How can current German and EU policies be improved to enhance the reduction of CO_2 emissions of road transport? Revising policies on electric vehicles informed by stakeholder and technical assessments

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Abstract

The electrification of the car fleet is an essential transformation to a meaningful reduction of greenhouse gas emissions in road transport. This has been a major goal of European transport policies, but other actions can also enhance the effectiveness of EVs to reduce emissions. In this paper we analyse four key European and German transport policies and assess how these could be improved to increase their potential to reduce emissions. Using iterative feedback from 12 interviews across various stakeholder groups, we have developed proposals for revised policies on electric vehicles. The results show that current policies in the EU and Germany are not making use of the full environmental potential of EVs, because they do not differentiate sufficiently between different EVs, and have been designed for the era of combustion vehicles. We suggest that the introduction of a new Bonus-Malus Registration Scheme and the overhaul of the existing Road Tax System are the most promising changes both in terms of their potential to reduce emissions and their likelihood of adoption.

Keywords: electric vehicles, GHG emissions, transport policy, policy effectiveness, Germany, EU

1 Introduction

In the last decades, political decision-makers have increasingly become aware of the need for action to mitigate the climate crisis. As a result, multiple emission reduction targets were introduced at local, national, and supra-national levels. Alongside European policy, Germany set targets to reduce transport emissions by 55% from 1990 levels by 2030 (German Government, 2019). More recently, the European Commission announced to ban new sales of combustion vehicles by 2035 (EC, 2021b). Yet, progress in decarbonising transport has been much slower than in other sectors (Figure 1), and therefore policy instruments should be revised to accelerate progress.

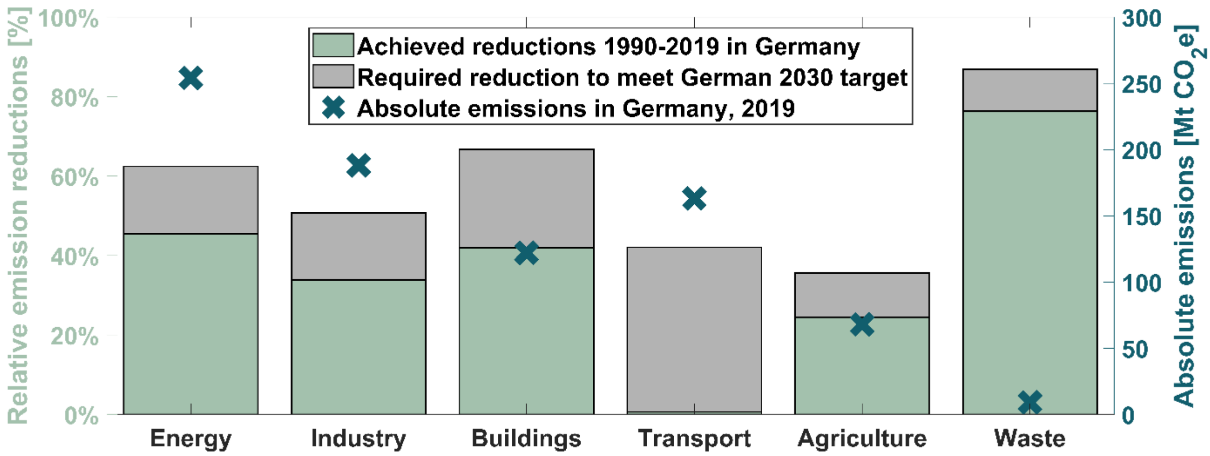


Figure 1: Left axis: Historic (1990-2019, turquoise) and targeted (2020-2030, grey) greenhouse gas emissions reduction, by sector. Right axis: Absolute emissions (2019, blue), by sector. Data: (BMU, 2020).

While around 94% of the transport sector´s emissions come from road vehicles, electrification has been and is likely to remain the single largest technological innovation to decarbonise this sector (Bunsen *et al.*, 2019; Crabtree, 2019). Light-duty vehicles comprise passenger vehicles and vans, and account for around three quarters of the European transport emissions (Destatis, 2021). Electric light-duty vehicles (EV) sales are ramping up at an accelerated pace – the market share of EVs in Germany has jumped from 1.8% in 2019 to 13.6% in 2021 (KBA, 2020, 2022). However, meeting the national 2030 EV fleet target requires reaching an EV market share between 40% and 60% by 2025 (NPM, 2019), which would imply a sustained growth of EV sales in the foreseeable future. Despite this accelerated growth, only 0.65% of German cars are fully electric (KBA, 2021a). These market characteristics highlight the dynamics and importance of the EV sector and consequently call for careful attention of policy-makers.

However, electric vehicles are no silver bullet in reducing Greenhouse Gas (GHG) emissions. Even though EVs have no tailpipe emissions, there are emissions during material production and manufacturing, and also from electricity generation. A widely adopted tool for quantitatively assessing and comparing environmental impacts is the Life-Cycle Assessment (LCA). Various LCA studies have found that throughout their entire lifecycle, many EVs emit overall less GHG than internal combustion engine vehicles (ICEVs) of similar size and usage. The geographic scope of these studies varied from a global perspective (Nordelöf *et al.*, 2014; Bunsen *et al.*, 2019; Helms *et al.*, 2019) over European boundaries (Ellingsen, Singh and Strømman, 2016; Messagie, 2017) to a Germany-focused scope (Wietschel, Kühnbach and Rüdiger, 2019; Helmers, Dietz and Weiss, 2020).

The magnitude of GHG lifecycle savings achieved by vehicle electrification depends on several interlinked variables, including patterns of use (e.g. lifetime mileage, test cycle vs. real-life emissions), vehicle design (e.g. fuel / energy efficiency, battery capacity, weight) and external factors (e.g. CO_2-intensity of the electricity, in- or exclusion of maintenance or End Of Life stage) (Egede *et al.*, 2015; Helms *et al.*, 2019). Abundant literature shows that embodied emissions of EVs are higher than for ICEVs (Ellingsen, Singh and Strømman, 2016; Bunsen *et al.*, 2019). Even though many ICEV components are replaced by fewer and less carbon-heavy electric drivetrain components, battery manufacturing requires a wide range of energy-intensive materials, which results in overall higher production and manufacturing emissions for EVs.

Additionally, several studies suggest that the mere electrification of transport alone will be not sufficient to meet the climate targets. Ellingsen, Singh and Strømman (2016) and Bunsen *et al.* (2019) have found that large EVs can produce the same cumulative emissions (Bunsen *et al.*) or even more (Ellingsen, Singh and Strømman) than small ICEVs across the full life cycle. Moreover, Cabrera Serrenho, Norman and Allwood (2017) found that if the UK's entire car fleet is electrified by 2050 but no significant changes in car-use demand or grid carbon intensity occur, the complete electrification of the car fleet would lead to only 5% reduction in emissions. Policy-makers must therefore avoid shifting GHG emissions from car use to electricity generation and car manufacturing facilities. Instead, potential emission savings largely depend on a whole range of parameters and therefore a carefully designed and well-balanced regulatory framework is paramount for decarbonisation of the personal transport sector.

