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Evidence for a global electric vehicle tipping point

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Abstract

Electric vehicles (EVs) can reduce road transport emissions and have recently seen rapid innovation, decline in cost and a rise in popularity. Achieving a transition to EVs hinges upon their accessibility to current users of internal combustion engine vehicles (ICEV). Here we show with historical evidence that globally, an irreversible private passenger EV diffusion tipping point may have been crossed, where sales of ICEVs decline in leading markets, as preferences for and access to EVs rise, in a self-reinforcing manner. We analyse the structure and dynamics between 2016 and 2021 of four leading car markets comprehensively. The pandemic has drastically affected ICEV sales: many models are now planned to be discontinued, while EVs see unaffected rapid growth and achieve cost parity within a few years. We suggest that coordinated policy incorporating EV mandates in the leading car markets could induce an EV transition in the rest of the world.

1. Introduction

Road transport emissions are rising rapidly, due to growing fleets worldwide, despite efficiency increasing in most vehicle markets¹. Private passenger road transport generates 45% of transport emissions and 30% of its growth, and thus requires urgent attention from policy-makers². Since the late 2000s, EVs have been seen as a major component of the solution for decarbonising private passenger road transport. Meanwhile, plug-in hybrid electric vehicles (PHEVs) have been seen as overcoming issues of range anxiety that may have slowed the diffusion of EVs in some cases³⁻⁷. EVs and PHEVs have seen their costs decline drastically following large scale investment, anticipating or benefiting from favourable policy environments, in the major car markets of Europe, North America and China, while discussions are ongoing in India and elsewhere. Notably, the stock market valuation of Tesla recently exceeded the combined value of its major competitors⁸.

In complex systems, a ‘tipping point’ is crossed when a small perturbation transforms the system and leads to an irreversible change in system trajectory⁹⁻¹¹. Technologies often see tipping points in their diffusion processes where their increased dominance self-reinforces, as costs decline due to increasing investment anticipating rising sales, and sales increase due to declining costs and improving consumer accessibility^{10,12-14}. This has occurred before in the 1920s with the onset of oil-based mobility¹⁵⁻¹⁷. It could occur with EVs once ownership costs and the diversity of models available on markets become comparable with incumbent alternatives. In particular, EVs should ultimately become cheaper to produce and more reliable. Widespread adoption requires the availability of a diverse set of vehicles that collectively cover the needs of highly heterogeneous consumers¹⁸⁻²¹. We hypothesize that a full set of conditions is required for the onset of a tipping point.

Costs and technological trajectories are driven by the leading car markets (US, Europe, China, Japan, Korea), where most innovation occurs. However, to mitigate climate change, emissions reductions are required worldwide. The affordability of electric mobility in developing countries is a key question that looms over the feasibility of achieving global emissions targets, agreed in 2015 in Paris at COP21 and re-iterated in 2021 in Glasgow at COP26. This has led to a proposal and agreement called the ‘Glasgow Breakthroughs Agenda’ for the major economies to cooperate on energy innovation to bring down the costs of key technologies and make them available to the rest of the world^{10,22-24}.

In this paper, we ask whether and when a cost parity point and a diffusion tipping point could be activated for EVs. We explore the diversity of both zero and high-carbon car markets and their evolution over recent years, including their diversity and cost trajectories, in four major markets (Europe, the US, China and India). We present a comprehensive analysis of the car market structure between 2016 and 2021 and the data on future car models from car manufacturers between 2022 and 2026. Using the FTT:Transport model²⁵, we simulate the diffusion of different vehicle technologies and examine the likely trajectories for costs and rates of uptake for EVs and ICEVs given historical observations. We then explore the role of different policy instruments, including notably EV mandates, for eliminating the sales of ICEVs. Using scenario analyses, we explore how different scenarios of international coordination in implementing EV support policies can bring forward EV cost parity in other regions or countries.

2. Economic and policy context

The 2020-2022 COVID-19 pandemic has changed car market conditions drastically in comparison to 2019 and earlier. Rapid diffusion of teleworking has led to an increased focus towards homes as workplaces, altering mobility patterns²⁶. Vehicle sales have seen increased volatility, while the oil prices went from negative values in 2020 to new highs in 2022. Meanwhile, the cost of batteries, which is the single most expensive component of making EVs, has gone down by over 85% since 2010²⁷⁻³⁶. This has been driven by rising investments, notably by Tesla in the US, followed by diverse companies in China and most European manufacturers. In contrast, the ownership lifetime cost of operating an ICEV, approximately 50% of which is fuel, has not systematically declined; instead cost changes followed the fluctuations in the price of fuel at the pump³⁷. Relevant innovation for ICEVs has focused on increasing energy efficiency but remains limited¹.

Debate has emerged on how social tipping points could develop or be achieved to accelerate emissions reductions, focusing on self-reinforcing social feedbacks^{9,10,38-40}. Here, two crucial self-reinforcing feedbacks—diffusion (Rogers' law¹²) and learning-by-doing cost reductions (Wright's law¹³) reinforce and strengthen each other. Diffusion is also self-reinforcing even without cost reductions, since the increased prevalence of a new technology implies increased availability to more consumers^{12,18}. Learning-by-doing partly makes the process irreversible⁴¹. This perspective is consistent with socio-technical transitions theory, for which substantial qualitative historical evidence exists¹⁷.

The traditional methods used in the climate sciences to identify tipping points require substantial amounts of time-resolved data to observe critical slowing down, increased volatility and other signatures of tipping processes⁴². This is often not possible with available economic data, and few attempts have been made to meaningfully predict socio-technical tipping points in sector-wide transitions such as a transition to EVs.

Policy contexts and consumer preferences are key drivers conducive of technology transitions^{4,43,44}. Policy developments in the past decade, notably since the adoption of stringent emissions targets in the EU and the UK, and pollution regulation in China, may have strengthened relevant positive feedbacks leading to a near term tipping point.

Zero-emissions vehicles (ZEV) mandates that set a target for the percentage of ZEVs in the car fleet to be sold annually also accelerate the shift to EVs⁴⁵. Ten states in the US have introduced ZEV mandates, with the ZEV credit requirement becoming increasingly stringent⁴⁶.

More recently, many regions/countries have introduced EV mandates alongside increasingly stringent CO₂ standards. In the EU, in addition to the existing fleet-wide average CO₂ standards, from 2020, a super-credit system increases the weighting of zero and low emissions vehicles in the calculation of average emissions⁴⁷. In China, manufacturers have been subject to a specific annual Corporate Average Fuel Consumption (CAFC) target. From 2019, a dual-credit scheme allows car manufacturers to use surplus New Energy Vehicle (NEV) credits from EV production to offset CAFC credit deficits⁴⁸.

As a result of these past transport policies which have induced necessary investments in energy innovation, based on the empirical data, many markets may now find themselves ripe for a rapid EV transition.

3. Empirical evidence and fleet simulations

Figure 1 shows the ongoing rapid rise in EV and PHEV sales concurrent with rapid declines in prices^{28,30,32-34,49-55}. In our combined Rogers¹² and Wright¹³ model of diffusion of innovations (see Methods), diffusion and learning-by-doing reinforce each other and cause one another to be stronger. This effect appears to have materialised during the past decade, where EV and PHEV sales have grown at a consistent global average of 40% per annum, while costs have declined by a consistent average of 17% per annum. The market dominance of China, the US, and Europe is visible. EV and PHEV sales are only beginning to take off in India.

Given the inertia involved in technological change, whether due to strengthening industry supply chains and/or increasing consumer knowledge and confidence in the technology, this rapid rise is unlikely to slow down or reverse in the near term unless policy frameworks regress drastically in all three major markets. The current trend is projected to continue (Extended Data Fig. 1), and the cost of batteries will continue to fall (Extended Data Fig. 2).

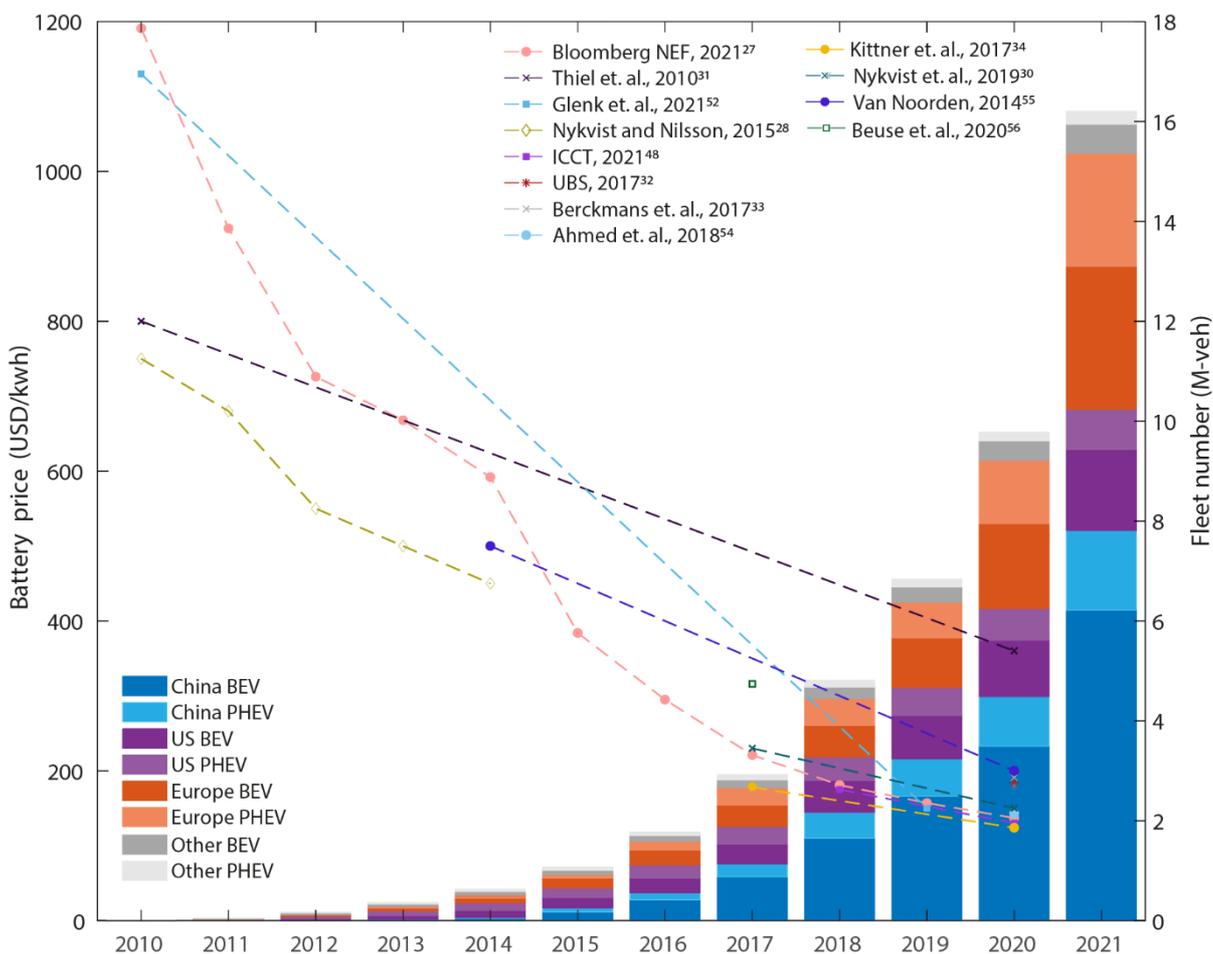


Figure 1 | Diffusion history for electric vehicles. Rapid rise of EVs and PHEVs in the major car markets and worldwide (right axis) and concurrent rapid battery cost reductions (left axis).

