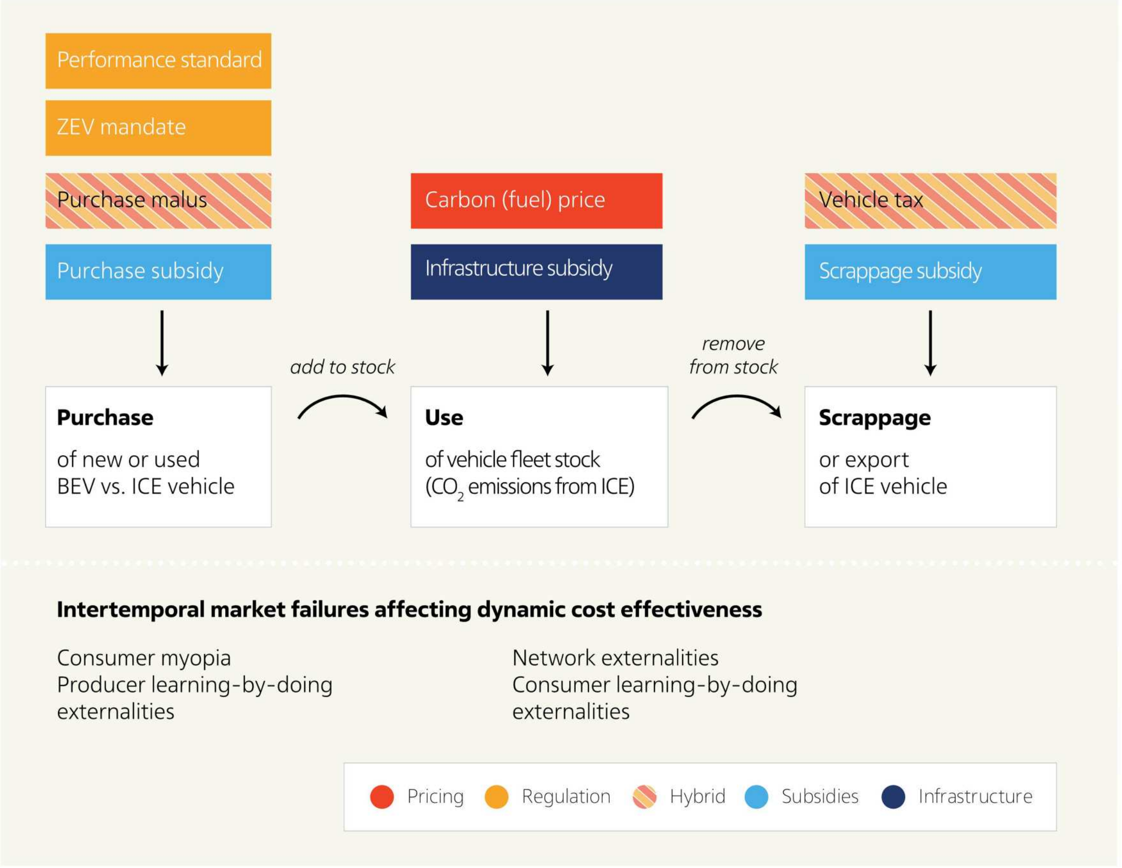


Figure 4. Consumer decisions driving dynamics of the LDV transition, related market failures and selected policy instruments addressing these.

Instrument	First order effect	Instrument description
CO_2 - Price	Reduce ICE usage	Pricing mechanism increases fuel costs. First order effects directly reduce use of ICE stock. Second order effects on purchase and investment decisions lead to diffusion of BEV and expansion of infra-structure, but effectiveness less certain.
Malus (tax on new vehicle purchase)	BEV sales	Hybrid mechanism which places increasing fiscal penalties on purchase of less efficient or higher emitting vehicles, favouring BEV purchase.
Malus (vehicle tax on existing vehicles)	ICE scrappage	Hybrid mechanism which places increasing financial penalties on operation of older less efficient ICE vehicles from the existing stock.
Zero emission vehicles (ZEV) mandate	BEV sales	Regulatory mechanism which places a quota on manufacturers for the percentage of sales which need to be zero carbon. Supply side mechanism with economic features through utilisation of tradable permits between manufacturers.
Performance standards	BEV sales	Regulatory standards which target the CO_2 intensity of new vehicles. Applies to manufacturers and is based off the anticipated emission performance of new vehicles.
Bonus/subsidy (for new BEV purchases)	BEV sales	Purchase subsidy to reduce market price to consumers. Intended to promote early diffusion of new technology by making it competitive under market selection pressures.
Scrappage subsidy (bonus)	ICE scrappage	Subsidy to promote removal of exiting ICE from the vehicle stock. Can alleviate distributional impacts associated with older ICE depreciation, or if fiscal penalties associated with use are in place.
Public infrastructure provision	Increase BEV usage	Public funding for infrastructure provision, primarily intended to provide early provision of charging networks which targets range anxieties and myopia on consumers.

Figure 5. Selected instrument options, first order effects and descriptions.

Note: A zero-emission vehicle (ZEV) is a vehicle that does not emit exhaust gas or other pollutants from the onboard source of power.

linked to the availability of charging infrastructure are an initial barrier to entry for BEVs (Sommer & Vance, 2021), which motivates policy support (Koch et al., 2022b). Stock turnover can also be accelerated through ICE *scrappage*, which becomes increasingly necessary as the transition proceeds. Increased operational costs caused by high carbon (fuel) pricing indirectly incentivizes ICE scrappage. In the absence of high stringency carbon pricing, additional instruments to reduce ICEs on the road are needed. One option is a stock focussed Malus-Bonus, i.e. an annual emissions-based ICE road tax on the existing fleet coupled with a scrappage subsidy, which to our knowledge, has yet to be deployed anywhere in the world.

We deliberately restrict the scope of our analysis to keep it tractable and focus on national level policy options (Figure 5). We do not consider, for example, LDV road tolls indexed to vehicle CO_2-intensity or ultra-low emission zones (ULEZ). Other policy options contribute to reducing overall LDV use include subsidizing public transport use and expanding cycling and public transport infrastructures (Bhardwaj et al., 2020). We treat these as complimentary measures, and part of the overall mobility transition, but outside the scope of our analysis. R&D support for BEV components (e.g. battery technologies) and investment in the production of required materials (e.g. semi-conductors) are also essential to advance technological learning and accelerate cost reductions (Zhu et al., 2022). We assume these complementary polices will be supported equally across pathways and thus exclude them from our construction and comparison of alternatives.

