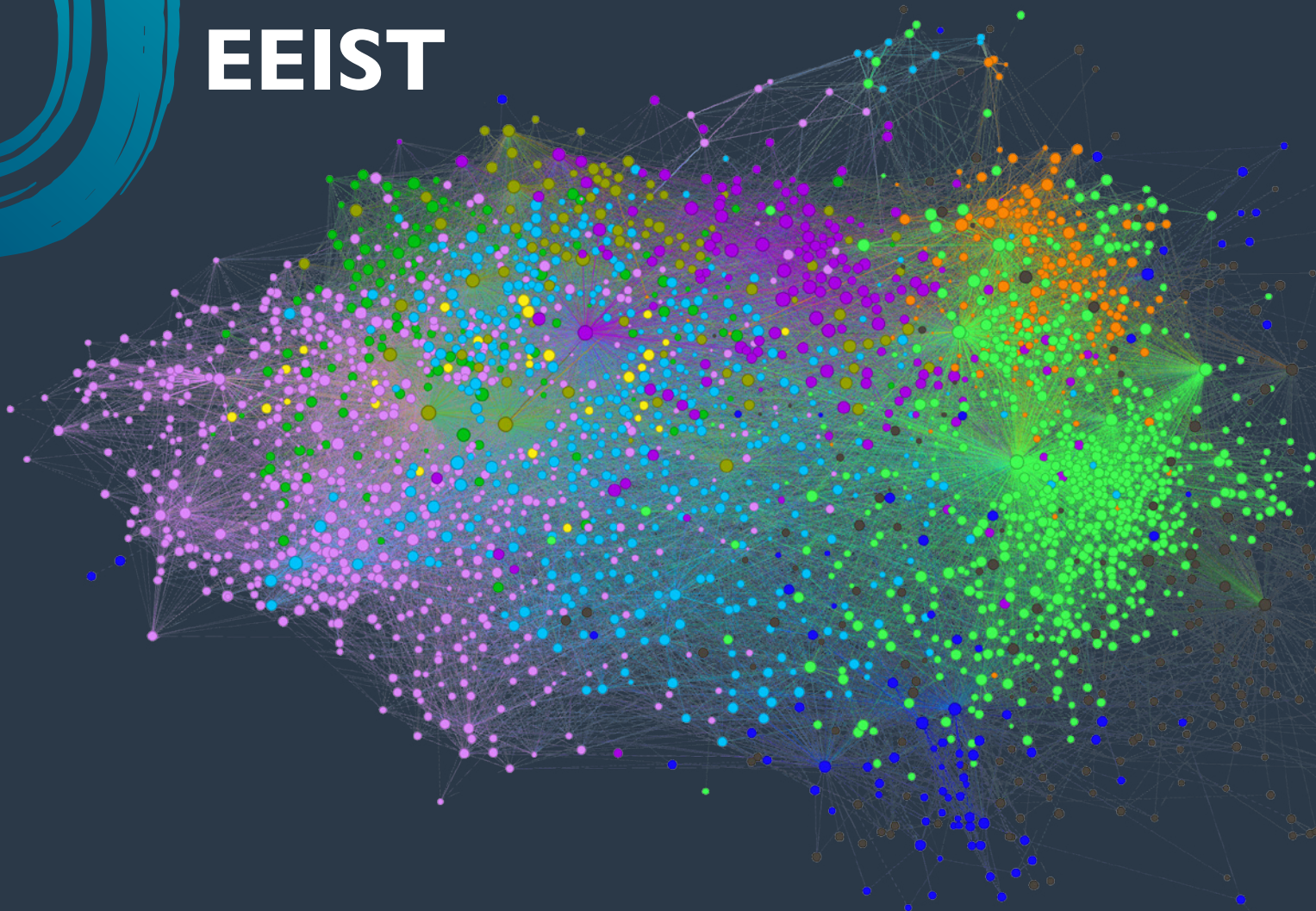




EEIST



TRANSPORT:

**ACTIVATING EV TIPPING
POINTS IN CHINA, INDIA,
EUROPE AND THE US**



This document presents only one of the modelling case studies in the ‘New economic models of energy innovation and transition: Addressing new questions and providing better answers’ report, produced by the EEIST project.