Researchers have also analysed transport policies in different regions. The International Energy Agency (IEA) has concluded that the EU has established a strong and well-diversified set of EV policies (Bunsen *et al.*, 2019). The policy portfolio includes financial and non-financial domains, the latter entailing fuel/energy economy requirements or hardware standards for charging infrastructure. While the IEA recommends increasing the EV adoption rate, it also encourages the development of new taxation systems alongside a European integration of the battery supply chain (Bunsen *et al.*, 2019).

Financial regulatory instruments are noticeably different across member states in the EU. For this reason, many studies were conducted aiming to know how financial policies differ across European countries and how impactful they are. A 2016 report from the International Council on Clean Transportation (ICCT) compared existing financial schemes intended to boost the EV adoption rate. As a result, they highlighted the importance of simplicity and transparency, especially towards the consumer's end (Yang *et al.*, 2016). Researchers from the Joint Research Centre showed that the Total Cost of Ownership (TCO) of EVs vary noticeably across Europe, but also found financial incentives to be effective in increasing the market share of EVs (Langbroek, Franklin and Susilo, 2016; Lévay, Drossinos and Thiel, 2017; Wang, Tang and Pan, 2017).

The EU Emission Standard for light-duty vehicles is considered a central piece of European road transport regulation. Based on registration-averaged fuel efficiencies, this policy sets binding CO_2 targets for car manufacturers and penalises exceedances severely (EP and Council, 2019). Yet, only tailpipe emissions (TTW) are considered in the regulatory scope, leading to EVs being factored into the registration-weighted fuel efficiency equation as zero-emission vehicles. This feature is intended to make EV sales economically attractive for car manufacturers, but may miss incentivising other effective opportunities of decarbonisation, as it favours electrification over lightweighting (Cabrera Serrenho, Norman and Allwood, 2017).

Current literature provides compelling evidence that although the deployment of EVs is essential to decarbonise road transport, electrification alone will not be sufficient to achieve complete decarbonisation by 2050. Yet, existing policies promote a fast adoption of EVs, but fail to consider the effect of various other variables which could accelerate the pace of decarbonisation of transport. Since progress in the decarbonisation of transport is much slower than in other sectors (Figure 1), there is urgency in revising policy instruments to promote an acceleration of transport decarbonisation. This requires a systematic assessment of existing policies to examine whether they exploit the full potential of EVs to decarbonise light-duty transport in time. This study addresses this gap by examining how current policies concerning passenger vehicles and vans could be improved to better tailor incentives, and by developing new policy proposals with iterative feedback from relevant stakeholder groups.

2 Methodology

Identifying key gaps in existing transport policies required various steps for this analysis. These are illustrated in Figure 2, and included synthesising several stages of reviews, data acquisition and theory generation. An initial literature review on the technical dimension was conducted to determine the most important emission parameters for EVs. This information was essential for the regulatory literature review as secondary and primary literature was analysed to see to what extent the parameters of interest were already addressed. The insights from those reviews formed the basis of the theory generation. Using a grounded theory approach (Bryman, 2012), the generated policy proposals were iteratively discussed and amended, guided by insights from expert interviews.

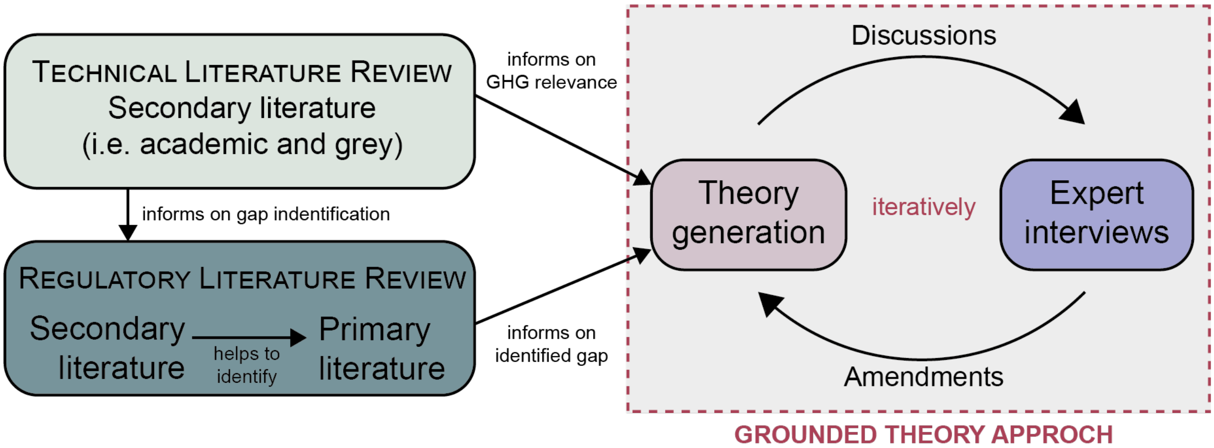


Figure 2: Methodology diagram of the different research phases and how they inform each other.

2.1 Identification of parameters

In order to find the most effective vehicle parameters to reduce lifecycle emissions, it was necessary to quantify their order of magnitude. Existing LCA studies provided the required information. Detailed information about this step can be found in Section 2 of the supplementary material.

2.2 Identification of policy gaps

Following the identification of the most critical parameters, a set of key policies to be examined was identified. These policies were selected based on their jurisdiction (EU or German), EV-relevance (direct implication for EVs) and reach (high level policies aimed at high impact). In the scope of this study, Germany was used as a case for multiple reasons, which are detailed in Section 1 of the supplementary material. To this end, existing policy reviews (secondary literature) were used, enabling the identification of primary sources (e.g. laws, directives, policy schemes). Primary sources included German Government and agencies as well as policy documents from the EU. A full list of sources consulted to select the key transport policies examined in this analysis is provided in Section 2 of the supplementary material for further information.

The selected key policies were examined to identify the extent to which they consider the previously identified parameters or whether there are policy gaps. Understanding whether and how the parameters were addressed in the current regulations required the analysis of primary literature, because many parameters were not discussed in secondary literature from a regulatory viewpoint. Notably, the identification of policies and their gaps was not a static process as the ‘grounded theory’ approach enabled a continuous update and more accurate assessment of regulatory gaps alongside the stakeholder interviews.

2.3 Development of policy proposals

The development of new policy proposals capable of enhancing the benefits of a transition to EVs comprised two steps. First, shortcomings in existing policies were addressed by the proposition of changes to appropriately consider the parameters of interest identified in section 2.1. The second step aimed at considering yet unaddressed parameters and entailed qualitative drafts of novel regulatory concepts.

To avoid academically crafted proposals that lack relevance or practical feasibility, the incorporation of multiple stakeholder groups was deemed essential. The format of semi-structured interviews was chosen, because understanding how the developed proposals might be amended to fit better in the industrial and political landscape required a flexible interaction with the experts (Knight and Ruddock, 2008).