Figure 2 shows the most likely direction of evolution of mid-range EV ownership costs and prices, according to the combined Rogers-Wright law, against ICEVs in all four major car markets until the policy horizon of 2050, given observed trends, existing uncertainties and assuming that current policy frameworks are maintained (see Extended Data Fig. 3-4 for other market segments). These projections were simulated using FTT:Transport on the basis of observed cost and diffusion data for the past 12 years (see Methods). Ownership costs include discounted lifetime fuel and maintenance costs with a consumer discount rate of 20%^{56,57}. A median learning rate of 20% for battery cost reductions is used as a central estimate²⁷⁻³⁵, along with $\pm 10\%$ variations to represent a 95% confidence range.

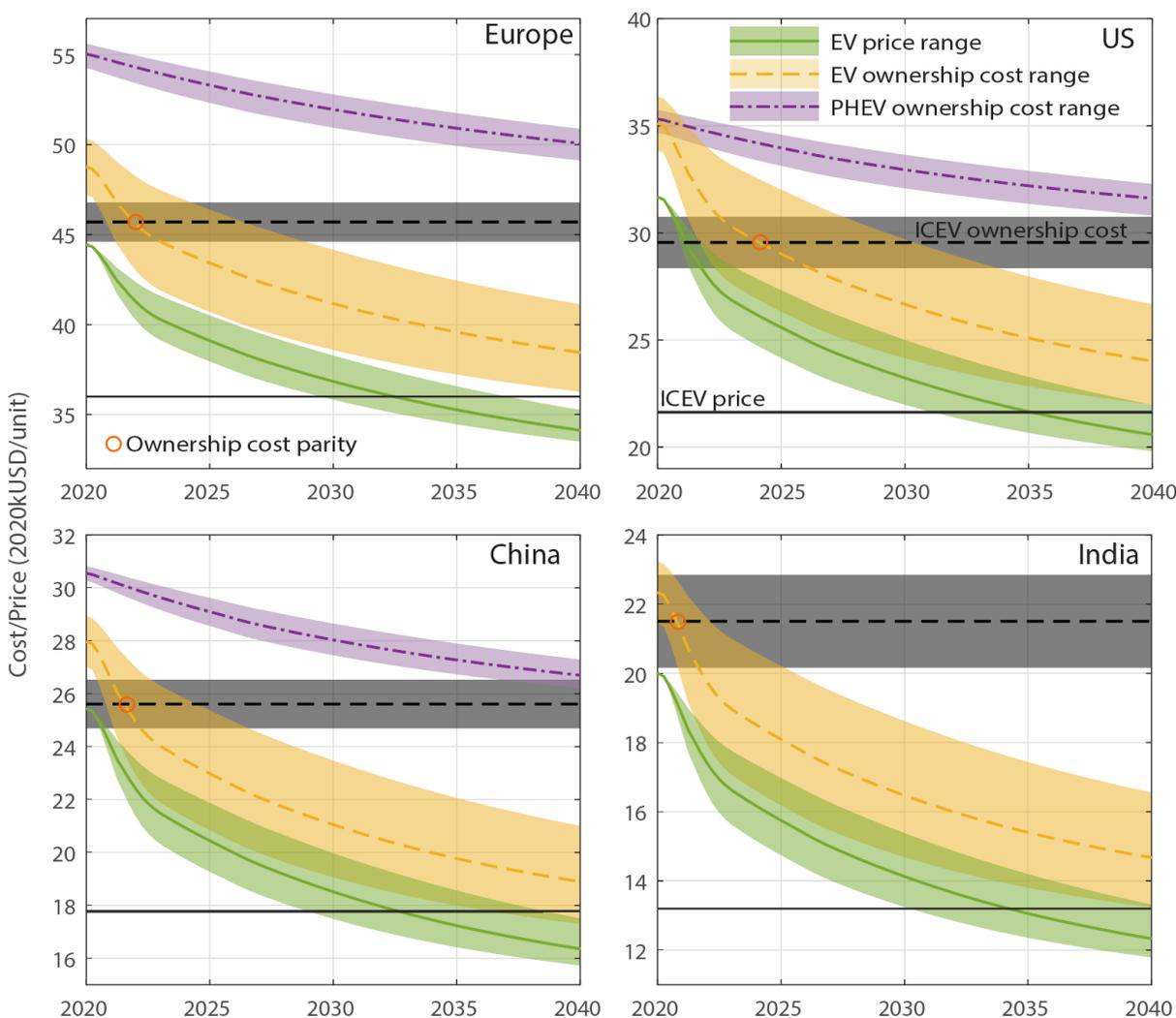


Figure 2 | Projected cost declines for EVs and PHEVs against ICEVs. Trajectory of total ownership costs (dashed lines) and prices (solid lines) of mid-range EVs/PHEVs/ICEVs (median and 95% confidence range learning rates).

For a mid-range car, ownership costs of EVs achieve parity with ICEVs between 2023 and 2025 in China, India and Europe, and by 2030 in the US. However, PHEVs never achieve cost parity with ICEVs, and are absent in India. Note that since approximately 50% of undiscounted lifetime ownership costs for ICEVs stem from fuel use and maintenance costs, while electricity accounts only for around 20%-30% of costs for EVs, ownership cost parity occurs earlier than vehicle price parity in all markets, with the exact timings depending

on electricity costs and consumer discount rates. Uncertainty ranges mainly stem from the fluctuating price of fuel and the rate of battery cost reductions.

Figure 3 shows a comprehensive dataset that covers 2452 models in the four leading vehicle markets, displayed as the frequency distribution of sale prices. Car sale prices are typically lognormally distributed, following the income distribution¹⁹. Here, we observe the evolution of those distributions through historical time, from 2016 to 2021. The trajectory of conventional vehicle sales clearly shows a dip starting in 2019, going into a deep trough for 2020-2021, with little sign of recovery in Europe, China and the US yet visible.

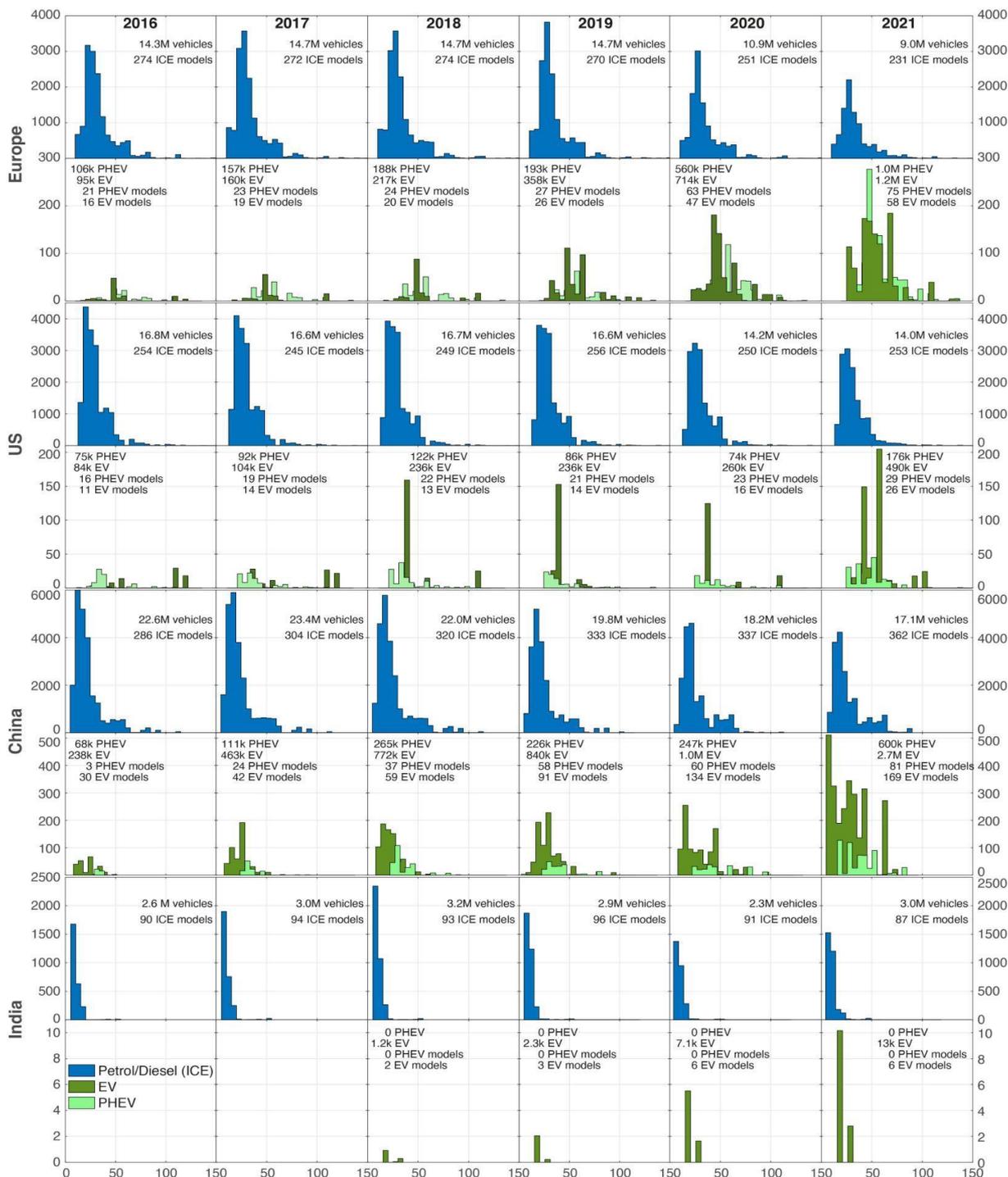


Figure 3 | Evolution of vehicles markets and prices. Price distribution time series for conventional petrol/diesel vehicles, EVs and PHEVs in Europe, the US, China and India.

Concurrently, we observe rapidly rising sales and an increase in variety for EVs and PHEVs. EVs far outpaced PHEVs in their growth, with the latter stagnating in 2019-2021. Crucially, EV sales are entirely unaffected by the COVID-19 pandemic. Note that overall vehicle sales have dipped in total as EV and PHEV sales have not compensated for conventional vehicle sales losses. Intriguingly, the peak and dip in conventional vehicle sales started before the pandemic in some regions, and thus cannot be entirely attributed to the pandemic.