5. Step 2 – assessing the status quo policy instrument mix pathway: policy as usual and EU fit for 55 package

The next step involves constructing and evaluating the status quo policy instrument mix. This includes tracing the historical emergence of the instruments in place, and anticipated trajectories, based on current available information from relevant national and international governmental bodies, and policy projections. The status quo instrument mix should be primarily evaluated on the basis of effectiveness, in terms of effects on stock turnover and use, suitability of attaining mitigation targets and anticipated GHG abatement. Approximation of required trajectories can follow a reverse induction approach (Dolphin et al., 2023), indicating the ambition gap between the current policy trajectory and rate of increase required. For more information on the status quo policy mix and our assessment, please see the supplementary information.

For our application, a 2030 transport sector GHG emission reduction pathway is specified in the German Climate Law (Bundestag, 2019). The LDV sector's GHG contribution towards overall transport sector target attainment was approximated from existing analyses and modelling work. We also adopt proxy targets from the government coalition treaty, in particular the deployment of 15 million electric vehicles (EVs) by 2030 (Scholz et al., 2021). The status quo mix includes the planned EU 'Fit for 55' reforms and policy instruments implemented at the national level as of January 2023.[2] In addition to GHG abatement, we incorporate attainment of related proxy targets (i.e. transport sector GHG emissions, BEV diffusion rates, and charging infrastructure). Available modelling analyses (ERK, 2022), evaluation of published updates to EU fleet standards (Gheuens, 2023), and our own assessment (Edmondson et al., 2022), indicate that the status quo policy mix is insufficient to attain the German 2030 transport sector GHG emission reduction targets. The current mix places large emphasis on supporting BEV purchase through subsidies, which currently supports early diffusion but may induce high fiscal costs as the market share of BEVs increases. More importantly, the current mix does not sufficiently target usage of the current ICE vehicle fleet or include instruments targeting ICE scrappage. Accordingly, the instrument mix is suited to supporting emergence, but does not actively change mainstream market selection conditions to help accelerate diffusion or displacement of the existing vehicle stock. Consequently, more ambitious pricing instruments and/or regulatory standards targeting the ICE stock and ICE vehicle usage are required soon to accelerate the transition and meet climate policy ambitions. Based on our assessment, we derive incremental policy patches to the status quo policy instrument mix which will form the basis of the pathways we construct in the next step.

6. Step 3 – constructing and assessing alternative policy mix pathways for the German LDV sector transition

The final step involves constructing and assessing alternative policy pathways. We construct three instrument mix pathways for the German LDV sector, before assessing and comparing their prospective durability. We construct illustrative pathways which aim at both covering key positions in the policy debate in Germany, and explore the option space to identify key similarities and differences across alternative policy mix pathways.

[2]As of January 2023, total purchase subsidy reduced to 4500 euros. In September 2023, eligibility was reduced to private car ownership.

6.1. Pathway design procedure

6.1.1. Construction logic

The pathways follow the fundamental design principle of being equally capable (from an environmental effectiveness perspective) of attaining the 2030 emission reduction target, and associated proxy targets from the German Government's goals for EV diffusion and infrastructure deployment. With these objectives in mind, we first devised instrument combinations at stringencies which are expected to be sufficiently effective to deliver these targets. Stringencies were calculated based on cumulative diffusion needed to attain the 2030 targets and then derived backward through a process of reverse induction (Dolphin et al., 2023). Instrument stringency ranges increase exponentially, and feature a collared flexibility-corridor to account for uncertainty while still guiding the direction of travel. For a detailed description of these steps for our application to the German LDV sector, please see the supplementary materials.

The pathway construction follows a 'policy patching' logic, which involves adapting the status quo policy mix rather than designing from a 'blank slate' (Howlett & Rayner, 2013). Pathway construction acknowledges conditions of uncertainty and aims to mitigate critical durability risks, with pathways differing in how they resolve trade-offs. We design each pathway to feature '*core*' and '*supportive*' instruments. *Core* instruments are essential to drive the transition, especially in terms of accelerating stock turnover in line with GHG targets. *Supportive* instruments help improve pathway performance and reduce durability risks. The latter include, for example, preventing leakage and evasion effects, or achieving more progressive distributional outcomes.

All pathways are designed to minimize fiscal costs relative to the status quo. We combine economic and hybrid instruments (fuel pricing, maluses) to create revenues, which are used to support subsidies, infrastructure, and redistribution mechanisms to alleviate regressive impacts among societal groups. Based on available evidence, we anticipate that progressive (income-based, lump-sum) revenue redistribution will increase public acceptance (Dechezleprêtre et al., 2022), but other configurations are conceivable (Kellner et al., 2022). All pathways also include EV charging infrastructure support in the short-term (Bauer et al., 2021). There is currently relatively limited evidence on the optimal magnitude of charging infrastructure support needed to facilitate market diffusion. We err on the side of caution, with the potential for state overinvestment, to ensure effectiveness.

Other pathways and instrument mixes could be defined and explored using our framework, e.g. in state (ministerial or agency-driven) climate policy planning processes and including stakeholder deliberation processes.

6.1.2. Temporality and sequencing: changing stringency over time

Instrument stringency is central to our pathway design process. Taking a temporal approach to construction and assessment allows instrument stringencies to change over time. We determine a stringency metric and range (0–100%) for each instrument type (Figure 6), which enables comparison across pathways. Stringency metrics and ranges are different for each instrument type, but apply to all instruments across the alternative pathways. For example, the maximum stringency for carbon (fuel) pricing (500 euros/tonne CO_2) is attained in only one pathway ('fuel focus') in the year 2035. Even so, this value provides the 100% stringency benchmark for carbon (fuel) pricing across all pathways.