Mitigating the risk of a one-sided stakeholder perspective, experts from three interest groups were contacted: industrial representatives, researchers/organisations and policy-makers. In total, 30 professionals from a multitude of institutions and interest groups were contacted. If no response was received, a second and a third contact approach was initiated, which led to a response rate of 90% (27 out of 30 individuals). Out of 27 replies, 12 interviewees from three stakeholder groups agreed to participate. These are identified in Table 1 of the supplementary information. A detailed methodologic description of the data analysis stages, including the coding process, can be found in the Section 2 of the supplementary information.

Dictated by the grounded theory approach, the data acquisition and analysis influenced the theory generation and vice versa. Consequently, the questions asked in later-stage interviews differed in focus and depth compared to early-stage interviews. This iterative approach significantly enhanced the quality and relevance of the proposals.

3 Results and discussion

The three-step methodology described in section 2 led to the identification of the most relevant emission parameters for EVs (section 3.1), the identification of policy gaps in existing German and EU regulations, and an assessment of each policy with proposed amendments, and their discussion (section 3.2). Readers interested in general insights from the expert interviews can refer to Section 3 of the supplementary material.

3.1 Relevant vehicle parameters

Characteristic GHG emissions of an EV can be categorised into its lifecycle phases, as shown on the left side of Figure 3. For a typical EV in Germany, the production phase account for around 40 % of the life cycle emissions, while the use phase is responsible for around 60 %. Acknowledging significant data uncertainty in the end of life stage, only a small number (<5%) of the lifecycle emissions stem from here, suggesting limited direct emission savings. A detailed description of this estimate, its sensitivity towards LCA assumptions and the derivation of parameters can be found in Section 4.4 of the supplementary material.

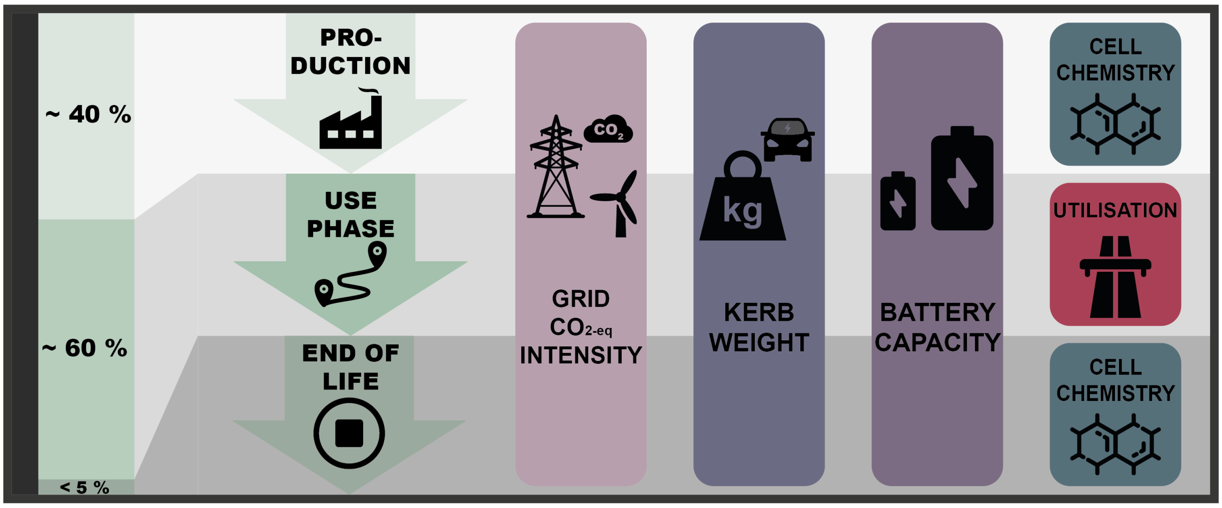


Figure 3: Share of GHG emissions of relevant parameters of an EV throughout its lifecycle. Section 4 of the supplementary material provides details on the lifecycle stage emissions estimates.

Production emissions are influenced by a multitude of factors, including material composition, vehicle size and weight, and manufacturing processes. Mineral extraction and material production entail combustion of fossil fuels and process emissions (Kelly, Dai and Wang, 2019). As a direct consequence, heavier vehicles require more material and therefore also more emissions than lighter vehicles of similar composition. Additionally, material production and manufacturing of lithium-ion battery technology results in emissions. Many studies investigated the impact of cell chemistries on the carbon footprint but poor data availability and different assumptions make a fair comparison almost impossible (Peters *et al.*, 2017). Yet, it seems clear that the chemistry and the upstream supply chain play an important part for the overall carbon footprint (Bunsen *et al.*, 2019; Ciez and Whitacre, 2019).

A battery is the single most carbon-emitting component of an EV, accounting for around 40% of the manufacturing emissions (Ellingsen, Singh and Strømman, 2016). As battery materials and manufacturing processes are emission intensive, the embodied emissions scale with the installed capacity, making the battery capacity of an EV a key variable in determining the emissions during the manufacturing stage. Because a large fraction of the required manufacturing energy is actually electricity, the carbon intensity of the grid is a key lever to reduce emissions during this phase (Ellingsen and Hung, 2018; Peters and Weil, 2018).

Use-phase emissions are also influenced by a multitude of parameters. The use phase emissions can be expressed as a product of the average carbon grid intensity used to charge the EV's battery, the average energy efficiency of the vehicle and the distance driven over its lifetime. Naturally, future changes in any of these factors proportionally affect the use-phase emissions and are therefore relevant parameters for the purposes of this work. However, since the scope of this analysis is on light-duty EV policy, and not on mechanisms to decarbonise the energy sector, we have not considered the supply and costs of low-carbon electricity.

The energy efficiency of an EV is determined by internal factors such as vehicle aerodynamics, the engine's power or the weight of the vehicle (Milliken and Milliken, 1994). As force and thus energy is required to overcome inertia, and mass is the largest contributor to the inertia (Hirz, 2015), heavier vehicles necessarily require more energy than lighter ones to travel the same distance, regardless of the type of vehicle. This effect, however, is weaker for EVs since a share of the kinetic energy can be recovered by regenerative breaking instead of getting heat dissipated (Spichartz, Dost and Sourkounis, 2014). Larger battery packs lead to higher weights and therefore to higher life cycle emissions (Ellingsen, Singh and Strømman, 2016)). A visual representation of the rising EV energy consumption with increasing mass is illustrated in the Section 4 of the supplementary material.

The energy requirements and emissions of running EVs is also obviously dependent on how longer and more frequently they are used. EV utilisation naturally results in higher emissions, but high longevity of batteries enable longer usage of EVs. However, the contribution of cell chemistries to the use phase emissions is not clear at this early stage as there is limited literature concerned with lifetime emission trade-offs as a function of cell chemistries (Preger *et al.*, 2020; Spitthoff *et al.*, 2020; Olmos *et al.*, 2021).