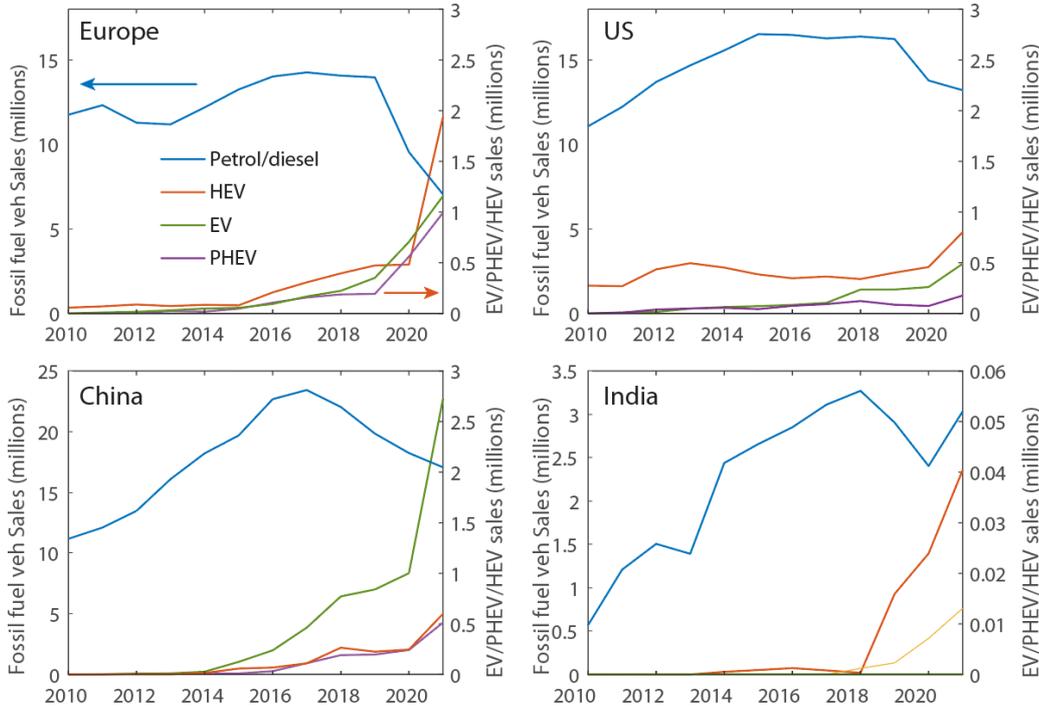
Figure 4 shows total sales as well as the total variety of models in the four markets for various technologies, including announcements made by manufacturers for the near-term future up to 2026. The variety of ICEVs remains constant over the historical period, but saturates, peaks or begins to decline in the projected period according to manufacturer announcements. Concurrently, the variety of low-carbon alternatives rises rapidly starting in 2018 and continues moderately in the near term.

The role of model variety is important in a technological transition, as it must increase over time whereby firms attempt to generate increasing sales revenue by operating in increasing numbers of market segments given consumer heterogeneity (Extended Data Fig. 5). In markets where very few EV/PHEV models are available, as in India and to some degree in the US, only a few consumers can find a low-carbon equivalent of the ICEVs. Consumer heterogeneity depends on income, family size, gender, distance driven, desired features, visual influence and social belonging¹⁸

To convince consumers to switch to EVs in markets where their variety is low, the subsidies that could break even on a cost basis must bridge potentially wide gaps between the prices of some conventional vehicle market segments and those of scarce zero-carbon alternatives. However, where variety is as large for EVs as for ICEVs, break-even subsidies can be relatively low, as they are only required to bridge the average price difference between EVs and their corresponding conventional counterparts, a difference that is becoming small in many regions (Extended Data Fig. 6-8). It is therefore imperative that the variety of EVs continues to increase in all markets to ensure a successful and cost-effective transition. Meanwhile, declining variety in ICEVs is a tell-tale signal that manufacturers are preparing for the transition.

EV subsidies may not be sufficient and do not ensure success in achieving transitions away from ICEVs, according to our simulations (Extended Data Fig. 9). Adopting subsidies to break cost parity with ICEVs does not ensure that bans on fossil fuel vehicles are achieved by their implementation date (notably 2035 in the EU) if manufacturers are not ready to supply the required amounts of EVs in time. Taxes on ICEVs or on fuel may similarly not achieve sufficient progress. These policies gain effectiveness as the deployment of EVs progresses. It is therefore highly likely that further policy action is required.

A. Sales volumes



B. Market variety

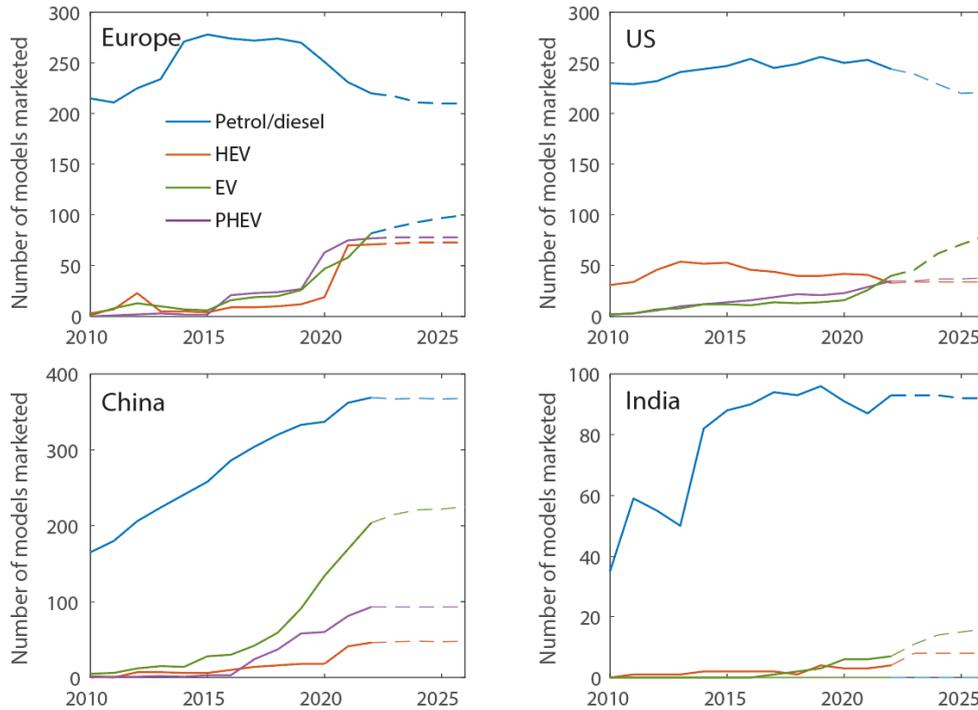


Figure 4 | Car market evolution in Europe, the US, China and India. A. Evolution of sales of petrol/diesel, electric vehicles (EV), plug-in hybrid electric vehicles (PHEV) and hybrid-electric vehicles (HEV). B. Numbers of different models available in markets for these four classes of vehicles.

Figure 5 shows simulated scenarios of fleet compositions in the four markets assuming the adoption of various layers of policies, going towards effective frameworks able to achieve bans (stated or hypothetical) on ICEVs by 2035. Column A shows the current technological trajectory until 2050, in which substantial but insufficient numbers of EVs come to diffuse in all fleets. Taking advantage of the fact that policy instruments can synergise⁵⁸, we sequentially add financial, regulatory and mandate policies in panels B-C-D (see

Methods for detailed policy frameworks; see Extended Data Fig. 9 for the effects of individual policies). Adding fuel and vehicle taxes for ICEVs and subsidies for EVs higher than breakeven values (column B) to existing frameworks incentivises faster evolution. Adding to this fuel economy regulations (column C) help reduce emissions faster in the near term but do not ensure zero emissions by 2050. Adding EV mandates (Column D), which guide manufacturers towards supplying specific numbers of EVs going gradually towards complete ICEV bans, ensures, in tandem with the other policies such as a biofuel mandate, that zero emissions at the tailpipe can be achieved by 2050.

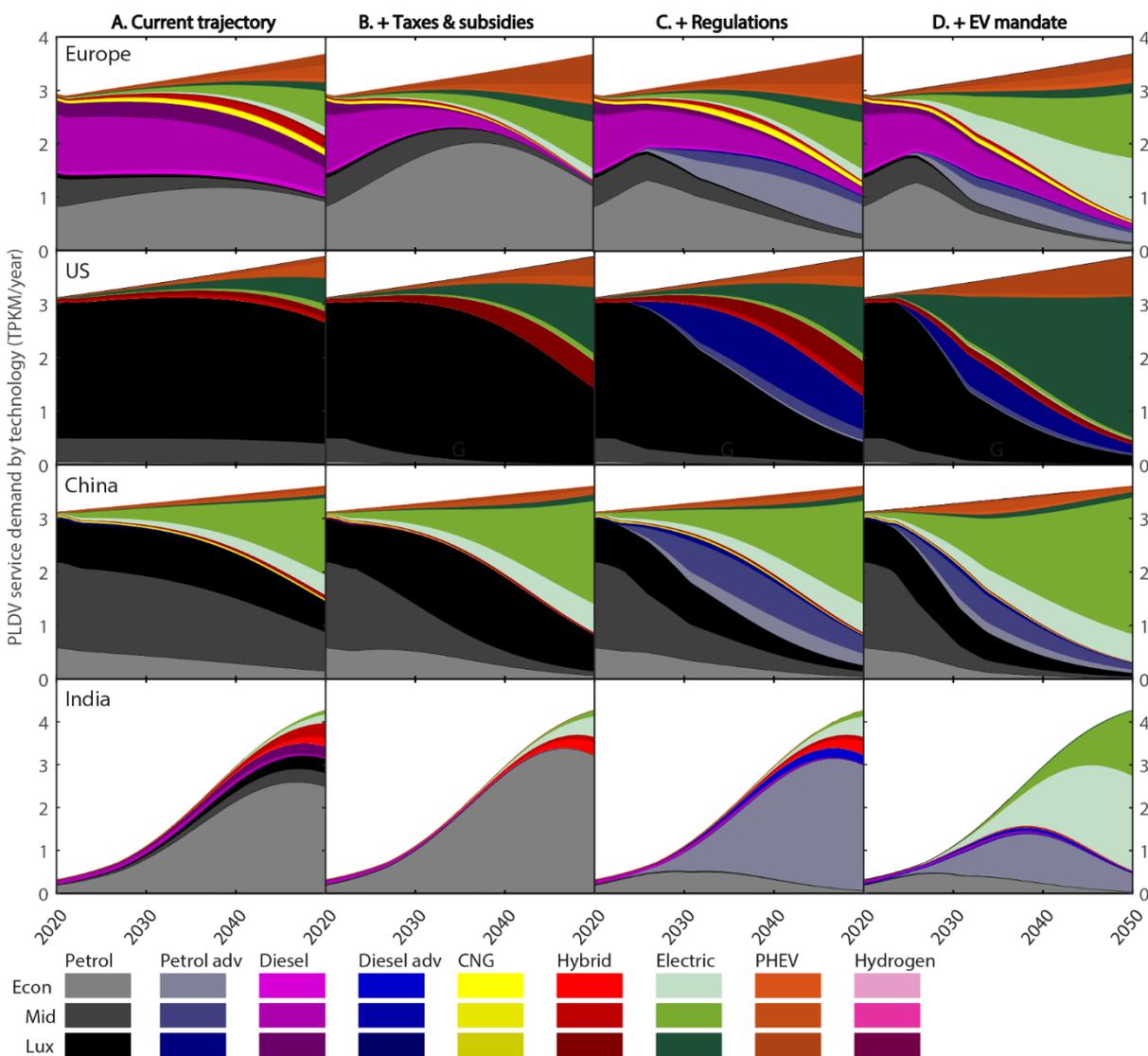


Figure 5 | Simulations of comprehensive EV policy scenarios for all major car markets. Current trajectory (A) indicates where markets are headed without additional policies. (B) The addition of more stringent road and vehicle taxes and EV subsidies have limited impacts. (C) Fuel economy regulations accelerate conventional vehicle emissions reductions but have limited impacts on the diffusion of EVs. (D) Adding EV mandates magnifies substantially the effect of the other policies as it expands their effect across vehicle users.