Stringencies metrics for other instruments are based on variables including: emission performance in terms of gCO_2/km (vehicle registration tax/malus, road tax/malus, EU fleet standards), subsidy value per vehicle and recipient (purchase bonus/subsidy, scrappage bonus/subsidy), and targeted sales market share of BEVs for car manufacturers (ZEV mandate).

We then sought to optimize attainment of evaluation criteria (i.e. addressing durability challenges) in each pathway following its respective design logic through three time periods:

1. Patching phase (2023–2025) – the status quo is recalibrated to the new pathway through immediately implementing reforms.
2. Ramping-up phase (2025–2030) – instruments are scaled-up to attain the 2030 sectoral targets.
3. Displacement phase (2030–2035) – all pathways operate at high environmental effectiveness, actively focusing on scrappage of ICE from the vehicle stock and rapidly accelerating the LDV transition in line with the economy-wide net zero GHG target for 2045.

Instrument	Metric (unit)	Stringency 0%	Stringency 100%	Fuel focus 2023-2025 (Low-high %)	Fuel focus 2025-2030 (Low-high %)	Fuel focus 2030-2035 (Low-high %)	Stock focus 2023-2025 (Low-high %)	Stock focus 2025-2030 (Low-high %)	Stock focus 2030-2035 (Low-high %)	Mix 2023-2025 (Low-high %)	Mix 2025-2030 (Low-high %)	Mix 2030-2035 (Low-high %)
CO_2 - Price	Price of Carbon in trading mechanism **(Euros/tonne CO_2)**	0	500	16-60 (Core)	18-78 (Core)	27-100 (Core)	7-11 (Supportive)	11-27 (Supportive)	16-45 (Supportive)	11-23 (Core)	14-43 (Core)	23-80 (Core)
Malus (tax on new vehicle purchase)	Vehicle emissions in taxable range **(CO_2 g/km)**	200	0	N/A	N/A	N/A	25-64 (Supportive)	35-100 (Supportive)	86-100 (Supportive)	25-64 (Core)	35-100 (Core)	86-100 (Core)
Malus (vehicle tax on existing vehicles)	Vehicle emissions in taxable range **(CO_2 g/km)**	200	0	N/A	N/A	N/A	N/A	0-17 (Core)	0-50 (Core)	N/A	N/A	N/A
ZEV mandate	Mandated number of ZEVs sales manufacturers need to attain **(% of LDV sales)**	0	100	N/A	N/A	N/A	N/A	40-100 (Core)	100 (Core)	N/A	N/A	N/A
Performance standards	Fleet emission performance requirements **(CO_2 g/km)**	130	0	27 - 38 (Supportive)	38 - 62 (Supportive)	62 - 100 (Supportive)	27 - 38 (Supportive)	38 - 62 (Supportive)	62 - 100 (Supportive)	27 - 38 (Supportive)	38 - 62 (Supportive)	62 - 100 (Supportive)
Bonus/subsidy (for new BEV purchases)	Maximum subsidy per vehicle **(Euros/vehicle)**	0	6000	N/A	N/A	N/A	20 - 57 (Core)	0 - 31 (Core)	N/A	20 - 57 (Core)	0 - 31 (Core)	N/A
Scrappage subsidy (bonus)	Maximum subsidy per vehicle **(Euros/vehicle)**	0	6000	N/A	N/A	N/A	N/A	12-42 (Supportive)	7 - 22 (Supportive)	N/A	N/A	N/A
Public infrastructure provision	Aggregate earmarked funding (Billion Euros)	0	3.2	100 (Supportive)	N/A	N/A	100 (Supportive)	100 (Supportive)	N/A	100 (Supportive)	100 (Supportive)	N/A

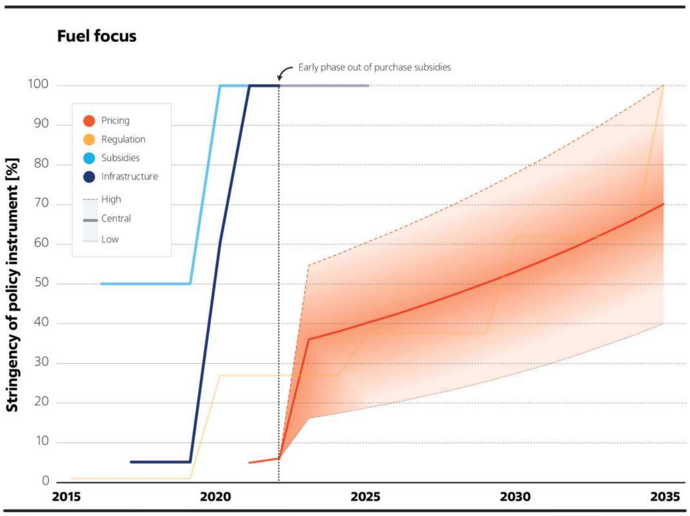
Core Supportive

Figure 6. Overview of alternative policy instrument pathway designs including core/supportive roles of instruments and scaling of stringencies across time.

6.2. Illustrative pathways: alternative policy instrument mix rationales and designs

The pathways we construct to demonstrate the usefulness of our approach are illustrative. Many alternative pathways are conceivable. We chose these for several reasons. First, they resonate with discourses which exist in the current German climate policy debate. Our pathways demonstrate these options across a consistent scaling for comparative purposes, and assess them according to the full range of durability criteria. Second, they represent different design logics and perform differently under assessment of durability challenges, thus illustrating the practical usefulness of our assessment framework. While each pathway is capable of delivering mitigation targets, some are more susceptible to risks of failure, either through undermining the effectiveness of the pathway, risks of backlash, or both. We discuss these risks while assessing the pathways.

Pathways differ by the *core instruments* and mechanisms driving the transition (Figure 6). One key difference across the considered pathways is the role of carbon pricing for fuels. Carbon (fuel) pricing effectively reduces



Instrument	Design
CO_2 - Price (core instrument)	- Immediate (2023) hike in nETS price, potentially free-floating right away or adjusted to meet GHG targets. - A nETS price collar could be implemented as soon as 2023 - Might plausibly reach 500 euros by 2035
EU fleet standards (supportive instrument)	- Follows Fit for 55 proposal, incl. ICE sales ban from 2035 - Strengthens credibility of pathway
Purchase subsidies - Phased out	- Early phase out of main purchase subsidies (Umweltbonus) - Low significance beyond current implementation
Public infrastructure (supportive instrument)	- Utilisation of currently earmarked funds - Potential for renewal in case of under-provision from private sector

Core instrument Supportive instrument

Figure 7. Design of 'Fuel focus' pathway. High stringency carbon pricing targets fuel usage in ICE to drive transition. Indirect effects drive stock turnover mechanisms by enhancing incentives for purchasing BEVs and scrapping ICE.