End-of-Life (EoL) emissions are subject to great uncertainty. As EVs have a lifespan of around 10-year and sale number were close to irrelevance one decade ago, there have been only a small number of EVs retiring so far (Hampshire *et al.*, 2018). Due to small-scale practices and consequent data uncertainties, many researchers exclude this phase from their studies' life cycle analyses (Helms et al., 2019). Similar to ICEV end-of-life processes, the energy and electricity carbon intensity as well as the mere quantity of material to be processed influences the EoL EV emissions (Helmers, Dietz and Weiss, 2020). Additionally, EV batteries contain valuable metals which could be recycled reducing the flow of virgin materials. Cell chemistry and the battery capacity are of importance since they heavily influence the economic part of the recycling equation. There are recycling models predicting both positive and negative net emission savings, based on the cell chemistry and recycling technique (Ciez and Whitacre, 2019; Mohr *et al.*, 2020).

3.2 Policy shortcomings and proposals

Following the methodology described in Section 2.2, four policies were identified as critical to the EV policy landscape — two at German national level and two at EU level. This include the EU Emissions Standard, German National Subsidy Scheme, German Taxation System, and the EU End-of-Life and Battery Directive. In this section, for each of these policies, we provide 1) an analysis about current emission reduction shortcoming, 2) a proposal for an improved policy design, 3) qualitative estimates on the proposal's carbon reduction impact and 4) its likelihood of adoption. These findings are compactly displayed in Table 1.

3.2.1 EU Emission Standard

The EU Emission Standard (Reg. EU 2019/631, formerly Reg. EC 443/2009) regulates the CO_2 emission limits of light-duty car manufacturers operating in a member state of the EU. Each car manufacturer (OEM) has an individual CO_2 target, which is influenced by the manufacturer cars' average fuel efficiency [$\frac{g-CO_2}{km}$] and the cars´ average kerb weight [kg] – the two axes in Figure 4. The baseline for the average is the cars sold by one OEM in one year. A mathematically constructed line, called the limit-value curve, divides the quadrant between these axes into two parts: a penalty region above the line (e.g. FCA in Figure 4) and a region below the line where no penalties apply (e.g. Renault in Figure 4). It follows from the line's right- and upwards orientation that higher average car masses result in higher allowed CO_2 emissions. The mathematical construction of this limit value curve is made by policy-makers and can be made more stringent by downward shifts, as illustrated by the 2015-2021 shift.

When averaging the fuel efficiency of an OEM, there are special accounting mechanisms for zero and low-emission: cars with tailpipe emissions below 50 $\frac{g-CO_2e}{km}$ are accounted using a weighting factor of 1.67, which is a strong incentive for OEMs to sell those cars (2020: 2-fold, 2021: 1.67-fold, 2022 1.33-fold). After 2025, a different crediting system will come into force, also incentivising sales of ZLEV.

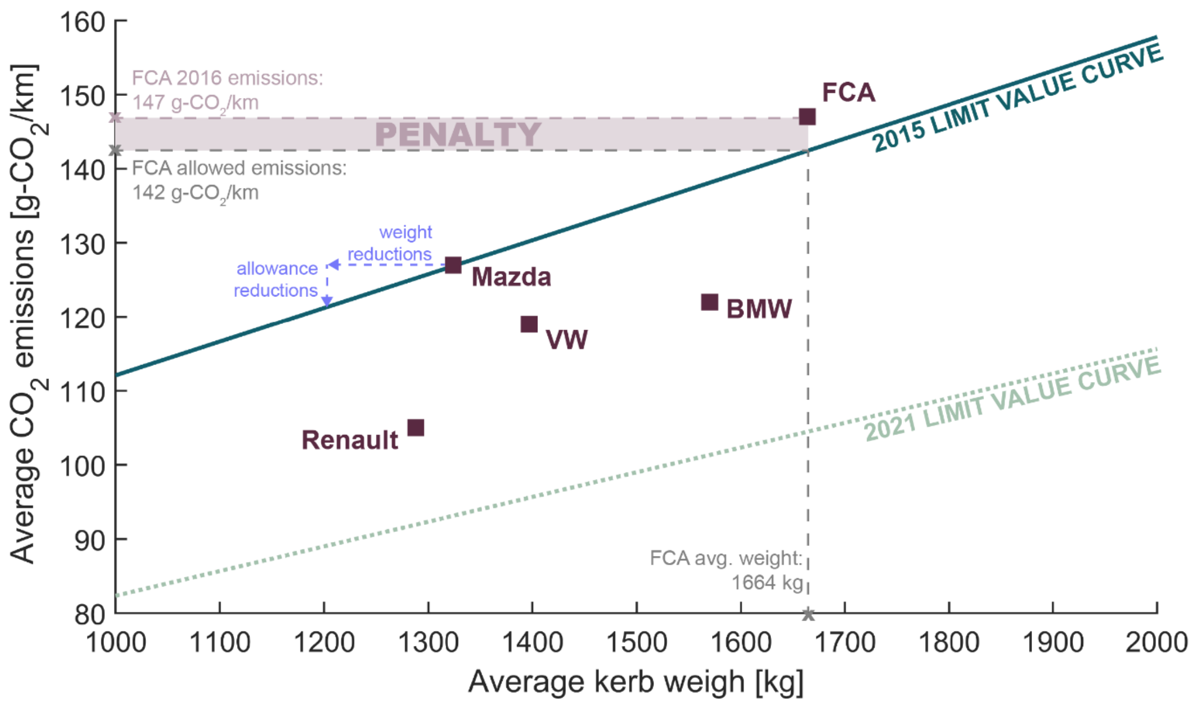


Figure 4: EU emission standard: the higher the average mass of a car manufacturer, the higher its allowed average CO_2 emission. 2016 basis for OEM data points, datapoints of OEMs is not extensive. Data from (EEA, 2017; EP and Council, 2019).

Current shortcomings

This policy design introduces shortcomings in three distinct ways:

- Weight reductions are disincentivised, as this implies stricter CO_2 targets (see light blue arrows in Figure 4). As shown Section 3.1, vehicle mass is a key determinant in energy efficiency. This policy, by design, devalues the attractiveness of a powerful efficiency lever, namely making cars lighter.
- Since only tailpipe emissions are considered, the policy does not distinguish between small and large EVs. With this regulatory tailpipe focus, car manufacturers have no incentive to reduce real-world emissions of EVs, e.g. by reducing the kerb weight of EVs – see Figure 4.
- Since EVs tend to be heavier than combustion vehicles of similar size, the sales of (heavy) EVs increases the average weight (KBA, 2021b). Consequently, the OEM's position in Figure 4 is shifted rightwards, ultimately increasing the OEM's CO_2 target.

These shortcomings show that this policy is not fully aligned with its goal to reduce real-world emissions. It not only promotes high kerb weights but it also incentivises OEMs to aim at high adoption rates of heavy EVs, which miss important opportunities to reduce further real-world emissions.

Proposal and GHG impact

By changing the use of mass [kg] to area [m^2] in this policy, this unfavourable reinforcing loop can be interrupted. 'Area', in this case, refers to the area between the four wheels, or the product of wheelbase and track width, also known as footprint area. It is important to realise that when choosing a new vehicle, customers usually care about the size and practicability, amongst others, but rarely about vehicle weight itself. Opposed to mass, which has a fundamental impact on the required energy to power a car, vehicle size, if anything, influences the vehicle's cross-section area and therefore indirectly aerodynamic drag.