EV transitions can be accelerated if costs are brought down by accelerating the scale of deployment. Notably, the adoption of EVs in developing countries, where the capacity to act with the public policy may be limited, can be induced by an earlier transition in the leading vehicle markets. In this mechanism, mass deployment in leading markets brings costs down below cost parity in outside markets, eventually inducing sales in countries without policy action.

Figure 6 shows the cost differences between EVs and ICEVs in different scenarios of international cooperation by the leading markets (sensitivities shown in Extended Data Fig. 6-8). Assuming that no regions implement bans on ICEVs induces the slowest rate of EV cost reductions, reaching parity for mid-range cars in around 2030 in Europe, UK and US, and 2025 in China and India. The adoption of policy frameworks that achieve ICEV bans by 2035 brings forward the year at which cost parity is achieved in all countries. Parity can be achieved as soon as 2025-2026 for Europe and the US, and around 2023 for China and India. This timing difference could be crucial for achieving climate targets. This has, however, diminishing returns, where early policy success in additional countries contributes less to accelerating cost reductions, once the three key leading markets and associated regulatory agencies in China, the US and Europe have aligned effective low-carbon policies. This suggests that policy action in these three markets could be determinant in inducing endogenous transitions outside of these markets for the rest of the world.

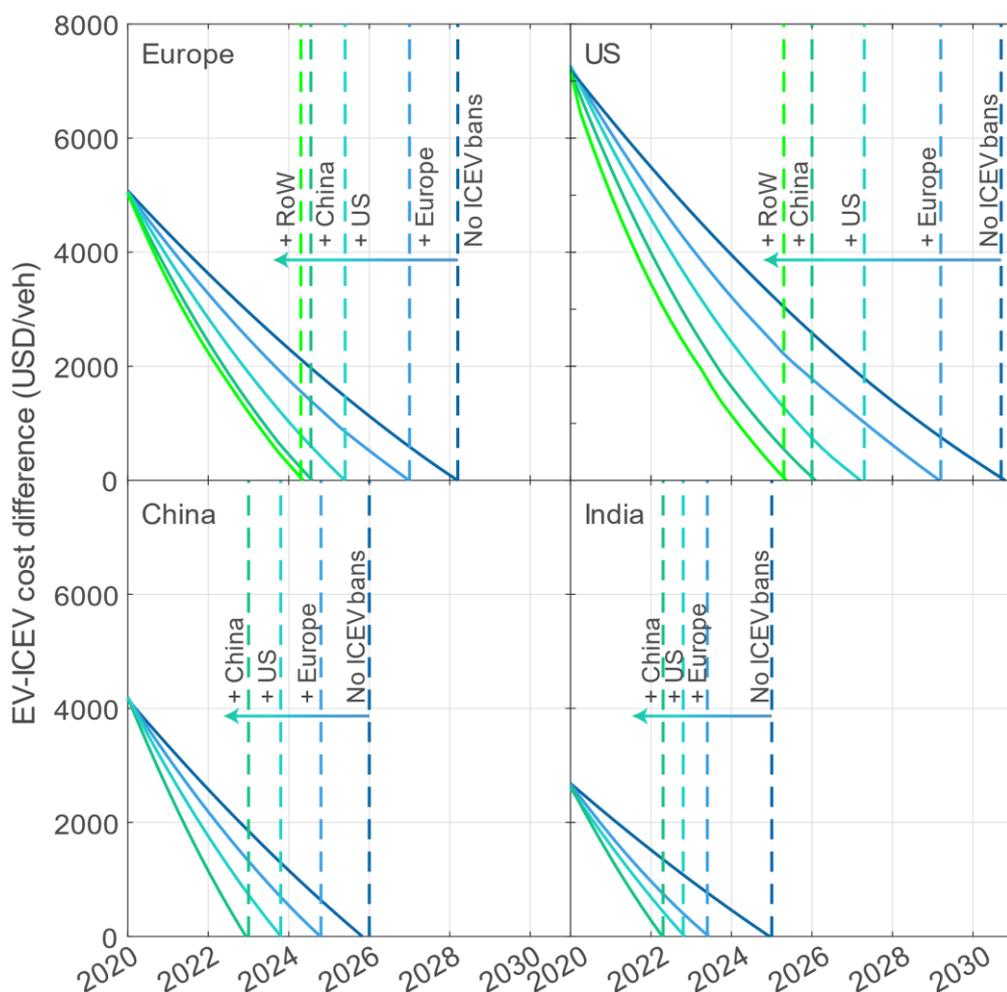


Figure 6 | International cooperation brings forward cost parity. Analysis of cost parity between ICEVs and EVs for different scenarios of international cooperation to bring EV costs down. The more countries join

in, the sooner the cost difference between EVs and ICEVs reaches zero. The impact of adding Rest of the World (RoW) is only visible for Europe and the US, where cost parity is reached later. The impact of adding India is not shown as induced differences are small, the market remaining small relative to others shown.

4. Discussion

Our data suggest that a tipping point towards EVs and away from ICEVs in leading vehicle markets could arise within the next decade. EV sales are rising exponentially while those of ICEVs are declining as manufacturers worldwide begin to discontinue many ICEV models while marketing increasing numbers of EV models. Rising variety in EVs concurrent with declining variety in ICEVs is a key indicator of tipping behaviour. This suggests the rising commitment of manufacturers towards electric mobility.

Importantly, the onset of reorganisation and retooling of production lines is costly and involves profit expectations over at least a decade, and therefore can be seen as irreversible within the climate policy timescale. Meanwhile, the EV market and the associated charging infrastructure will grow and coevolve⁵⁹. There may be no way back towards ICEVs once the tipping point is activated. The pace of the transition to be expected is highly uncertain, however, since the magnitude of social feedbacks remains largely unknown.

A successful transition to EVs in leading vehicle markets is highly likely to eventually spill out into developing countries. Developing country markets could enable further scale expansion and drive costs down even further back in the leading markets. This could happen once cost parity between EVs and ICEVs is achieved in leading markets, after which the costs of mobility begin to decline below ICEVs worldwide. This mechanism can be critical to achieving a zero-carbon mobility transition in countries where agency on vehicle sales and manufacturers is limited.

A transition to EVs is also likely to lead to a drastic transformation of economies at the macroeconomic level. It may substantially reduce the reliance of most countries on foreign oil supplies, and thereby reduce trade imbalances. For example, in India, a transition to EVs could save USD200bn/y on oil imports by around 2030 and USD300bn/y by 2040⁶⁰, thereby reinforcing the national financial system, currency and international purchasing power. We stress that reductions in oil imports that necessarily come with EVs more than compensate for the trade balance effects of importing EVs. A double dividend arises where they are made domestically.

Given that an irreversible EV tipping point appears to be close in leading markets, policymakers in all countries may be better off rapidly getting on board. This could accelerate the transition to the pace needed to decarbonise in time to achieve transport emissions reductions consistent with the Paris Agreement, while drastically reducing exposure to oil market volatility and dependence on foreign supplies⁶⁰. International cooperation and coordination on investment and policy in the leading car markets could substantially bring down mobility costs, benefiting all, as costly and complex oil extraction is abandoned and replaced by inexpensive renewables to power increasingly simple and flexible electric mobility devices. To achieve this, policymakers must facilitate the development of increasing varieties and sales volumes of EVs to accelerate

cost reductions. This includes developing conducive trade policy, investing in infrastructure, building domestic comparative advantage in EV-related value chains, adopting bans on ICEVs with strict guiding EV mandates, and helping create markets in developing countries for low-cost EV technologies.

5. Appendix: Methods

Vehicle population and price distribution time series An extensive original database detailing the technological profile of vehicles and their populations was developed starting in 2012, and yearly since 2015, until 2021¹⁹. The data for vehicle sales by model and technology (i.e. ICEVs, EVs, PHEVs etc.) were obtained from MarkLines⁶¹, which provides sales data by brand-model since 2004 for more than 60 countries. To verify that MarkLines comprehensively covers all models available and sold in each country in a way that is consistent with official national statistics, we checked total MarkLines vehicle sales across models against the annual sales data from official sources (e.g. China Statistical Yearbook⁶², Eurostat⁶³, US Bureau for Transportation Statistics⁶⁴).

Since vehicle prices can vary significantly between countries for identical brand-models, we visited each manufacturer's website for each brand-model in China, the US, Germany, France, the UK and India, and collected the suggested retail prices (MSRP), engine sizes (for ICEVs, HEVs and PHEVs) or battery sizes (EVs and PHEVs), energy consumption, weight and driving ranges (EVs only). Given that price variations across EU countries are generally within a range of 20%, we use prices in Germany as a proxy where data is not otherwise available. In cases where a brand-model is sold in some EU countries but is not available in Germany, we use price and specifications data from the manufacturers' websites in France or the UK. We further verified the brand-model coverage of MarkLines by cross-comparison with the manufacturer website data thus obtained. To create a comprehensive database to study the diffusion of different vehicle technologies, this exercise was carried out for all four regions each year from 2016 to 2021.

This database is also used to examine the diversity of vehicle brand names in each regional market. We determined the weighted mean and standard deviation of prices and the fuel economy for each vehicle technology and market segment (economic, mid-range and luxury, see Suppl. Note 1), which are used to calibrate FTT:Transport. The number of brand-models sold each year between 2010 and 2021 is used as a time series for vehicle variety in different car markets over time. This time series was extrapolated until 2026 by adding or removing brand-names on the basis of reports published by MarkLines for each Original Equipment Manufacturer (OEM). This documents current vehicle models and their successors, future plans of the OEMs to continue/discontinue existing brand-models and plans to launch new brand-models.

EV/PHEV price projections We construct a relationship between battery prices and EV/PHEV prices according to manufacturing costs. Electric vehicle manufacturing costs are estimated based on MSRP and the cost-to-price markup factor. Vehicle prices are distinguished from vehicle manufacturing costs due to automaker profits and dealer markups⁶⁵. The markup factors vary across vehicle segments, where markup factors for small vehicles are lower than larger ones. Subject to uncertainty, the current markup factors for EVs are lower than for ICEVs, around 10% for compact cars, and 20% for sport utility vehicles^{65,66}. However, markups are subject to uncertainty since they may constitute both strategic and economic choices for vehicle manufacturers²⁷. Some manufacturers may also be cross subsidizing their EVs using profit margins from ICEVs to gain market share^{27,30}. We assume that to stay competitive, vehicle manufacturers do not increase EV

markups until EVs achieve price parity with ICEVs. Uncertainty over this is discussed in Suppl. Note 2 and Suppl. Tables 4-11.

Manufacturing costs for EVs depend on four key factors: battery price, platform choice, driving range and the vehicle's energy use efficiency (where more efficient use of electricity allows for smaller and cheaper batteries for a given driving range)²⁷. Among these key factors, the fall in the cost of batteries typically accounts for 75% of current falls in EV manufacturing costs. Battery costs are estimated dynamically with a learning curve based on Wright's law (see below), and changes in the cost of batteries are included in vehicle manufacturing costs to determine prices on the basis of markups.

Historically, affordable EVs have had short ranges, while long-range EVs have generally been more expensive due to larger battery sizes. Over time, as the costs of batteries fall, it has been a common trend for many car manufacturers to increase the battery size rather than cut EV prices, which thus increased the availability and variety of long-range EV. In our analysis, EVs were segmented on the basis of battery sizes, since the latter is proportional to power and range and can thus follow our ICEV engine size classification (see Suppl. Note 1 and Suppl. Figure 2 for vehicle segmentation). We consider that driving range increases as consumers switch market segments in our model.