To view other parts of the full report, including case studies on the global energy transition, the power and industrial sectors, transport, impacts of the transition, national decarbonisation plans and finance, go to <https://eeist.co.uk/eeist-reports/new-economic-models-of-energy-innovation-and-transition/>

About

The Economics of Energy Innovation and System Transition (EEIST) project develops cutting-edge energy innovation analysis to support government decision making around low-carbon innovation and technological change.

By engaging with policymakers and stakeholders in Brazil, China, India, the UK and the EU, the project aims to contribute to the economic development of emerging nations and support sustainable development globally.

Led by the University of Exeter, EEIST brings together an international team of world-leading research institutions across Brazil, China, India, the UK and the EU.

The consortium of institutions are **UK**: University of Exeter, University of Oxford, University of Cambridge, University College London, Anglia Ruskin University, Cambridge Econometrics, Climate Strategies, **India**: The Energy and Resources Institute, World Resources Institute, **China**: Beijing Normal University, Tsinghua University, Energy Research Institute, **Brazil**: Federal University of Rio de Janeiro, University of Brasilia, Universidade Estadual de Campinas (UNICAMP) **EU**: Scuola Superiore di Studi Universitari e di Perfezionamento Sant’Anna.

Contributors

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The contents of this report represent the views of the authors, and should not be taken to represent the views of the UK government, CIFF or the organisations to which the authors are affiliated, or of any of the sponsoring organisations.

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CASE STUDY:

Activating EV Tipping Points in China, India, Europe and the US

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Policy question(s): Which policies, individually and in combination, are most effective in driving the transition to electric vehicles? How does a fast transition compare to a slow transition, in terms of costs with the road transport sector, and in terms of macroeconomic consequences?

Region: Global

Methods: E3ME-FTT:Transport

Key finding(s): A cost-parity tipping point between electric vehicles (EVs) and internal combustion engine vehicles (ICEVs) is near, in major markets. An EV subsidy that closes the cost gap between EVs and ICEVs can be made revenue-neutral with only a small tax on ICEVs. Regulations and mandates are more cost-effective than financial incentives for driving the transition towards EVs when used individually and can also contribute to highly effective policy packages. A fast transition to EVs saves costs compared to a slow transition. The macroeconomic consequences of the transition to EVs are likely to be more positive for large oil-importing countries, and more negative for large oil-exporting countries.

Engagement: This study was informed by interactions with governments in several of the EEIST partner countries in which policymakers expressed interest in knowing the level at which EV subsidies would be effective, the relative cost-effectiveness of different policies, and the effect of implementing a given policy with varying levels of stringency.

Summary: The authors use the E3ME-FTT:Transport model to consider how a set of policies used individually and in combination can accelerate the transition to zero-emission vehicles in India, China, the US and Europe.

Introduction

The transport sector represented 23 per cent of global CO₂ emissions from fuel combustion in 2021.¹⁴⁵ Private passenger road transport generates 45 per cent of transport emissions and 30 per cent of its growth, and thus requires urgent attention from policymakers.¹⁴⁶ Electric vehicles (EVs)¹⁴⁷ have been seen as a major component of the solution for decarbonising private passenger road transport.¹⁴⁸ Due to sustained EV policy support already introduced around the world, the number of EVs on roads has increased dramatically, with about 16.5 million EVs globally in 2021. At the same time, battery prices have fallen significantly from US\$1,100/kWh in 2010 to US\$137/kWh in 2020¹⁴⁹ – an 88 per cent drop that is largely a result of economies of scale in production and innovation through various forms of learning as production and sales increase. However, after a decade of declines, battery packs across all sectors have increased in cost to around US\$150/kWh in 2022, as a result of material prices elevation.¹⁵⁰