ICE use (Frondel & Vance, 2018) and can accelerate the overall transition process, depending on its design and how other challenges are addressed (Sallee et al., 2016). The first pathway uses high-stringency carbon (fuel) pricing and expected indirect effects on fleet turnover (scrappage and purchasing decisions) to drive the transition. The other pathways more directly target carbon intensity at the point of stock turnover by employing taxes on ICE registration and road usage (purchase and stock maluses).

All pathways also retain the EU fleet CO_2-intensity standards as proposed by the EU Commission in its Green Deal package (Held et al., 2022). Alone, the rate of transition enshrined in this instrument is insufficient to deliver the German GHG transport sector reduction targets (Tietge et al., 2021), and our pathways are designed to deliver a higher level of ambition. Still, as a member state, Germany is obliged to retain this instrument, and we anticipate it will play a supportive role in terms of legitimacy of policy commitments and directionality, which should help maintain political momentum.

6.2.1. Pathway 1: 'fuel focus'

The 'fuel focus' pathway immediately implements a high and rapidly increasing carbon price on gasoline and diesel fuels, as the only *core* policy instrument (Figure 7). The pathway continues current support for infrastructure provision until the mid-2020s, with the potential to extend support if private sector provision does not sufficiently mobilize. Otherwise, the pathway phases-out purchase subsidies, and does not introduce any additional core instruments. Proponents – often economists – argue this approach can achieve GHG abatement most efficiently, often emphasizing the high static cost effectiveness of carbon (fuel) pricing. These claims are based on assumptions of rationality, both for consumer choices and investment from manufacturers to scale-up production and deliver timely costs reductions. Consequently, transition dynamics (purchase and scrappage) are only induced indirectly via anticipated cost reductions due to lower operational costs.

Our illustration draws on economic modelling of carbon prices required in an EU-wide ETS-2[3] for transport and buildings towards 2030 (Pietzcker et al., 2021). To guide the trajectory, the pricing mechanism could feature a price collar, as envisaged in the currently implemented German national ETS for transport and buildings (nETS). A carbon tax is, in principle, an alternative option. Even so, given large ex-ante uncertainties over the

[3]In 2023, a new, separate emissions trading system was created: Emissions Trading System 2 (ETS 2), covering fuel combustion in buildings, road transport and additional sectors (mainly small industry not covered by the existing EU ETS).

prices required to achieve climate targets, and current evidence which suggests relatively low elasticities for ICE use at currently implemented carbon pricing levels (Goetzke & Vance, 2021), potentially much higher prices than those depicted in this illustration might be needed. Accordingly, a price adjustment mechanism is needed to facilitate adaptability. A flexibility mechanism would be an inherent feature of a cap-and-trade system, whereas a carbon tax pathway would require adjustment by the state. If some form of restriction or price ceiling is implemented in an ETS, or a carbon tax is not raised to the required level, any resulting shortfall in mitigation would need to be achieved via additional instruments or the environmental target is missed.

6.2.2. Pathway 2: 'stock focus'

The second pathway focuses on accelerating vehicle fleet stock turnover (Figure 8). The pathway initially refrains from penalizing the use of the existing ICE stock (Vogt-Schilb et al., 2018), and uses instruments which are expected to be less salient to voters (Klenert et al., 2018). The pathway uses a (purchase) bonus-malus mechanism, coupled with a ZEV mandate to drive purchases. The carbon pricing stringency remains modest in this pathway and creates some incentive for reduced usage of current ICE and scrappage, but not a strong signal. Instead, another malus-bonus instrument targeting car *ownership* (rather than registration) is implemented and increases in stringency over time to accelerate the scrappage of ICE from the existing stock. The annual vehicle tax (stock malus) is indexed to increasing vehicle CO_2-intensity.

Distributional impacts of the stock malus can be reduced through instrument design, increasing stringency over time, and targeted compensation mechanisms. We suggest initial implementation at relatively low stringency (both emission range and tax value) to improve acceptance, and then increasing via exponential scaling. The stock taxation mechanism is complemented by a scrappage subsidy (scrappage-bonus) seeking to compensate the most vulnerable (low-income groups). It could be designed to support the purchase of both new and used BEVs (or the conversion of existing ICE République Française, 2022), making switching more affordable and accessible for those reliant on LDV-based mobility. The stock malus could be implemented in more populated regions and cities first, thus alleviating distributional inequalities associated with lower access to charging infrastructure, public transport, and other transport modes in rural areas. Even so, additional measures (such as fiscal support or subsidized access to public transport) may also be needed to compensate hardship cases.