In the current trajectory scenario, we assume that vehicles are developed and manufactured using platforms modified from existing ICEVs. In the next ten years, it is possible that many EVs will be designed and produced based on new specially designed platforms^{27,61}. Over time, production costs and indirect costs, including research and development as well as amortised costs for investment in expanding EV production capacity are all likely to decline. There are fundamental uncertainties regarding platform choices in the long run. In our analysis, these uncertainties are treated as part of the price sensitivity analysis (see Suppl. Tables 4-11).

Total costs of ownership The total cost of ownership (TCO) is the present value of all relevant costs in owning and using a car^{67,68}. Here we express this as:

$$TCO_i = Pr_i + (VT_i - S_i) + \sum_{n=1}^N \frac{(FC_i + MC_i) \times TD + RT_i}{(1+r)^n} \quad (1)$$

Vehicles prices (Pr_i) for vehicle category i are those discussed above, while $(VT_i - S_i)$ is the net tax/subsidy applied to that vehicle category, and RT_i is a yearly road tax.

Fuel Costs (FC_i) Depend on the vehicle's energy consumption per kilometre, obtained from official manufacturers' websites in 2020, where fuel/electricity prices are obtained from various data sources listed in the Suppl. Table 1. In the reference scenario, we assume that future gasoline prices follow the IEA baseline scenario⁶⁹. The retail gasoline price is subject to uncertainty. We analyzed the effects of low and high oil prices on EV adoption and cost parity for ICEVs (see Figure 2 and assumptions in Suppl. Dataset). Electricity cost for EV depends on the price of electricity at different charging sites. In the reference scenario, there are

three charging scenarios, representing 100%, 75%, 50% of charging at home at a lower cost, and 0%, 25%, 50% via public charging at a higher cost.

Maintenance costs (MC_i) are uncertain and here assumed to be \$0.04, \$0.05, \$0.06 per kilometer for all three ICEV market segments (economic, mid-range, luxury)⁶⁵. Conventional EVs have fewer moving parts than ICEs, and hence maintenance and repair costs are typically lower compared to ICEVs. We assumed that EVs cost 50% ($\pm 20\%$) less to maintain^{32,65}. PHEV per kilometre maintenance cost is assumed to be the equal to the cost of ICEV for each vehicle segment⁶⁵.

The baseline analysis assumes that each vehicle's yearly distance driven (TD) is 15,000 km and that consumers use a 20% discount rate (r), on average. In the sensitivity analysis, we examine how the TCO varies with different discount rates and annual mileage (see Supplementary Note 2 and Suppl. Tables 4-11). Note that the lifetimes of vehicle ownership can vary from 3 years⁷⁰ to up to 15 years⁷¹ typically following a smooth survival function with life expectancy of around 11 years. Due to the uncertainty in the EV resale value, a 12-year ownership period, is considered in this research⁷². Given a high baseline discount rate and car depreciation⁷³, we consider the resale value of a car after 12 years negligible.

EV and battery pricing Battery price is considered the main barrier to widespread EV adoption. Falling prices for lithium-ion batteries are the biggest driver supporting rapid EV penetration²⁷. Existing studies have modelled battery production cost reduction using conventional learning curves^{28,74–77}. Also known as Wright's Law¹³, the concept of the learning curve is based on the empirically observed phenomenon that the unit cost of a technology declines by a constant percentage for each doubling of cumulative production volume (e.g. cumulative installed capacity), as described by the following equation:

$$C_t(P) = C_0 \left(\frac{P}{P_0} \right)^{-b_i} \quad (2)$$

Where P is the total global cumulative production of the technology (i.e. the total kWh capacity of cells produced), C is the cost per unit (USD/kWh), C_0 and P_0 are the initial cost and cumulative production at the start date of scenarios, while b is the learning exponent. The latter is related to the cost reduction that results from every doubling of production, what is known as the learning rate (LR) (within a range of 10%-30%), through

$$LR = 1 - 2^{-b} \quad (3)$$

Importantly, this model assumes that knowledge diffuses globally (vehicle manufacturers operate globally and/or source batteries from a common set of competitive technology suppliers), and therefore that production in all countries contributes to declining costs in all countries. As a result, costs in all countries are influenced by sales in other countries. This is supported by the empirical evidence in a wide range of cases¹³.

Several studies have developed multi-factor learning functions that consider factors such as economies of scale, learning by searching and material costs^{78,79}. However, in practice, multi-factor and two-staged

experience curves are difficult to construct due to data limitations. For example, EV battery learning through research or spillover effects from other industries are difficult to reliably quantify⁸⁰. Hence, in this article, we adopt the single factor learning curve, which is the most widely used approach for battery cost forecasts^{33,55,76,77,81}.

In the current trajectory scenario, we derived the projected nickel and cobalt prices from existing studies^{82,83}, and the impact of material price changes on the battery pack price is based on an analysis by Bloomberg NEF²⁷ (see Suppl. Dataset for details). We consider the surging rare metal prices a result of recent supply disruptions and increased global demand for batteries⁸⁴. The battery prices may pick up as a result of the rare metals price surge in the next few years⁸⁴. We analysed the effect of rare metal price shock on the cost parity in Suppl. Note 8. As demand for battery materials increases, more investment flows into expanding the global capacity for mineral extraction²⁷. Overall, the impact of material prices on the price of a battery pack and the TCO is moderately low relative to other factors^{27,85} (see Suppl. Tables 4-11). Furthermore, as battery energy densities improve over time, reliance on critical materials decreases. The impact of improvement in battery energy density and higher critical material costs is examined in the sensitivity analysis (Supplementary Note 8 and Suppl. Tables 4-11).

Estimated current EV lithium battery costs vary widely and are subject to great uncertainties²⁷⁻³⁵. Figure 1 and Extended Figure 2 illustrates the historical and projected battery pack costs reported by different automakers and studies³². For our current trajectory scenario, an average battery cost of \$150/kWh in 2020 at the pack level is assumed.

Analyses of lithium-ion cells have estimated a wide range of learning rates, spanning 6% to 30%²⁷⁻³⁵. In the reference scenario, we use a 20% learning rate, which matches the median estimates of the observed battery learning rates between 1991 and 2020. A sensitivity analysis was carried out using the reported ranges found in underlying data (see Suppl. Tables 4-11).

Overview of the vehicle fleet projection modelling framework. The Future Technology Transformations for transport (FTT:Transport) model is a submodule of the integrated assessment model named E3ME-FTT-GENIE, a simulation framework that covers the economy, technology and the climate. The FTT family of models consists of FTT:Power⁸⁶, FTT:Transport²⁵, FTT:Heat⁸⁷, and FTT:Steel⁸⁸ and is a bottom-up representation of the technological change that reproduces past and projects future diffusion patterns for individual technologies calibrated on observed trends. The FTT framework models technological diffusion using a set of coupled finite differences equations of the Lotka--Volterra family, which represent gradual technological substitution processes⁸⁶. Under the FTT framework, consumers are proportionally more likely to choose a technology that has a higher market share as a result of its availability, visibility, social influence and network effects, all of which we represent combined simply as adoptions proportional to the current market shares. Such bandwagon effects are well known and substantially influence the profiles of diffusion of vehicle models^{3,18}. Including this network effect in an otherwise standard discrete choice model is

mathematically the same as the replicator dynamics equation of evolutionary systems, and generates the widely observed S-shaped technology diffusion profile (Rogers' law)^{12,89} (See Suppl. Note 3).

In the FTT-Transport model, we assume revealed preferences, where the observed cost distribution for recent vehicle sales corresponds to the heterogeneity of consumer preferences and choices^{19,25}. Following evolving choices and preferences, a flow of market shares generally arises from any arbitrary technology (i) category towards every other category (j), denoted as follows:

$$\Delta S_{i \rightarrow j} \propto \frac{S_i S_j}{\tau} F_{ij} (\Delta C_{ij}) \Delta t \quad (4)$$

A reverse flow also exists from technology to technology as shown here:

$$\Delta S_{j \rightarrow i} \propto \frac{S_j S_i}{\tau} F_{ji} (\Delta C_{ji}) \Delta t \quad (5)$$

$\Delta S_{i \rightarrow j}$ denotes the flow of shares from vehicle category i to category j , τ is the turnover rate for vehicles (the frequency at which new vehicle buying choices are made). F_{ij} represents the fraction of agents that prefer technology i over j based on the difference in mean generalised (perceived) cost of the two vehicle options relative to agent diversity ΔC_{ij} (see Suppl. Note 4). The latter is derived from observed cost distribution. The net flow of shares between vehicle categories generates the composition of sales in the next time period. These are used to determine the composition of vehicle fleets over time.

Total vehicle ownership projections. To project battery costs, a scenario for EV and PHEV sales is required, which itself requires projections of total vehicle ownership across markets. Vehicle ownership models are used to forecast transport demand, energy consumption, and emission levels. Among the different model types, one of the most well-known approaches is an econometric estimation of an income-car stock model based on a logistic function⁹⁰. The Gompertz curve is an S-shaped growth curve that relates per capita vehicle ownership to GDP per capita. While vehicle scrappage is not explicitly included, it has been tested empirically to represent the growth trend of vehicle stock⁹⁰. We examine trends in the growth of vehicle fleet numbers for a large sample of countries and employ the Gompertz function to estimate the relationship between the number of vehicles and per capita income (see Suppl. Note 5). The fleet numbers for individual technologies are calculated based on the projected shares of the technologies and the total fleet number.

Policy scenario analysis *Current trajectory* The baseline scenario is used as a benchmark against which to assess policy scenarios with added policy action. Existing policies are assumed to remain in place implicitly through our reliance on economic, energy, price and technology diffusion (behavioural) data.

Current Trajectory with taxes and subsidies Vehicle registration, purchase taxes and EV subsidies are added to the policies implicitly assumed in the current trajectory. The costs of taxes and subsidies (negative cost) are added to Equation 1. Here, we assume that all taxes on ICEVs are becoming increasingly stringent: 50% higher than the current levels in each country. The level of EV subsidy/tax credit will be 50% higher than the current level, but this will be reduced gradually after 2030, and phased out after 2035. We assumed that the EV subsidy scheme will not be revived after it has been removed (e.g., in China).

Current Trajectory with taxes and subsidies and regulations. Besides financial incentives, fuel economy standards require automakers to design more efficient vehicles or to shift sales towards more efficient models. Following the proposals by the EU and US, we assumed that ICEVs with below-average fleet-wide CO₂ emissions in 2020 will be phased out in 2025 in all regions for consistency, replaced by more advanced models that are on average 20% more efficient than that of the current ICEVs (see the Suppl. Dataset for the assumptions).

Fuel economy regulations are modelled by influencing the flow of market shares in each technology category. We assume that there are no new market shares gained in the categories being phased out.

Current Trajectory with taxes and subsidies, regulations and EV mandates. Since the EV mandates are absent in most states in the US, EU, India, we assumed that these would be introduced and that their stringency would lead gradually towards a complete ban on ICEVs in 2035. We assume that market shares flow from ICEVs to EVs by setting exogenous market share additions at specific points in time to be consistent with the mandate, although EV market shares can exceed the mandate value.

Our approach is not exactly the same as that of the real-world EV mandates, for which the government either sets an EV production quota (e.g. the China New Energy Vehicle (NEV) mandate and the California ZEV mandate program) or assigns extra credits for producing EVs (e.g. super credits for zero- and low- emissions vehicles (ZLEV) in the EU). Our approach mimics most closely the impact of EV mandates in which the government imposes increases in the share of EVs in total sales.