As EV sales increase, a number of countries have set targets to make all new cars zero emission.¹⁵¹ For instance, the EU has now agreed to require all new car sales to be zero emission by 2035. However, some leading markets, including the US and China, have so far only set interim targets – aiming for EV shares of car sales by 2030 of 50 per cent and 40 per cent respectively. Their decisions on the pace of the transition are likely to take into account perceptions of feasibility, estimates of the future affordability of EVs¹⁵² and expectations of the impact of policies on industrial competitiveness, jobs, energy security and economic growth.

This case study presents evidence that major markets are nearing irreversible EV diffusion tipping points. It also identifies policy packages that could accelerate the transition to zero-emissions vehicles (ZEVs) and that could accelerate reductions in their cost; and it highlights the macroeconomic benefits of a fast transition (leading to 100 per cent ZEV sales in 2035 in the leading markets) compared to a slow transition. Early policy success in the leading car markets could induce an EV transition in the rest

of the world by increasing the affordability of EVs, while at the same time, the adoption of EVs in the rest of the world could bring forward cost parity between EVs and fossil-fuelled cars in the leading markets. These projections were simulated using FTT:Transport on the basis of observed cost for more than 2,000 vehicle models, and diffusion data for the past 12 years. The E3ME model was used to estimate macroeconomic outcomes.

FTT:Transport model description

Overview

The Future Technology Transformations (FTT) model is a loose framework method that models technological diffusion dynamically, based on technological competition in markets. The FTT:Transport model assumes the presence of an adaptive, evolving, path-dependent vehicle market with consumers who are heterogeneous agents, and vehicle manufacturers who supply the market in response to demand. We assume revealed preferences, in that the observed cost distribution for recent vehicle sales corresponds to the heterogeneity of consumer preferences and choices.

The FTT framework models technological diffusion by a set of logistic differential equations of the Lotka-Volterra family, which represent gradual technological substitution processes. The diffusion processes are path-dependent and involve positive feedbacks which are captured by the FTT framework. Under the FTT framework, consumers are more likely to choose a technology that has lower costs, and that has a higher market share as a result of availability, visibility, social influence and network effects, as well as if it is cheaper.

Modelling heterogeneity with the discrete choice theory

Consumers in the vehicle market are heterogeneous and choices are made in a probabilistic fashion. We assumed that the market heterogeneity can be derived from consumer's 'revealed preference' (i.e. their vehicle choices). This is simulated by consumers making purchases based on the availability and cost of car models in the market and the model

¹⁴⁵ IEA. (2021). World Energy Outlook.

¹⁴⁶ IEA. (2021). World Energy Outlook.

¹⁴⁷ EVs include both battery electric vehicles (BEVs) and plug-in electric vehicles (PHEVs).

¹⁴⁸ IEA. (2022). Global EV Outlook 2022.

¹⁴⁹ Bloomberg NEF. (2021). Electric Vehicle Outlook.

¹⁵⁰ Bloomberg NEF. (2022). Electric Vehicle Outlook.

¹⁵¹ UK Government. (2021). COP26 declaration on accelerating the transition to 100% zero-emission cars and vans. <https://www.gov.uk/government/publications/cop26-declaration-zero-emission-cars-and-vans/cop26-declaration-on-accelerating-the-transition-to-100-zero-emission-cars-and-vans>

¹⁵² Bloomberg NEF. (2021) Hitting the EV Infection Point.

implicitly assumes that car manufacturers supply the market in a way that matches consumers' preferences. In the discrete choice theory, consumers have heterogeneous taste and place different utility weights on different product characteristics.