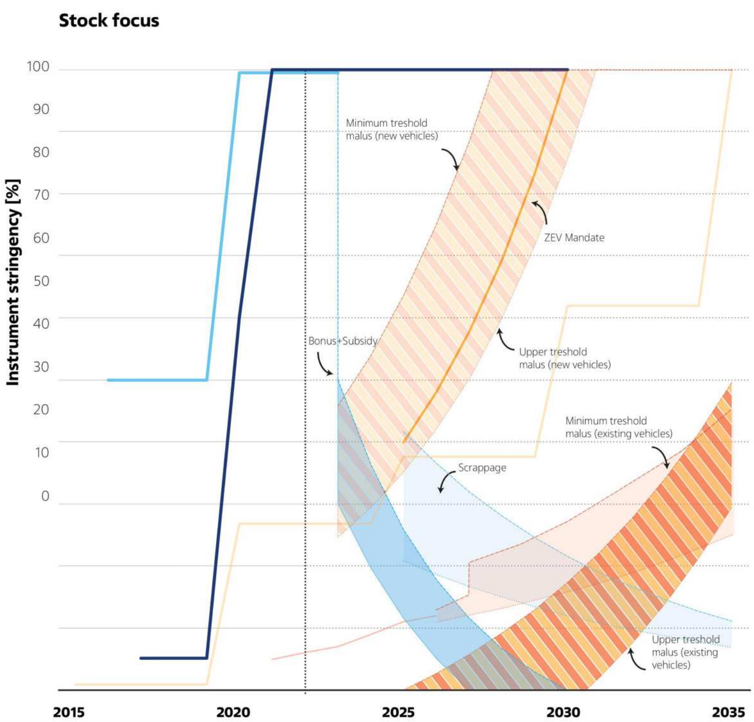
6.2.3. Pathway 3: sequencing

This pathway combines the design logics of the previous pathways sequentially. Its design shifts from an initial emphasis on stock focussed instruments to an eventual fuel focus through an incremental carbon pricing trajectory (Figure 9). The sequencing approach aims at exploiting the strengths of previous pathways while acknowledging the potential limitations of a purely fuel or stock focussed approach. The pathway focuses on instruments targeting stock turnover in the short- to mid-term, helping decrease BEV investment risks and increase commitment, while avoiding immediate high costs to the existing ICE stock which reduces potentially regressive impacts and backlash from a large population group. Carbon (fuel) pricing increases in stringency more gradually, and becomes the pathway's core instrument in the 2030s, driving reduced usage and scrappage of ICE.

The stringency and sequencing of instruments can be adjusted, which allows greater adaption to potentially adverse conditions such as supply bottlenecks and component shortages. Additional unanticipated challenges may also emerge as the transition unfolds which need to be addressed through adaptation and/or targeted interventions. Consequently, recalibration of the pathway incurs governance requirements. Having a narrower uncertainty range provides more credibility, commitment, and certainty than the fuel focus pathway, while also not overcommitting to a deployment schedule which risks being undeliverable due to uncontrollable and less predictable conditions. Potential calibration errors could reduce dynamic cost effectiveness, but do not carry significant risk of critically impeding the delivery of the 2030 GHG targets.

6.3. Assessing durability challenges of policy instrument pathways

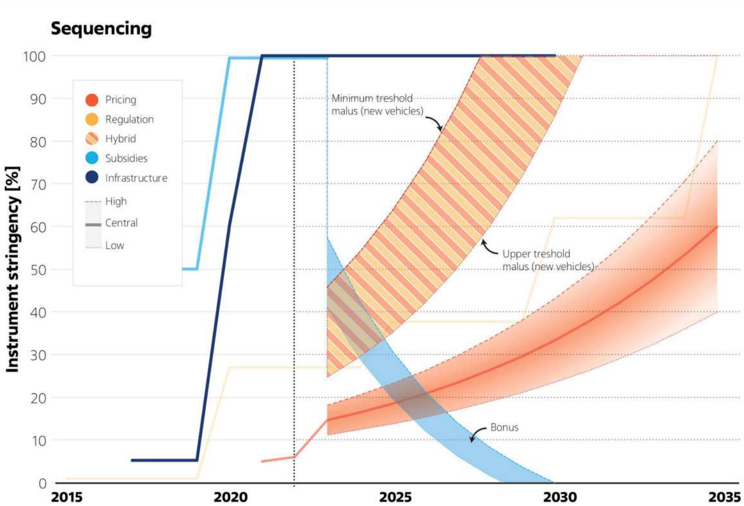
Having demonstrated the utility of our construction approach, we illustrate the use of our analytical framework of durability challenges as an assessment and comparative tool. In practice, assessment is an iterative and reflexive process through which pathways can be recalibrated. Durability risks can be reduced through strategic



Instrument	Design
CO_2 - Price	-Initially low level, increasing after 2026 -Current nETS remains in place until 2026, followed by ETS-2 or nETS with price collar
Registration Malus	-Implemented alongside **ZEV mandate** to mitigate potential leakage from other countries - Vehicle registration tax implemented immediately (2023) - Incremental tax rate after threshold - High upper tax rate (e.g. 40,000€)
Stock Malus	-Annual vehicle tax for existing ICE based on emissions -Introduced around 2025 -Phases-out more polluting vehicles with high annual pricing (i.e., thousands of euros) at upper threshold -Stringency starts low and increases over time (sequencing)
ZEV mandate	- ZEV sales mandate on vehicle manufacturers - 100% ZEV sales around 2030 -Tradeable permits between manufacturers increase efficiency
EU fleet standards	- Follows Fit for 55 proposal, incl. ICE sales ban from 2035 - Strengthens credibility of pathway
Purchase subsidies	-Core instrument, early stimulus, high in the short- to mid-term -Financed by revenues from **Registration Malus**
Scrappage bonus	-Core instrument, early stimulus, high in the short- to mid-term -Financed by revenues from **Registration Malus**
Public infrastructure	-Utilisation of currently earmarked funds until 2025 - Renewal after 2025 until 2030 -Sensitivity to market provision - phase out by ~2030 the latest

Core instrument Supportive instrument

Figure 8. Design of 'Stock focus' pathway. 'Stock focus' – directly targets stock turnover dynamics (purchase and scrappage) via 'Bonus-Malus' mechanisms, as well as zero-emission vehicle (ZEV) mandate for purchase decisions.



Instrument	Design
CO_2 - Price	- Moderate price hike to around 65 Euro (window 50-80 Euro) - More gradual price increase within a price corridor - flexibly adjusts
Registration Malus	- Vehicle registration tax implemented immediately (2023) - Base tax rate for **all new ICE vehicles** (e.g. 500-1000 euros) - Incremental tax rate after threshold - High upper tax rate (e.g. 40,000€)
EU fleet standards	- Follows Fit for 55 proposal, incl. ICE sales ban from 2035 - Strengthens credibility of pathway
Purchase subsidies	- Revenues from Registration Malus are partly and temporally redistributed to subsidise BEV purchases - Subsidy per vehicle reduces over time, in line with reducing manufacturing costs.
Public infrastructure	-Utilisation of currently earmarked funds until 2025 - Renewal after 2025 until 2030 -Sensitivity to market provision - phase out by ~2030 the latest

Figure 9. Design of 'Sequencing' pathway combines the logic of the previous pathways over time. Initially targets BEV purchase (via Bonus-Malus) and increasingly relies on carbon (fuel) pricing to reduce ICE use and drive scrappage.