By changing the regulation from mass- to a footprint-based system, higher CO_2 allowances would apply for bigger vehicles (larger footprint) instead of heavier vehicles, thus decoupling vehicle weight and CO_2 allowance but more accurately linking the consumers' demand and the allowed emissions. To meet their CO_2 targets, OEMs would be incentivised to reduce weights for cars across all categories as the resulting emissions savings would no longer be undermined by lower CO_2 targets (Figure 5). Notably, heavy duty vehicles, such as trucks and semi-trailers, have a different vehicle design and usage patterns and their emissions are thus regulated with a different approach (Regulation EU 2019/1242).

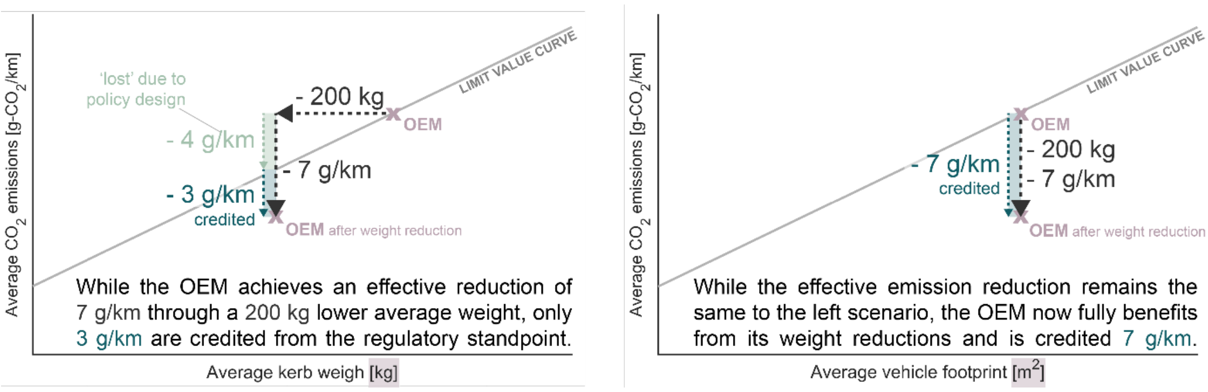


Figure 5: In a footprint-based regulation emissions savings from weight reductions would no longer be undermined by lower CO_2 allowances. Figure based on (Mock, Tietge and Dornoff, 2018)*.*

Over the past decade, the share of larger and heavier Sport Utility Vehicles (SUV) has increased continuously, accompanied by increasing average kerb weights (KBA, 2021b). This is particularly problematic because EVs are heavier than ICEVs across all car categories and SUVs have the highest relative net weight gain comparing combustion and electric vehicle types (KBA, 2020). Higher EV adoption rates and a strong SUV demand are likely to further increase average kerb weights. The implementation of this policy could mitigate this trend and benefit the adoption rate of lighter cars (INT-VDA, 2020). Combining these considerations, the potential emissions savings of this proposal can be considered to be high.

Likelihood of adoption

Some industrial representatives voiced concerns that the current legislation is artificially increasing policy compliance costs, by effectively disincentivising cost-effective weight reductions (INT-VDA, 2020). Decoupling the CO_2 target and kerb weight - as proposed - allows OEMs to make use of weight reductions to avoid penalties more economically. Moreover, given current consumer preferences and business practices, larger vehicles offer a higher profit margin for OEMs than smaller cars (INT-BMW, 2020; INT-VDA, 2020). With this proposal, OEMs could maintain profit rates with larger cars while decreasing their weight. LCA studies of lightweight automotive applications have shown that some substitutes can have higher lifecycle emissions than the original material, as is the case of Carbon Fibre Reinforced Polymer (CFRP) (Witik *et al.*, 2011; Kelly *et al.*, 2015). However, Aluminium and High-Strength Steel (HSS) are produce less emissions than ordinary mild steel (Cabrera Serrenho, Norman and Allwood, 2017).

The interviewed stakeholders were familiar with the current regulation as it was developed and proposed in large parts by two of the interviewees' organisations: German Association of the Automotive Industry

(VDA) and the European Commission (EC). If discussed, all interviewees agreed that due to the inertia in the existing policy, any conceptual changes are very unlikely to happen (INT-EC, 2020; INT-VDA, 2020; INT-ICCT, 2020). Instead of conceptual changes, tightening existing targets are to be expected (INT-NPM, 2020). For this reason, and despite the above-mentioned upsides and positive reactions from most interviewees, the likelihood of consideration of this policy is likely to be low.

3.2.2 National subsidy scheme

The German government has established a scheme supporting the uptake of plug-in hybrid vehicles and EVs through purchase subsidies. Until the end of 2021, EVs with a list price below 40,000€ are eligible for a 9,000€ subsidy whereas EVs with a list price between 40,000€ and 65,000€ receive a 7,500€ subsidy (German Government, 2020). After a modification due to the COVID-19-induced economic recovery package, federal sources now cover two-thirds of the costs of this programme, while manufacturers contribute with one third (Bundesanzeiger, 2020). This subsidy can significantly reduce EVs' procurement costs: e.g. decreasing a VW E-Golf by 28% from 31,900 € to 22,900 €.

Current shortcomings

While there is a positive relationship between kerb weight and price as shown by Figure 6, the existing subsidy scheme provides only a limited incentive to the purchase of EVs. Not only the vehicle price is a suboptimal proxy of a vehicle's environmental performance, but also step-function-like cuts in subsidies are prone to gaming and fail to differentiate adequately between the varying GHG emissions within one price group.

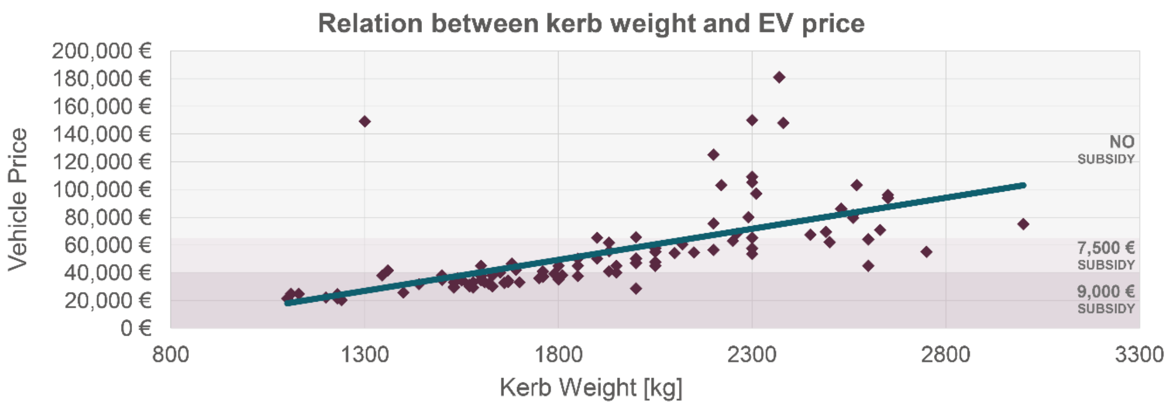


Figure 6: Plotting the kerb weight and vehicle price for 100 EV (database consists of existing and announced EVs in Europe and stems from (EV-Database, 2020)). Linear least square curve fitting to indicate trend (R^2 value: 0.4): positive relation between higher weights and vehicle prices.