The FTT model uses a modified version of discrete choice theory in the form of an evolutionary theory. It uses observed distributions of costs to represent agent heterogeneity (a form of revealed preferences). Consumer decisions are modelled with chains of binary logits. In the discrete choice, choices are made in a probabilistic fashion, which means that unobserved factors such as taste variation and interpersonal heterogeneity are taken into account in the discrete choice model. In terms of transport, the probability of choosing a particular vehicle is influenced by the width of the cost distribution for each segment of car technology and the market share of the technology. Hence, a policy does not lead to an instant diffusion of EVs and consumers do not respond to the incentives simultaneously.

The levelised cost of transportation (LCOT)

For the decision-making component of this model, we separate the investor in transport technology from the consumer of transport services. We think of them as separate entities for clarity, even though in some cases they might be the same person. Whether the roles are fulfilled by the same actors or not, they are quite distinct, where the investor purchases a vehicle to sell a transport service to the consumer. This is done to clarify the distinction between technology investment and associated market competition, and the consumption of the service that technologies produce. It also allows for the possibility that a person who purchases a car can still travel by train or plane and not use the car they purchased. The mode choice is distinct from the technology choice, even when performed by the same person. The cost of the vehicle, as perceived by the investor purchasing a vehicle or unit of transport technology, must be taken to include all components relevant to the decision making. Many of the components are easy to quantify from available data. Others are not straightforward, and we show here how this is done. When a vehicle is purchased, an initial investment is made, or a loan is obtained, for the capital cost, and henceforth fuel and maintenance costs are:

$$LCOT_i = \frac{(I_i - EVS_i) + \sum_t \frac{RT_i(t)}{CF_i} + (F_i(t) + FT_i(t)) * (FE_i(t) * Dist_t) + MR_i(t)}{\sum_t \frac{1}{(1+r)^t}}$$

Figure 41: Equation showing the levelised cost of transportation. Here I_i , F_i , and MR_i are the mean capital costs (in US\$), fuel cost (in US\$/litre) and maintenance cost (in US\$/km), respectively. EVS_i represents EV subsidies, paid to car purchasers (and therefore, negative cost) at the purchase time. FT_i is the fuel tax, in USD/litre. The fuel cost depends on the fuel consumption $FE_i(t)$ and the distance travelled each year ($Dist_t$). RT_i is the annual registration tax, which is vehicle and class-specific, paid by car owners once per year. CF_i is the capacity factor, in km/y.

As inferred from the price distribution of sales, transport costs are not the only factors that consumers consider when purchasing a vehicle. Many additional aspects (e.g. comfort and luxury) are valued by the consumer, of which we have little information beyond the price distribution of what is purchased. We keep in mind that technologies have different pecuniary costs, particularly across engine size classes; despite this, higher costs are in effect compensated by higher perceived benefits, such that higher-cost luxury vehicles co-exist alongside much cheaper economic vehicles.

Were we to simulate technology diffusion based on bare LCOT distribution comparisons, the lowest LCOT technologies would diffuse more successfully, which is not consistent with our historical data. Clearly, components would be missing in the LCOT – for instance, comfort, acceleration and style – which we may call the ‘intangibles’. We define intangibles for this model as the difference between the generalised cost, which leads to observed diffusion, and the LCOT, as calculated from pecuniary vehicle properties for which we have data. The value of the intangibles is an empirical parameter obtained from making the FTT diffusion trajectory match the trajectory observed in our historical data, at the year of the start of the simulation.

Vehicle population projection

Car 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 function. Historically, GDP growth and economic development are associated with an increase in vehicle ownership. Past studies have made projections of passenger car ownership based on GDP.

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 growth trend of vehicle stock.¹⁵³ We examine trends in the growth of vehicle stocks for a large sample of countries and employ the Gompertz function to estimate the relationship between the number of vehicles and per capita income.

$$V_{i,t} = V_i^* e^{ae^{BF_{i,t}}}$$

Figure 42: Following the previous studies, we estimate car stock with a Gompertz model.