Regions Europe includes EU27, Norway, Iceland, Switzerland and the United Kingdom. The rest of the world includes Japan, Korea, Australia, New Zealand, Canada, Brazil, Chile, Mexico, Argentina, South Africa, Indonesia, Thailand, Malaysia, Cambodia. Other includes countries under 'the rest of the world' and India.

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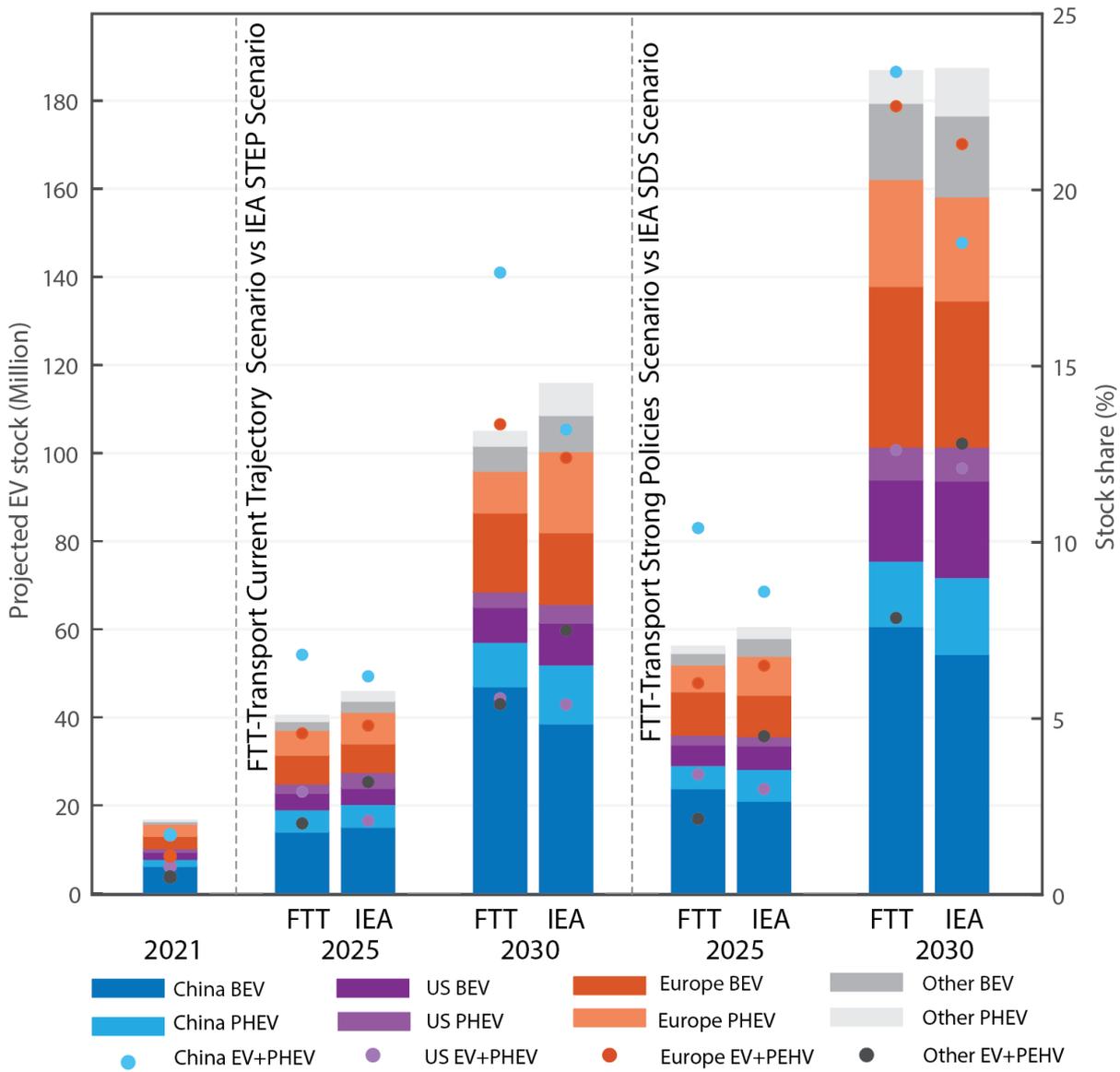
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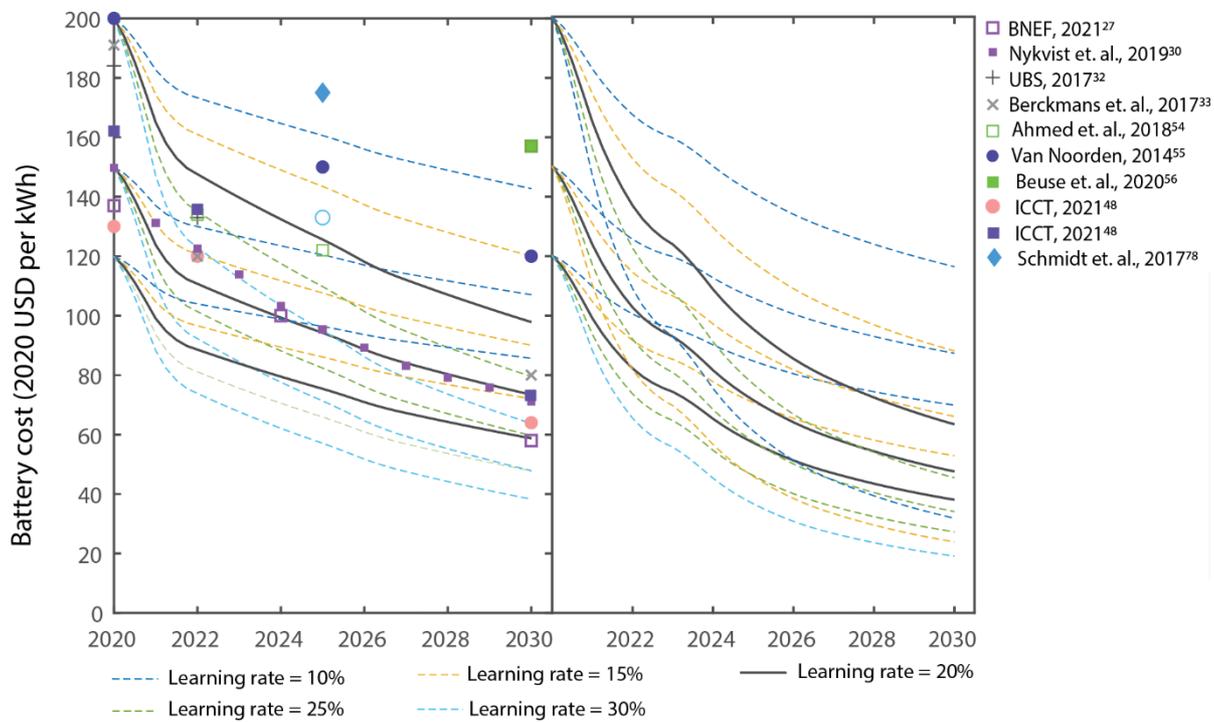
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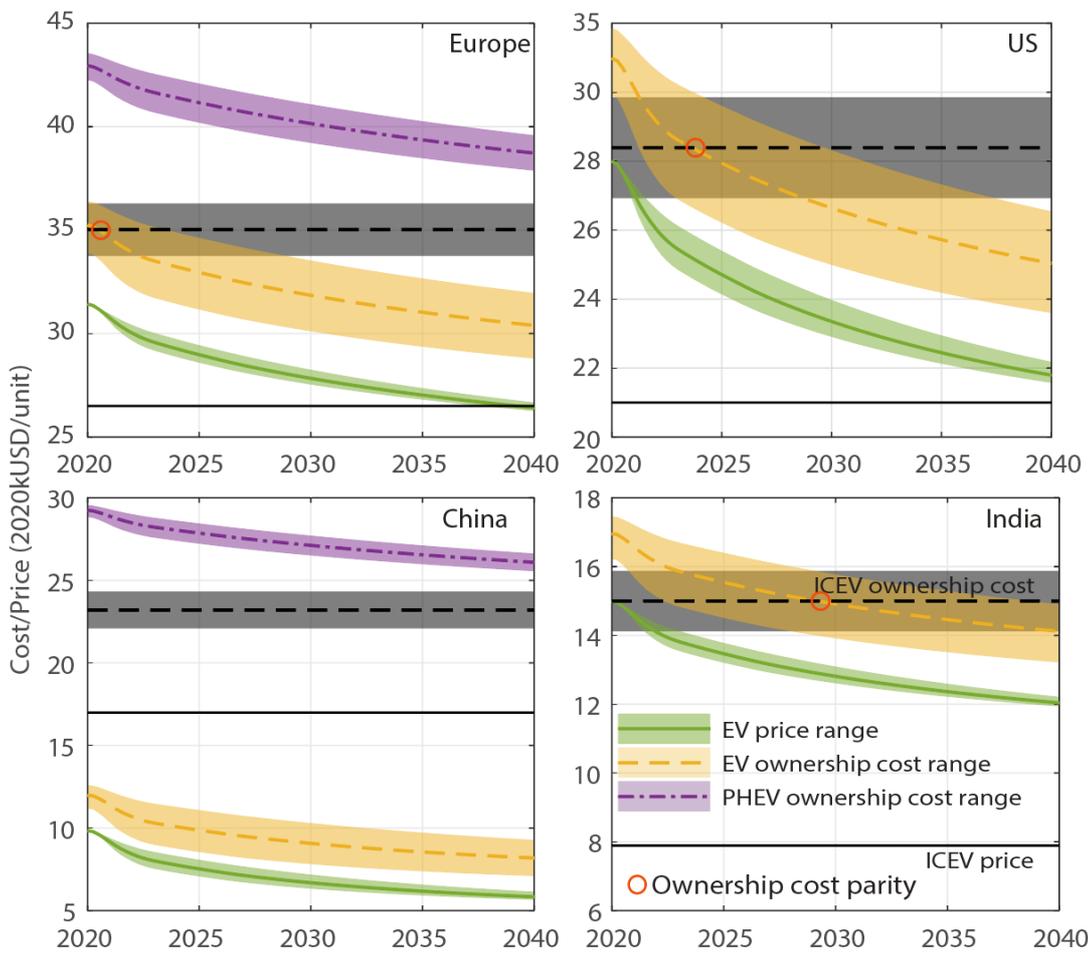
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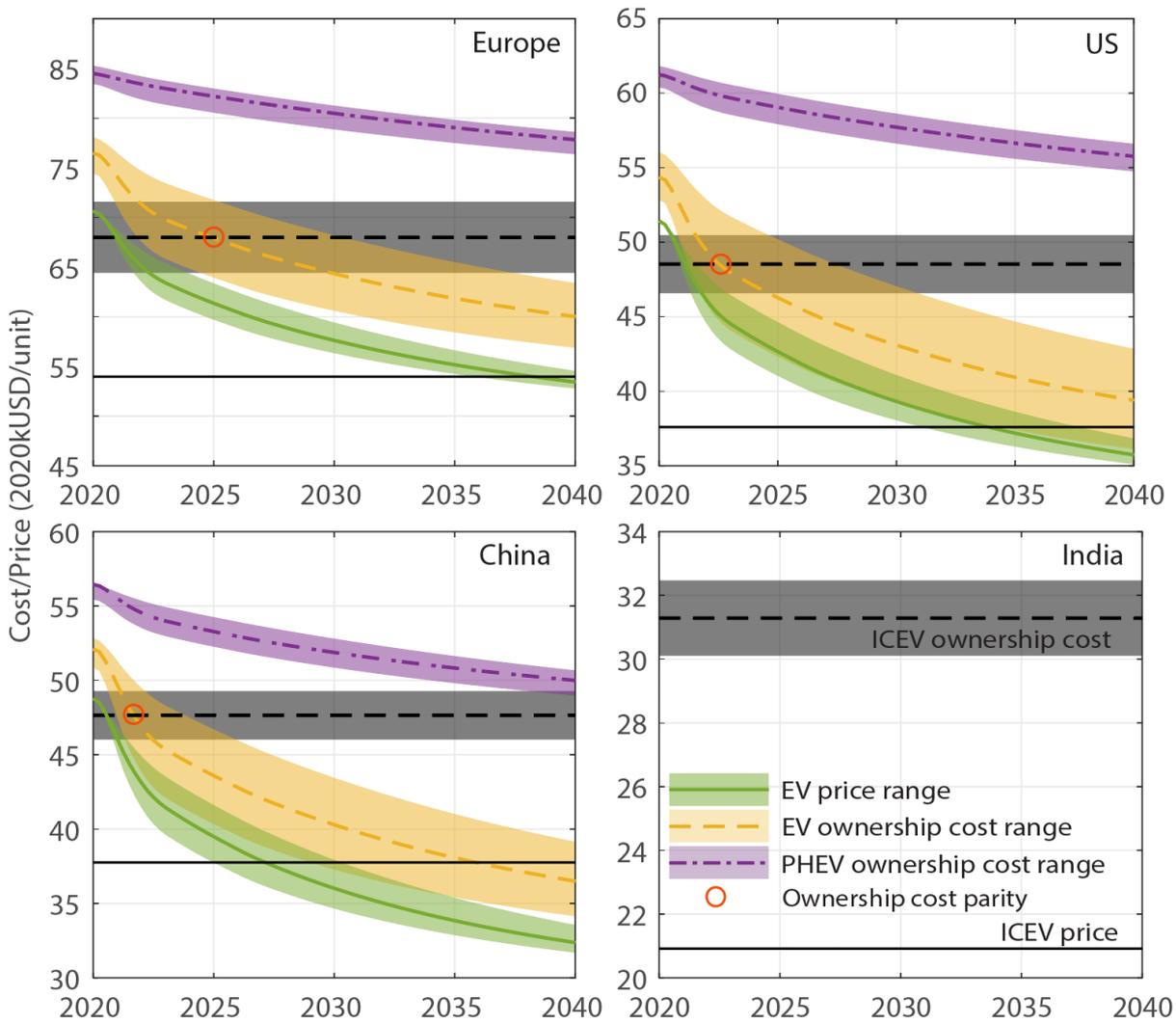
Extended Data Fig. 1 | Projected EV stock and stock share in 2025 and 2030. Comparison between the Current Trajectory Scenario and the Strong Policies Scenario presented in this paper, alongside IEA projections in the Stated Policies Scenario (STEPS) and Sustainable Development Scenario (SDS)⁹¹. The bars are the projected EV stocks and the dots are the projected EV stock shares.