Proposal and GHG impact

The proposed scheme would apply a tax to vehicles that exceed the current average EV-weight by a certain factor, see Figure 7. At the other side of the spectrum, EVs that are lighter than the current EV-average are progressively subsidised.

For every sold EV which is lighter than the average EV weight, a progressively rising subsidy would subsidise the purchase. On the other hand, OEMs have some leeway when surpassing the average weight before facing an also progressively rising tax (Figure 7). By creating this neutral area, only EVs that noticeably exceed the average weight are effectively penalised. The policy design must consider the rapid developments on the EV market and thus, calling for an annual readjustment of the average EV weight.

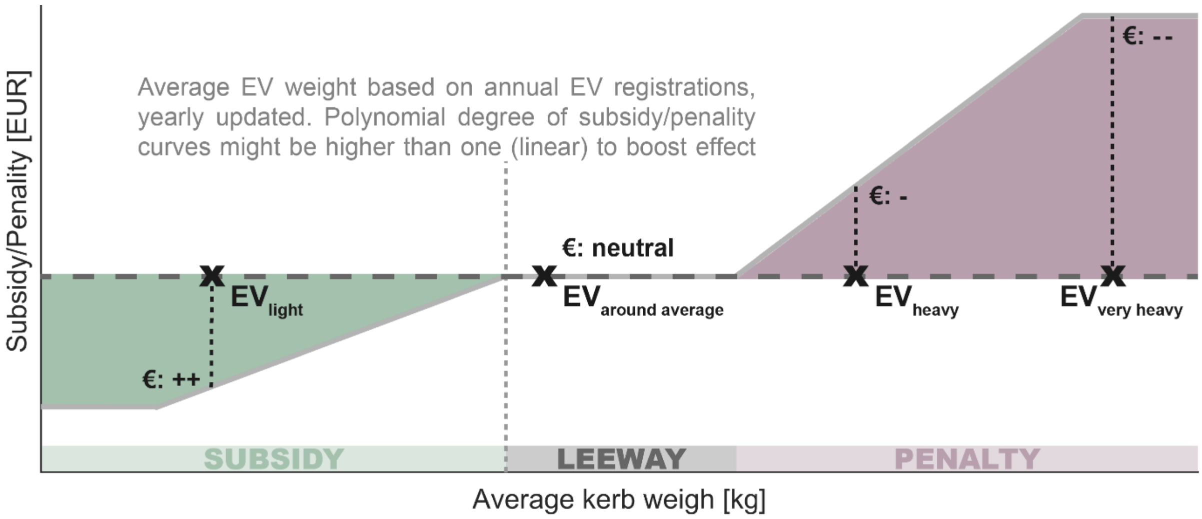


Figure 7: Proposed bonus-malus scheme in Germany. The amount of tax/subsidy is dependent on the relative difference between the EV and the current EV average weight.

EVs with lower weight require less energy than their heavier analogue and there is an accelerating trend of rising average weights (KBA, 2021b). The GHG emission savings effect of this policy might take some time to become apparent, as emissions are saved cumulatively throughout the vehicles' lifetimes. Since this policy targets only EVs but acts on a leverage point at an early stage of adoption, we have classified the potential GHG impact of this proposal as medium.

Likelihood of adoption

This proposal does not influence OEM's high-level compliance costs, but focuses on EV-specific characteristics. This would be the first policy in Germany directly aiming to decrease EV-specific emissions. Bonus-malus schemes, similar to this, are already deployed in France and the Netherlands, and are generally considered effective (Cambridge Econometrics, 2013; Yang, 2018). By coupling the tax/subsidy with EV kerb weight instead of fuel efficiency, a financial incentive would encourage OEMs to reduce EV weights. Additionally, this policy can be financially self-sufficient or even generate revenue as the total collected taxes might exceed granted subsidies.

As there are currently only policies in force supporting the EV deployment but not guiding the development and design of EVs, this policy might be perceived as constraining, potentially retarding the adoption rate and make EVs less profitable for OEMs in the short term. Moreover, some stakeholders expressed concerns that defining kerb weight as the central variable might be too granular and limit the OEM's innovation potential (INT-BMW, 2020; INT-FDP2, 2020). This proposal does not target efficiency directly, and it rather aims at vehicle mass, but there are good reasons for this. The efficiency estimates are based on standardised driving cycles (NEDC and WLTP) which are known to severely underestimate the real-life emissions (EC, 2015; Fontaras *et al.*, 2017; EEA, 2019). The discrepancy between the type-approval driving cycle and the real-life emissions are increasing over time, having reached a staggering discrepancy of over 40% for some vehicles in 2018 (Muzi, 2018; Craglia and Cullen, 2019; Dornoff, Tietge and Mock, 2020). In early 2021, the EC has adopted a regulation to monitor the gap between type approval and real-world emissions but no concrete measures are planned to eliminate it (EC, 2021a). While this discrepancy substantially undermines the real climate change mitigation potential, targeting weight reduction delivers energy and emissions savings regardless of any progress in vehicle efficiency. For this reason, a policy focus on weight may be more effective in reducing emissions and energy uses than a focus on measured (rather than real) efficiency.

The adoption of this revised policy may raise equity concerns. Shifting the subsidy awarding criteria from price to weight, could enable awarding subsidies to very expensive light vehicles, purchased mostly by the wealthy. However, most of such luxury vehicles are heavier than the average (Figure 6), and the proposed policy could be combined with a cut-off price beyond which the subsidies would not be awarded.

While this policy has proven popular with the majority of the interviewees, it might be difficult to communicate its structure and implications effectively to consumers. Consumers may often prefer lighter EVs when knowing that an explicit subsidy is granted for their choice. Thus, and in order to maximise the policy's impact in terms of consumer behaviour, clear communication is pivotal (INT-ITF, 2020). Since stakeholder assessments were based on the currently uncovered regulatory domain and the noticeable potential GHG impacts, the likelihood of political consideration can be classified as medium.

3.2.3 Taxation system

While Germany's current light-duty vehicle registration taxes are relatively low, all registered vehicles are required to pay an annual tax. The levy comprises of two components: (1) for cars which emit more than 95 g-CO_2/km, the levy rises with every exceeded $\frac{g-CO_2e}{km}$ (BMJV, 2017). Vehicles emitting less than this threshold – including EVs and PHEVs – are excluded from this levy; and (2) a levy component directly proportional to the engine's cylinder capacity [cm^3], for which EVs are exempt since this metric is technically inapplicable for EVs.