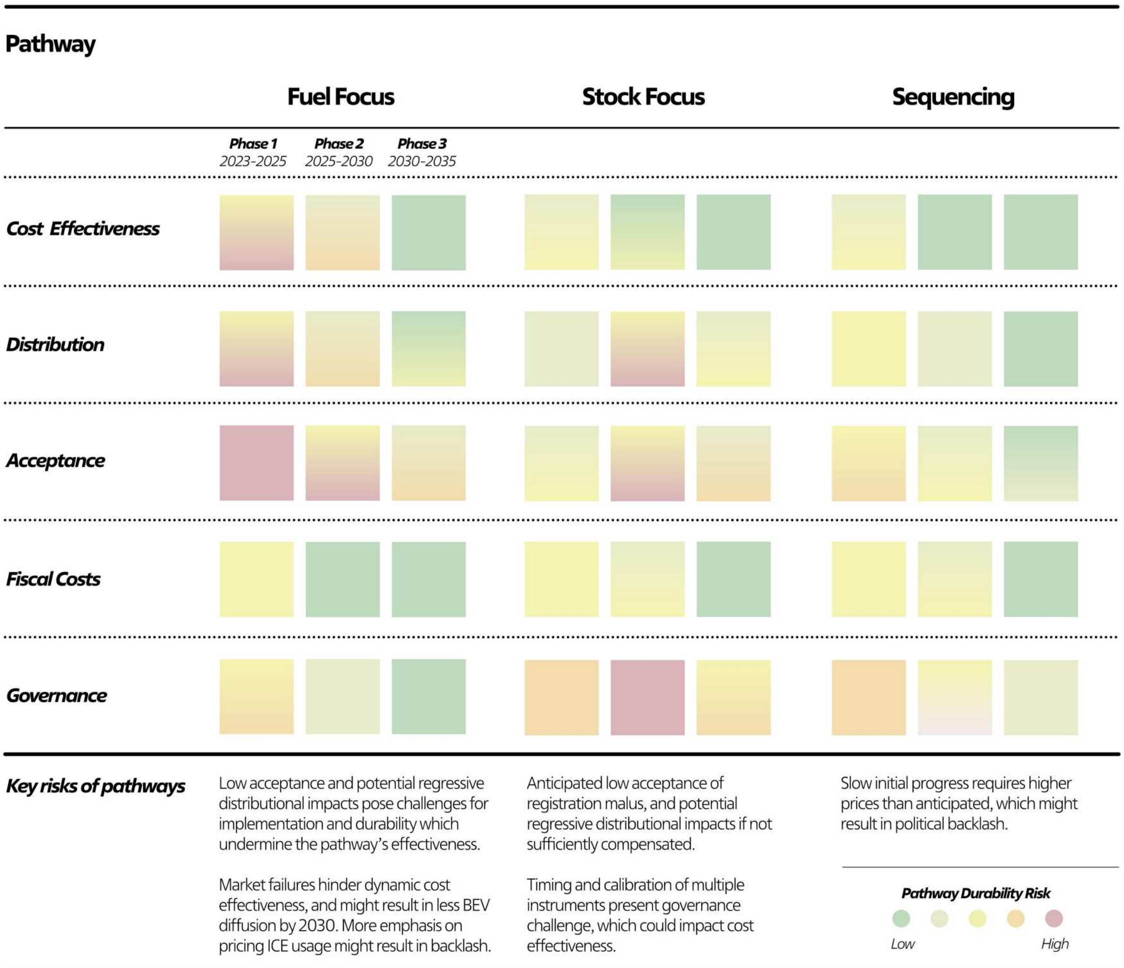


Figure 10. Comparison of pathways across key assessment criteria. Author's assessment. Multiple colours indicate uncertainty ranges of assessment for respective durability risk.

instrument combinations, temporal instrument stringency scaling and dynamic sequencing. Here, we present summative and comparative assessments to illustrate key differences in durability challenges across the illustrative pathways, having optimized each pathway (to the extent possible) according to their construction logic (Figure 10).

Assessments are conducted by drawing on an extensive synthesis of literature and evidence (Step 1) of selected instrument types, design features and instrument interactions according to durability challenges (see supplementary information), and anticipated market trends. Importantly, we highlight that anticipated effects in some assessment categories are dependent on contextual factors, which make projecting future effects less precise due to a range of potential outcomes. For such indicators, the assessment indicates uncertainty within a range (e.g. medium-high). Similarly, for some instrument designs (e.g. unprecedented stringency) there is currently insufficient evidence to draw robust conclusions about the potential risk. In such cases, we highlight these key uncertainties as potential high-risks, and elaborate further in the following text.

Pathways differ in how they adapt to uncertain future market conditions. Endogenous conditions relate to the behaviour and adaptation of both consumers and firms. Innovation from domestic firms is influenced by national policy and market conditions, so reducing risks could help mobilize higher levels of private R&D

and investment within German car manufacturers (Foxon et al., 2013). Still, production costs are closely associated with exogenous global supply chains, component availabilities and economic conditions, which are less predictable. Given these significant uncertainties, each pathway adapts differently to ensure targets are met, but faces design challenges presenting practical implications for successful enactment and durability. We discuss the key challenges facing the pathways, which could threaten their ability to meet the mitigation targets or would necessitate patching or branching points from the pathway designs we have illustrated.

6.3.1. Pathway 1: fuel focus

The 'fuel focus' pathway relies on an adaptive price mechanism (either ETS or tax) to achieve GHG targets. Uncertainties remain about the effectiveness of an immediate hike in carbon (fuel) pricing on stimulating consumer BEV purchase decisions. It assumes firms will increase investments due to increased market demand, or relies on innovation to happen exogenously. If cost reductions are disrupted, or not sufficiently incentivized, it then relies on further ramping of the carbon price stringency to make up mitigation shortfalls. How quickly this is achievable lacks supportive evidence. Historical evidence indicates that some LDV transport demand is inelastic, and without significant stock turnover there are limits to how much targeting usage alone can deliver. The implementation of such high carbon prices would face significant political acceptance issues. If the redistributive mechanism is not correctly managed, implementation at such high stringencies would also induce regressive outcomes. These uncertainties increase the risks associated with this pathway, which in a worst-case scenario could lead to non-attainment of the 2030 target.