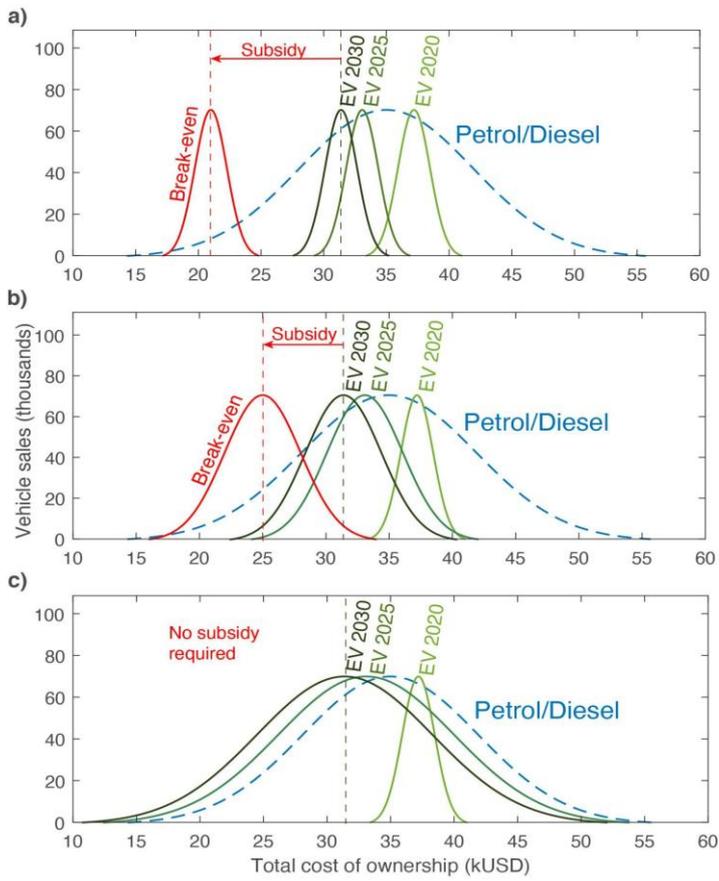
Extended Data Fig. 2 | Projected cost of Li-on battery packs in EVs. Three initial battery costs (in 2020) are taken to reflect the uncertainties in the cost of battery packs reported by existing studies or lead manufacturers. The black curves are the projected battery costs under the assumption of a 20% learning rate. The dash curves reflect the projected battery costs under different learning rate assumptions. Left panel: projected cost of battery packs under the Current Trajectory Scenario, in comparison with the results from the existing studies. Right panel: projected costs of battery packs under the Strong Policies Scenario.



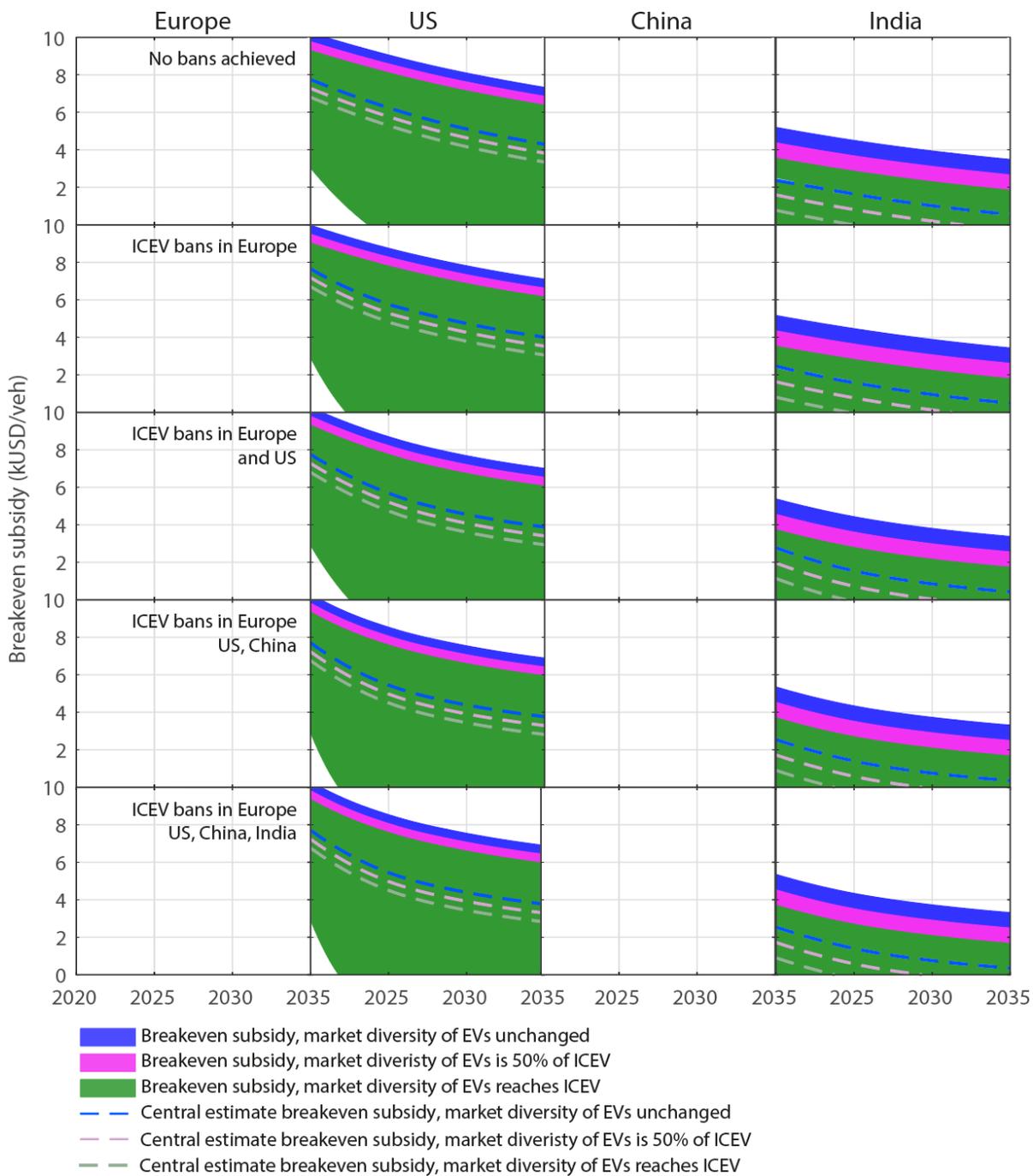
Extended Data Fig. 3 | Projected cost declines for economic EVs and PHEVs against equivalent ICEVs. Trajectory of total ownership costs (dashed lines) and prices (solid lines) of economic EVs/PHEVs/ICEVs (median and 95% confidence range learning rates).