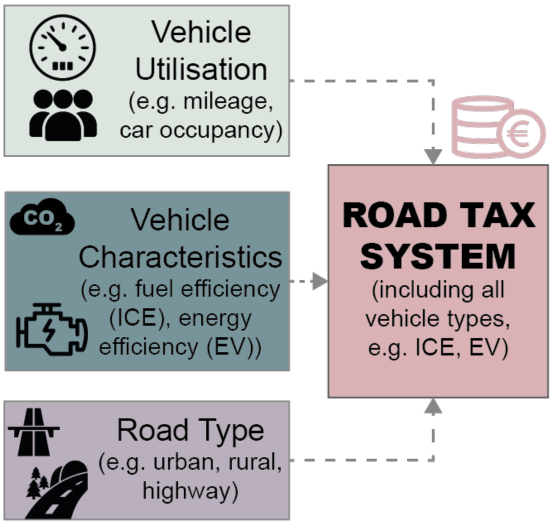
Current shortcomings

The German government has adopted a bill in late 2020 which strengthens the CO_2 component and weakens the importance of the cylinder capacity parameter (Bundesgesetzblatt, 2020). However, as all EVs remain exempted from the vehicle tax, there is once again no differentiation of EVs' environmental performance.

Proposal and GHG impact

The goal of this proposal is to strengthen the 'polluter pays' principle and correlate annual taxation with annual GHG emissions in an inclusive and equitable manner. In that, it is paramount to avoid a regulatory hotchpotch but ensure a transparent and easy-to-communicate policy. As illustrated in Figure 8, the suggested vehicle taxation is influenced by three factors:

Figure 8: Components of the proposed road tax system.



- car usage information split into quantity (mileage) and quality (car occupancy) will be factored into the taxation system.
- vehicle characteristics, e.g. fuel/energy intensity or vehicle weight, which can be influenced by the consumers at the purchase stage.
- information about the typical road type used by a vehicle, which is used as a proxy for the existence of feasible, less emitting substitute services, such as public transport, shared mobility, or bike lanes. For example, an old, big petrol SUV commuting daily between two districts in central Berlin would be taxed more than a small EV travelling occasionally between two rural hubs.

This proposal not only incorporates all propulsion systems, including EVs, but also relates road tax to a number of parameters. A powerful lever of behaviour change can be tapped, provided that a transparent policy design allows consumers to link their behaviour to tax savings. Combined with the change of the taxed metric from currently $\frac{g-CO_2}{km}$ and cm^3 to the ecologically more sensible $\mathrm{g}-\mathrm{CO}_2$, the potential GHG impact of this policy can be regarded as high.

Likelihood of adoption

Given the current regulation with broad EV exemptions, tax revenues from the vehicle sector are set to decline progressively. This foreseeable gap in tax revenue creates important incentives for the legislator to explore new taxation systems and finance investments in a low-carbon transportation infrastructure (INT-ITF, 2020; INT-CON, 2020). However, while this policy may be popular with policy-makers due to its financial self-sufficiency, it may be poorly received by the public. Since there is currently no road tax for passenger vehicles in Germany, public resistance is expected against additional taxes. Additionally, one disadvantage of this policy's flexibility and granularity is that it is more complicated compared to the current taxation system which may make it less understandable and obscure its environmental merits.

Moreover, higher embodied emissions of EVs would only be outweighed if the EV is utilised beyond a certain mileage. It may send a skewed signal to incentivise purchases of EVs – with high embodied emissions – but simultaneously encourage low usage of cars. However, if high occupation rates are factored in at lower taxes, consumers may be encouraged to adopt more responsible mobility choices.

Considerable implementation barriers must be acknowledged as infrastructure investments would be required to ensure robust and backwards compatible operation. Currently, trucks are taxed mileage-based and must either install a compatible chip or register every ride online with the authorities (Steen, 2020). While this chip could be declared mandatory for new cars, it remains questionable if a chip-technology is the best solution for retrofitting existing cars. Building an extensive infrastructure on highways, urban and rural streets which reliably registers licence plates, travel distance and passenger occupancy is technically challenging, expensive and prone to evoke privacy concerns. Additionally, it would not be straightforward to compare 'sufficiency' and 'affordability' of public transport across different states and cities.

Assessing the likelihood of consideration, many experts agreed that a novel and more honest taxation system is crucial to ensure long-term sustainability of the transport sector. Yet, its implementation and perception barriers may make this approach appear less tangible and desirable for policy-makers. For these reasons, balancing the necessity, the GHG impact and political realities, the likelihood of adoption of this proposal is considered to be low.

3.2.4 End of Life Vehicles Directive and EU Battery Directive

The End of Life Directive (Dir 2000/53/EC; national law: 'Altfahrzeug-Verordnung - AltfahrzeugV') states that OEMs are responsible for the EoL treatment of their brands' decommissioned vehicles. From 2015 onwards, the reuse and recycle target is set to 85% with respect to the vehicle mass (EP and Council, 2000). This policy can be considered effective as the EU and German average in 2017 were 88% and 90% respectively, therefore exceeding the already ambitious legal requirement (Eurostat, 2020). Introduced in 2006, the EU Battery Directive (Dir 2006/66/EC; national law: 'Batteriegesetz – BattG') is concerned with the collection and recycling of batteries. Similar to the EoL directive, the responsibility of old batteries lies with the entities that initially introduced them to the market.

In late 2020, the EC proposed an overhaul of the existing directive (EC, 2020) which is currently assessed by the European Council and the European Parliament's responsible committee (EP, 2021). Because the proposal is still undergoing the European legislative process, only the current enacted regulation was subject to this analysis.

Current shortcomings

This Directive groups batteries into three categories: portable, industrial and automotive (EP and Council, 2006). Automotive batteries refer to 12-Volt starter batteries, but not 400-Volt traction batteries used to power EVs. Lithium-Ion battery cells contained in EVs are still classified as 'other' cell chemistries in the 'industrial' category. The recycling efficiency target for all 'other' cell chemistries lies at only 50% of the total mass of batteries, regardless of the retrieved minerals (EP and Council, 2006; EC, 2014). On top of having no quotas for critical minerals, not only the battery cells but also the casing count towards the total mass. Consequently, around 50% of the target recycling rate can be achieved by the mere recycling of the casing which ultimately reduces the required recycling efficiency rate of the battery cells with respect to mass down to 25% (Tytgat, 2013). This leads to little regulatory environmental incentive and allows corporations to focus on economic aspects (Hampshire *et al.*, 2018).

Proposal and GHG impact

There is an opportunity to address the shortcomings of this policy by addressing the economic, environmental and social issues adequately. This requires that lithium-ion batteries are recognised as their own category (Li-ion) within the existing regulatory framework. Two types of targets should be defined for the newly created Li-ion category:

- ambitious targets for Li-ion battery's recycling efficiency with respect to mass;
- special quotas should be defined for the minerals whose mining involves high environmental and social cost.

When the capacity of the cells has decreased over time beyond a certain threshold, they are considered unfit for mobile operation. However, there is still market potential for second-life applications which remains currently mostly unexploited. Since manufacturers know the detailed composition of batteries, they are best equipped to facilitate end-of-life steps, e.g. recycling. For this reason, EV batteries sold for second-life applications should remain under the responsibility or ownership of the initial battery manufacturers. This increases transparency and planning security for both parties.