Low political acceptance of high stringency carbon (fuel) pricing presents a major barrier to implementation. A sudden and substantial increase in the stringency of the carbon (fuel) price imposes immediate costs on all owners of the existing ICE stock and increases the potential risks of unequal distributional impacts across income groups. It is therefore likely to be strongly opposed, both at the time of implementation and afterwards. Strong horizontal inequalities across income deciles of how consumers are affected by carbon (fuel) pricing, makes it is very challenging (but not impossible) to design revenue recycling schemes addressing hardship cases, i.e. most vulnerable population groups (Maestre-Andrés et al., 2021). This adds significant governance requirements to manage effectively. The consequences of error, or lack of political commitment to fully implement, would lead to negative outcomes including adverse distributional impacts, and political backlash. While, this pathway could potentially generate significant short-term revenues, removal of purchase subsidies may further reduce both public and firm acceptance. If revenue recycling can be implemented quickly and progressively, then generation of visible benefits could potentially mobilize supportive coalitions to protect the pathway post-implementation. However, these effects remain highly uncertain and dependant on effective governance.

The pathway is immediately susceptible to considerable risk of political backlash while implementing a significant price hike, and in the medium to long-term when very high carbon price levels might be required for attaining climate goals. Moreover, in the event of governance failure in the monitoring of the mechanism, effectiveness is compromised. Strong reliance on a single instrument amplifies these risks, which may also undermine the pathway's credibility. Accordingly, this approach carries significant risks which could undermine the pathway's effectiveness, in addition to high risk of political backlash exerting pressure to relax ambition, which combined compromise the delivery of the 2030 target.

6.3.2. Pathway 2: stock focus

The 'stock focus' pathway uses multiple instruments which directly target anticipated failures and signal stronger directionality and commitment to the new technology (BEV) paradigm. This provides greater market certainty for private sector investment in innovation, manufacturing, and infrastructure. The pathway focuses on attainment of the 15 million EV target by 2030 via the combination of a ZEV mandate and purchase bonus-malus, and carries relatively low risks for effectiveness of the instruments. Still, the pathway places less emphasis on short-term emission reductions via targeting ICE usage reductions (through fuel/carbon pricing), and results in higher initial static costs of GHG abatement. Instead, the pathway places emphasis on dynamic cost effectiveness and accelerating stock turnover. Consequently, the total vehicle stock by 2035 in this pathway may be higher than the other options.

Strong emphasis on stock turnover could also be a potential weakness of this pathway, if anticipated cost reductions do not materialize as predicted. This renders the pathway susceptible to risks related to component shortages or other supply bottlenecks (largely exogenously determined). If anticipated cost reductions are slow to materialize, an ambitious BEV diffusion target enshrined in the ZEV mandate may incur higher economic costs. These increased costs would mostly effect company vehicle purchases (currently 65% of German market) and affluent consumers who purchase new vehicles. The distributional effects should be less regressive than immediately high carbon prices which immediately penalizes lower income groups, but are uncertain and present an important area for future research. Furthermore, if supply bottlenecks are severe and persistent then stock turnover rates could be compromised, and higher stringency carbon (fuel) pricing could be needed to make up the mitigation shortfall.

The pathway faces governance challenges due to the relatively high number of instruments requiring continuous monitoring, enforcement and updating. This is most prominent with the introduction of new mechanisms through the malus on existing vehicles and scrappage subsidy. Effective testing and enforcement capacities are needed to mitigate evasion and ensure the effectiveness of the stock malus, while some additional administrative capacity is need for targeting and distribution of a scrappage subsidy. More instruments also increase uncertainty, likelihood of unintended outcomes, and potential calibration errors.

The pathway is also susceptible to potentially regressive distributional impacts, and potentially low acceptance of the stock malus. The pathway logic depends on the accelerated diffusion of BEV, both to increase new sales and more rapidly create a used-car market for E-mobility, making it more affordable and accessible to a broader range of population groups. If supply bottlenecks associated with turbulent exogenous global market conditions mean that diffusion is limited, early diffusion is slowed and the subsequent introduction of a malus on existing higher polluting ICE might face more political resistance, due to less availability of more affordable used BEV. Importantly, if the stock malus is not possible to implement at sufficiently high stringencies, the rate of transition is compromised. In these eventualities, more stringent carbon (fuel) pricing, or other instruments will be needed in the mid- to long-term to incentivize ICE scrappage.

6.3.3. Pathway 3: sequencing

Through targeting both accelerated stock turnover and reducing LDV usage, the 'sequencing' pathway balances transition dynamics. This reduces dependency on implementing immediately high stringency instruments, which mitigates major distributional and political risks. The use of complementary core instruments to drive the acceleration of BEV diffusion can address multiple market failures, enhancing dynamic cost effectiveness compared to the 'fuel focus' pathway. Compared to the 'stock focus' pathway, static cost effectiveness is increased through a more prevalent role of carbon (fuel) pricing (e.g. closer to anticipated EU ETS prices in other economic sectors). Governance requirements are also lower due to the reduced number of core instruments, and associated monitoring, enforcement, and calibration capacities. Potential distributional impacts and political challenges of implementing a (rapidly increasing) ICE stock malus are also avoided. As with the 'fuel focus' pathway, one critical parameter is the effective implementation of revenue recycling (e.g. via income-based, lump-sum recycling) to avoid regressive distributional outcomes and increase political acceptance. This is particularly important if very high carbon pricing levels towards 2030 and beyond are required to achieve climate targets.