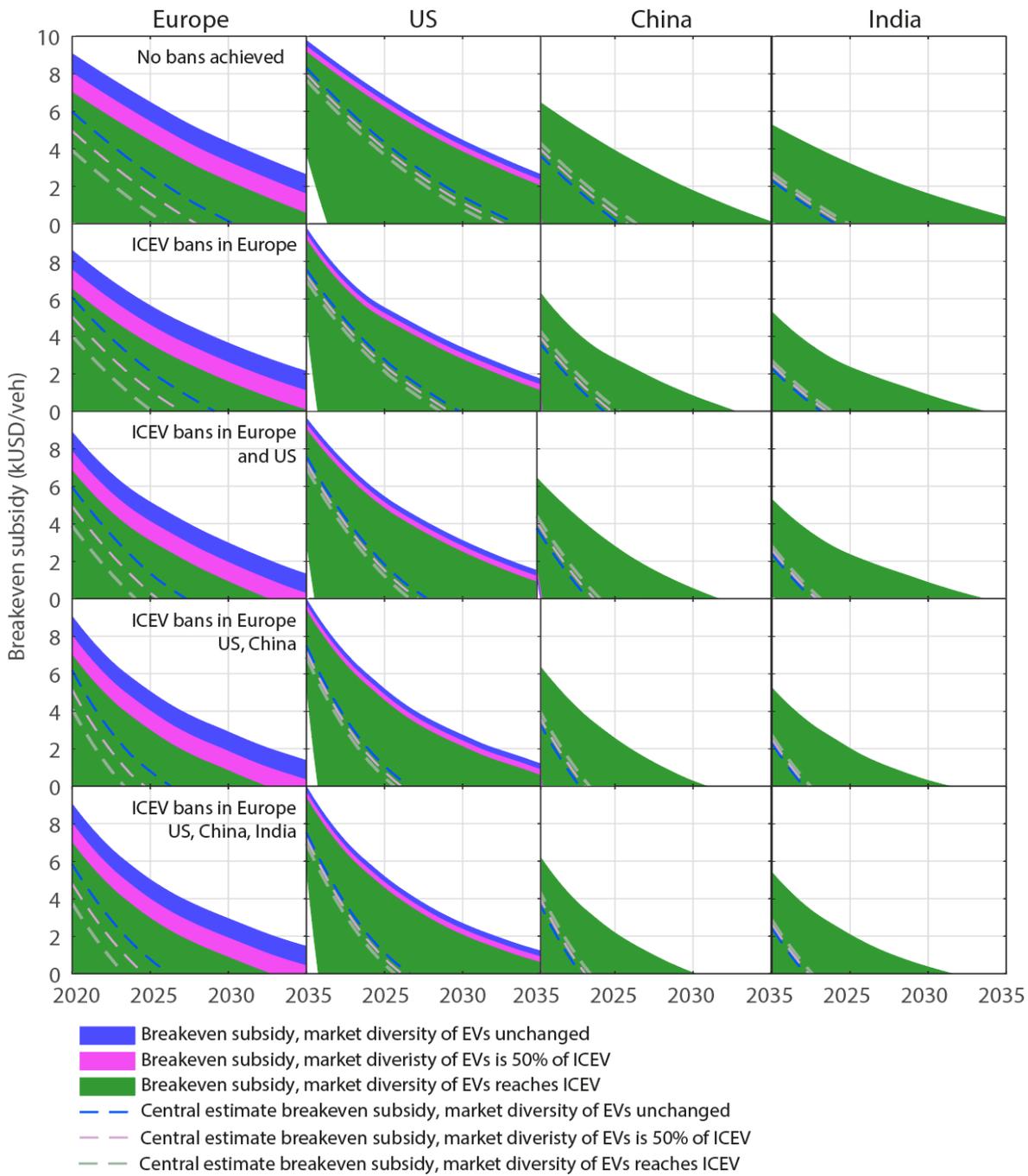
Extended Data Fig. 4 | Projected cost declines for luxury EVs and PHEVs against equivalent ICEVs. Trajectory of total ownership costs (dashed lines) and prices (solid lines) of luxury EVs/PHEVs/ICEVs (median and 95% confidence range learning rates).



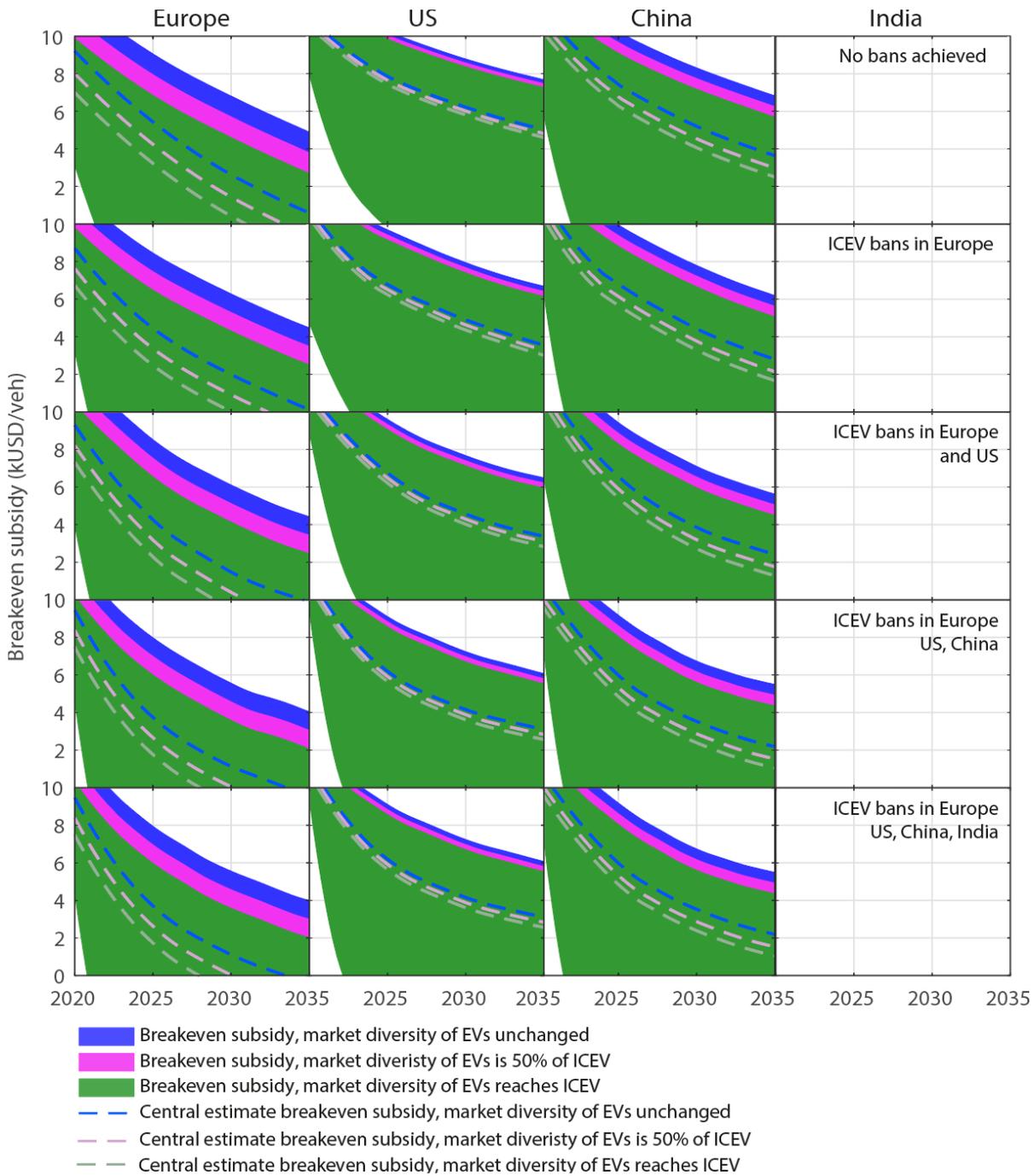
Extended Data Fig. 5 | Relationship between model variety and the breakeven subsidy. The breakeven subsidy declines as costs decline with rising investment, for (a) constant EV variety, (b) doubled EV variety and (c) EV variety matching the current variety of petrol/diesel vehicles.



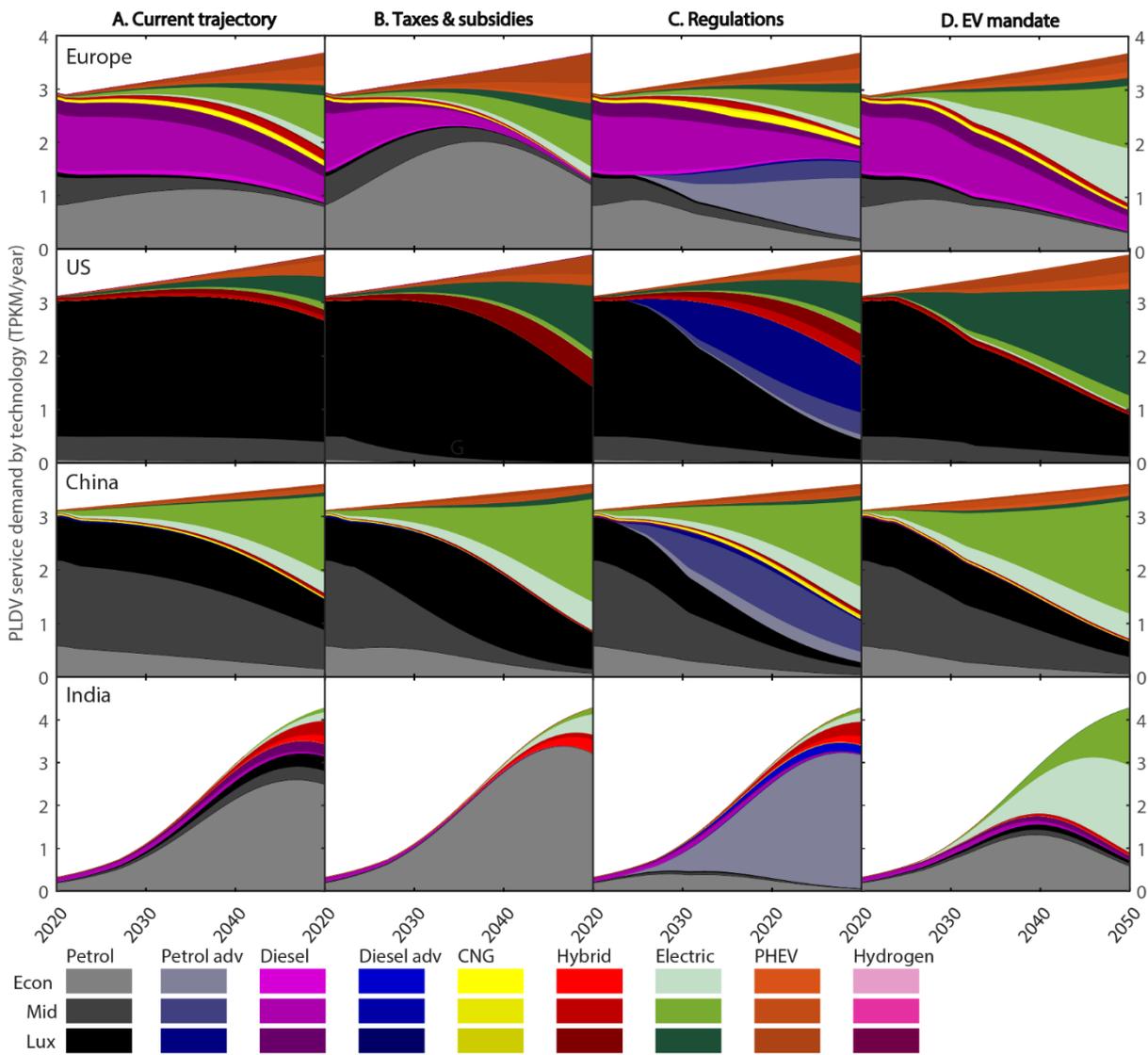
Extended Data Fig. 6| Break-even subsidies to achieve cost parity with sensitivity analysis for economic cars. Break-even subsidy analysis for different scenarios of international cooperation to bring EV costs down. The more countries join, the sooner the break-even subsidy becomes unnecessary. The empty panels indicate that cost parity was reached in the EU and China.



Extended Data Fig. 7 | Break-even subsidies to achieve cost parity with sensitivity analysis for mid-range cars. Break-even subsidy analysis for different scenarios of international cooperation to bring EV costs down. The more countries join, the sooner the break-even subsidy becomes unnecessary.



Extended Data Fig. 8 | Break-even subsidies to achieve cost parity with sensitivity analysis for luxury cars. Break-even subsidy analysis for different scenarios of international cooperation to bring EV costs down. The more countries join, the sooner the break-even subsidy becomes unnecessary. The empty panels indicate that there is no luxury segment EV sold in India currently.



Extended Data Fig. 9 | Simulations of individual EV policies for all major car markets. Current trajectory indicates where markets are headed without additional policies. The policy scenarios indicate where policy incentives are introduced individually.

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