As discussed briefly in section 3.1 and in greater detail in Section 4 of the supplementary material, there is substantial uncertainty tied to the GHG emission contribution of the end-of-life stage. Namely, studies come to diverging estimates when assessing the net emission savings of recycling. Therefore, and until industrial-scale recycling data becomes available and enables the reduction of uncertainty on their GHG mitigation potential, the current impact of this proposal on potential emission reduction is considered to be low. Contrary to GHG emissions, recycling studies are more conclusive about positive effects of recycling in other environmental categories, e.g. eco-toxicity (Mohr *et al.*, 2020; Yang *et al.*, 2021).

Likelihood of adoption

This proposal aims to reduce the imbalance between economic, ecologic and social dimensions in current battery recycling practices. Since wide battery-component recycling is currently not profitable, greater amounts of virgin minerals than necessary are extracted and processed in current supply chains (INT-VDA, 2020, INT-TEC, 2020). Introducing quotas could lead to faster learning rates and thus sooner economic operation. Lifting the strain on virgin material could also entail, for instance, lower levels of local pollution during extraction. Potential benefits of this proposal depend on the status-quo extraction practices and cell chemistry. Incentivised through this proposal, OEMs can improve the impact of their business activities by taking strategic decisions on design for reuse and recyclability (Helms *et al.*, 2016).

Part of future OEM strategies includes questions around battery resource supply security and affordability. As volatile mineral prices and supply chains disruptions pose considerable planning insecurity for battery manufacturers, a stream of locally recycled and refined critical metals can mitigate some of this risk (Evans *et al.*, 2017; Bunsen *et al.*, 2019). Transparent regulation around recycling of critical metals will help in creating a European stream of required material and reducing planning insecurity for OEMs and their supplier.

In late 2020, the EC has published their proposal to overhaul the existing battery directive. It was proposed to change the legal structure from a directive to a regulation, reducing regulatory leeway for directives when translated into national laws. The EC recognised not only severe gaps in the current directive but also the importance of the battery (recycling) industry. As suggested in this study, the EC proposal intends to create a dedicated category electric-vehicle batteries, and sets from 2025 onwards general recycling efficiencies and individual recovery targets for critical metals used in battery manufacturing, such as cobalt, copper, nickel and lithium (EC, 2020). Additionally, other innovations include the mandatory declaration of the batteries' carbon footprint, quotas on minimum recycled content or the provision of use phase information enabling better planning for second-life applications. If an agreement is reached between the Council, the Parliament and the EC without substantial modifications, this proposal has the potential to introduce an innovative, ambitious, and environmentally sensible policy framework. Considering that the directive is already in rework, the likelihood of consideration of this proposal's core ideas is considered to be high.

4 Conclusion and policy implications

The results show that current policies in the EU and Germany are not making use of the full environmental potential of EVs and therefore regulatory gaps have been identified. It was shown that existing policies do not differentiate sufficiently between different EVs. While the regulatory focus on tailpipe emissions might be reasonable for the era of combustion vehicles, regulation risks with this current scope to turn a blind eye to real-world carbon emissions of EVs and therefore undermine climate mitigation efforts. It was also shown that an unguided deployment of electric vehicles is not enough to meet the country's climate targets but a diligently planned regulatory framework is required.

Our results suggest that the introduction of a Bonus-Malus Registration Scheme (National subsidy scheme) and the overhaul of the existing Road Tax System (Road taxation) yield the highest priorities for action, when considering both their potential to accelerate emissions reductions and their likelihood of adoption. As a result, decision makers across the EU can consider this priority estimate to focus their attention on the most powerful policy levers. This is shown in Table 1, which summarises the analysed transport policies, key opportunities for change, and which also displays their potential GHG emission impacts and anticipated likelihood of adoption.

A revised National subsidy scheme was found to be of high priority as it offers an attractive combination of a medium potential GHG saving and a medium likelihood of consideration. Only moderate changes in the current regulation would be necessary to better align the policy´s steering effect with stronger climate change mitigation efforts.

Equally, the Road taxation proposal was also found to be of high priority, given the currently untapped steering potential of a road tax, and the high potential to reduce emissions. Extensive policy design efforts and considerable implication barriers keep the political attractiveness of this proposal low. Yet, this proposal addresses pressing questions, including the taxation of EVs, which will become all the more relevant in the coming decades.

Despite the high emissions saving potential of a revised EU Emission Standard, interviewed experts identified substantial political inertia as a key barrier for consideration. Additionally, the relevance of this policy will inevitably decline in the coming decades as it is designed to regulate a vehicle fleet dominated by combustion-engine vehicles.

In recognition of the need for an updated EU directive on batteries for emerging EVs, the EC is currently undertaking a review of the EU Battery Directive. While the GHG mitigation potential of this proposal is likely to be low, positive environmental impacts in non-GHG emission areas are expected.

Table 1: overview of identified polices, their respective shortcomings and improvement proposals

Targeted policy	**EU Emission Standard**	**National subsidy scheme**	**Road taxation**	**EU Battery Directive**
Introduced (last updated)	2009 (2019)	2016 (2020)	1906 (2017)	2006 (2018)
Level	EU	National	National	EU through national
Policy intention (EV-specific)	• Increase of car fuel efficiency • Increase of EV adoption rate	• Increase of EV adoption rate	• Increase of EV adoption rate	• Definition of clear responsibilities
Identified shortcomings	• Incentive for high kerb weights • No differentiation between EVs	• Insufficient differentiation between EVs	• Exclusion of EVs from tax until 2030 • No differentiation between EVs	• Insufficient consideration and targets for Lithium-ion batteries
Proposal description	Modification of policy by changing the relevant parameter from mass to footprint area	Introduction of a Bonus-Malus Registration Scheme by subsidising lighter than-average EVs and vice versa	Overhaul of the Existing Road Tax System by factoring in utilisation, road type and vehicle specifications	Overhaul of policy by defining EV-battery specific recycling efficiency targets
Addressed parameter in proposal	Kerb weight	Kerb weight	Utilisation	Cell Chemistry
GHG impact of proposal	**High**	**Medium**	**High**	**Low**
Likelihood of consideration	**Low**	**Medium**	**Low**	**High**
Priority for action	**Medium**	**High**	**High**	**Waiting for EU legislators**

While this work provides a qualitative assessment of four changes in existing policies, the quantification of GHG impacts of these policy proposals over time could enable more detailed insights and tuned definition of targets. Additionally, especially when assessing policy proposals for the coming decade, it may be helpful to regulate the adoption of plug-in hybrid vehicles. These vehicles, in addition to EVs, are expected to play an important role in the transition from combustion to fully electric vehicles.

Despite the focus on German and EU regulation, this analysis has implications for decision makers outside these jurisdictions. Given the technical lens used for the identification of emission-related EV parameters and the universal nature of these findings, they can be the foundation of policy assessments in different regions. In particular, our policy proposals are designed deliberately in a qualitative fashion and at a high level of abstraction to allow policy-makers and researchers from other countries to utilise this work's findings.

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