The 'sequencing' pathway carries the least risks associated with potential backlash, as it utilizes design features which mitigate high risk of negative feedback mechanisms and engenders most flexibility for GHG abatement and ability to adapt. Initially, purchase-focused instruments can directly target market failures, and a clear trajectory enshrined in the purchase malus stimulates a strong acceleration market share of ZEVs. Commitment reduces investment risk for manufacturers and infrastructure providers, which increases dynamic cost effectiveness. The political risks from imposing immediate costs on the entire ICE fleet stock are reduced by targeting stock turnover. Combined with utilization of higher stringency carbon pricing than the 'stock focus' pathway, the dependence on BEV diffusion to meet mitigation targets is reduced and allows some flexibility by reducing existing ICE usage. Accordingly, if BEV cost reductions materialize slower than anticipated due to component shortages and/or trade disruptions, higher carbon (fuel) pricing allows some adaptability to reduced early diffusion rates, via increasing emissions abatement though reduced use of ICE stock. As a result, the total stock of vehicles on the road (LDV ownership/usage) in this pathway may be less than the 'stock focus' pathway, which may be more desirable from an energy system or broader sustainability perspective. A balanced approach also helps dampen the potential critical failures of the other pathways associated with over-emphasis on one abatement option (i.e. usage reduction vs stock turnover).

6.3.4. Comparing across pathways

When comparing across pathways attention should be directed to the overall implications of the durability assessments with respect to the risks of backlash, critical failures, and implications for effectiveness and goal attainment.

Across the three illustrated pathways, key differences relate to uncertainties in the distributional impacts and political acceptance of core instruments, and pathway adaptation under uncertain market conditions. Uncertainties in assessing distributional impacts for the 'fuel focus' and 'stock focus' pathways result from a current lack of empirical ex-post evidence to draw on, due to the unprecedented high stringencies of envisaged core instruments. Both pathways have uncertainties linked to horizonal inequalities and associated risks of adverse outcomes. While balancing of distributional outcomes is possible, doing so is very challenging. The 'sequencing' pathway aims at mitigating the most significant uncertainties by avoiding immediate hikes in policy stringency and allowing for learning and adaptation processes. By foregoing the immediate carbon (fuel) price hike, it reduces the potential for politically disruptive distributional impacts on the owners of existing ICE stock in the short term, allowing more time for adjustment of citizens and firms, as well as re-calibration of instruments and redistributive mechanisms if needed. By mitigating the greatest potential durability risks, while still providing directionality and credibility towards accelerating BEV market shares by 2030 the 'sequencing' pathway offers the highest likelihood of target attainment.

7. Conclusion and outlook

We develop and apply a multi-criteria assessment framework and anticipatory climate policy mix pathway construction methodology. The framework addresses key climate policy design and durability challenges: maximizing dynamic cost effectiveness, addressing distributional conflicts, building and sustaining political acceptance, reducing fiscal costs and ensuring effective governance of the policy mix. Effective climate policymaking requires addressing these challenges, as each has the potential to inhibit attainment of climate targets (Meckling et al., 2017). These generalizable climate policymaking design challenges will play out differently across regions, sectors, and time.

Policy assessments narrowly focusing on one or few evaluative dimensions reduce analytical complexity. This can allow deeper focus, requires less resources, and can generate useful insights. Yet, there are important trade-offs arising from limiting the scope of analysis. By omitting important variables or treating interaction effects as exogenous, they do not account for key dynamics in a complex system and may overlook critical durability challenges. Moreover, narrowly focussed analyses rely on policymakers' ability to correctly interpret outputs and integrate insights into decision-making, which is challenging and error-prone. We therefore argue that, whilst requiring significant analytical efforts, conducting integrated climate policy assessments which employ and advance our framework offers significant value. Systematically exploring alternative policy mix pathways can help anticipate, and mitigate, challenges potentially compromising political durability. Accordingly, such assessments can increase the likelihood of successful policy implementation and improve prospects for attaining climate targets.

Our application to the road transport sector illustrates the magnitude of increased ambition for instrument stringency implementation needed to accelerate the transition. Our illustrated pathways cover different normative perspectives on policy mix design still prevalent in the climate policy debate. One pathway is predominantly price-based and market-demand driven, while another is more focussed on stock turnover through accelerated BEV supply and discontinuation of ICE, with a more prominent role of regulatory standards. Our application demonstrates the limitations of focussing on either strategy too narrowly, and demonstrates the value of a balanced approach for policy instrument mix design. Illustrating the effects of each pathway on key durability challenges might contribute to facilitating substantive dialogue between more polarized opinions on policy preferences. This exercise might even lead to more collective consensus on mitigation pathways, and focus attention to effective implementation and supporting social learning processes by clarifying key differences among alternative policy positions.

Our application also highlights a key aspect of pathway construction and assessment: *designing under conditions of uncertainty*. Limitations include the availability and reliability of data when assessing unprecedented ambition levels, and quantification of some metrics and analytical indicators (e.g. behavioural dynamics). Given the scale and required speed of the challenge of climate change mitigation, there are uncertainties which cannot be resolved through limited ex-post evidence or inherently assumption-driven modelling exercises. Yet, our analysis also highlights the value of conducting timely rigorous ex-post analyses of policy mixes to inform their updating. We foresee integration of durability challenges and anticipatory design principles into applied planning processes and further work on reflexive governance (Edmondson et al., 2024; Wiarda et al., 2024), as important areas for both future research and policy practice.

As transitions progress, policy mixes need to adapt. Anticipatory design requires the inclusion of instrument flexibility mechanisms and planned revision steps, allowing recalibration of instruments to readdress durability challenges as they change over time. Effective implementation requires establishing governance structures and institutions which enable learning and recalibration (i.e. reliable data collection and provision, monitoring, and policy evaluation). Our framework could practically be integrated into existing planning and strategic exercises conducted in many countries and jurisdictions, which inform the development and review of climate policy strategies and instrument implementation. These processes should not only comprise expertise from various disciplines and sectors, but also feature broad stakeholder engagement to incorporate the best available expertise and key societal concerns and priorities. Further integration could help with procedural standardization and improve comparability of assessments, increase transparency, and foster higher degrees of policy learning. Analysts and practitioners sceptical of large-scale, long-term planning processes and advocating more incremental policy approaches will not meet this approach with enthusiasm. Yet, an approach based on strategic planning, learning, and adjustment, should offer a higher likelihood of attaining climate targets than incremental crisis management and 'muddling through' without strategic guidance.

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