Passenger transport demand projection

Transport demand is driven by income, population, urban density, family structure and other demographic factors. The demand estimation in this section consists of two parts. The first part is the construction of an econometric model that predicts the demand for passenger light-duty vehicles (PLDVs) (in km per vehicle) using fuel prices, income, urbanisation, road infrastructure, urban density and fuel economy. Then we use the econometric model to predict the future private passenger vehicle transport demand (per vehicle). In the second part, we develop a model for vehicle stock and project future car ownership, which is then used to make projections for the total demand for PLDVs.

Policy simulations and interactions in the FTT:Transport model

Financial incentives such as EV subsidies, road tax and fuel tax affect the cost of operating a vehicle and are calculated in Figure 41 directly. Fuel economy regulation is modelled by influencing the flow of share values in the technology category for old inefficient vehicles, while new ICEVs continue to be sold. When a fuel economy regulation is introduced, sales of vehicles that fail to meet the required standard of efficiency are prevented. The stock of vehicles on the road will gradually be replaced by more energy-efficient vehicles as a result.

For EV mandates, it is assumed that the policies exogenously change the shares of vehicle types at a specific point in time. We assume that market shares flow from conventional cars to EVs by assigning the minimum exogenous shares corresponding to the mandate to the new vehicle technology. This approach models mandates

with targets that require manufacturers to achieve specific percentages of EVs in their sales. This represents the simplest version of the policy, and is not exactly the same as some of the real-world EV mandates, where the government sets an EV production quota and this can be met through a system of credits. Here we assume the EV mandate is effectively enforced, so that the EV share of car sales follows the target trajectory set by the government.

In the FTT model, each layer of policy plays a specific role in the decarbonisation of the transport sector. When the policies are simultaneously simulated in the model, they influence each other's effectiveness. For example, taxing high-emission vehicles with a vehicle tax will encourage consumers to purchase low-emission vehicles. In a consumer market with limited EV models available, a consumer will be more likely to choose a lower-emission petrol car rather than an EV. However, in the presence of the EV mandate, manufacturers are encouraged to accelerate the deployment of EVs, which increases choice for consumers. This then makes the tax more effective at guiding consumer choices for reducing emissions than would be the case without the mandate. Furthermore, when more EVs are produced, their costs fall more quickly, leading to a higher rate of diffusion. In this way, the model represents the S-shaped technological diffusion curve. Hence, policy interactions emerge endogenously in the FTT:Transport model.

Nearness of EV tipping points

Although EV purchase prices at present can be higher than those of petrol and diesel vehicles, EVs are easier to maintain and cheaper to operate. This combination means that battery costs are declining rapidly and EVs appear soon likely to become the cheaper option in terms of total ownership costs, which could lead to a social ‘tipping point’ where EVs become the preferred option for the majority of consumers.¹⁵⁴ Several studies have analysed projected EV and ICEV costs for representative models^{155 156 157 158} and concluded that EV cost parity¹⁵⁹ (total cost of ownership) begins to be reached in the 2022–2027 timeframe in Europe, the US and China. However, depending on the discount rate and other factors influencing decision-making, parity of upfront purchase price can be a more important consideration than parity of total cost of ownership, for the consumers.

¹⁵³ Meyer, I. et al. (2012). Scenarios for Regional Passenger Car Fleets and their CO2 Emissions. *Energy Policy*, 41: 66–74.

¹⁵⁴ Sharpe, S. and Lenton, T. M. (2021). Upward-Scaling Tipping Cascades to Meet Climate Goals: Plausible Grounds for Hope. *Climate Policy* 21: 421–433. <https://doi.org/10.1080/14693062.2020.1870097>

¹⁵⁵ Bloomberg NEF. (2021) Hitting the EV Inflection Point.

¹⁵⁶ Lutsey, N. et al. (2021). Evaluating Electric Vehicle Costs and Benefits in China in the 2020–2035 Time Frame. *International Council on Clean Transportation (ICCT)*.

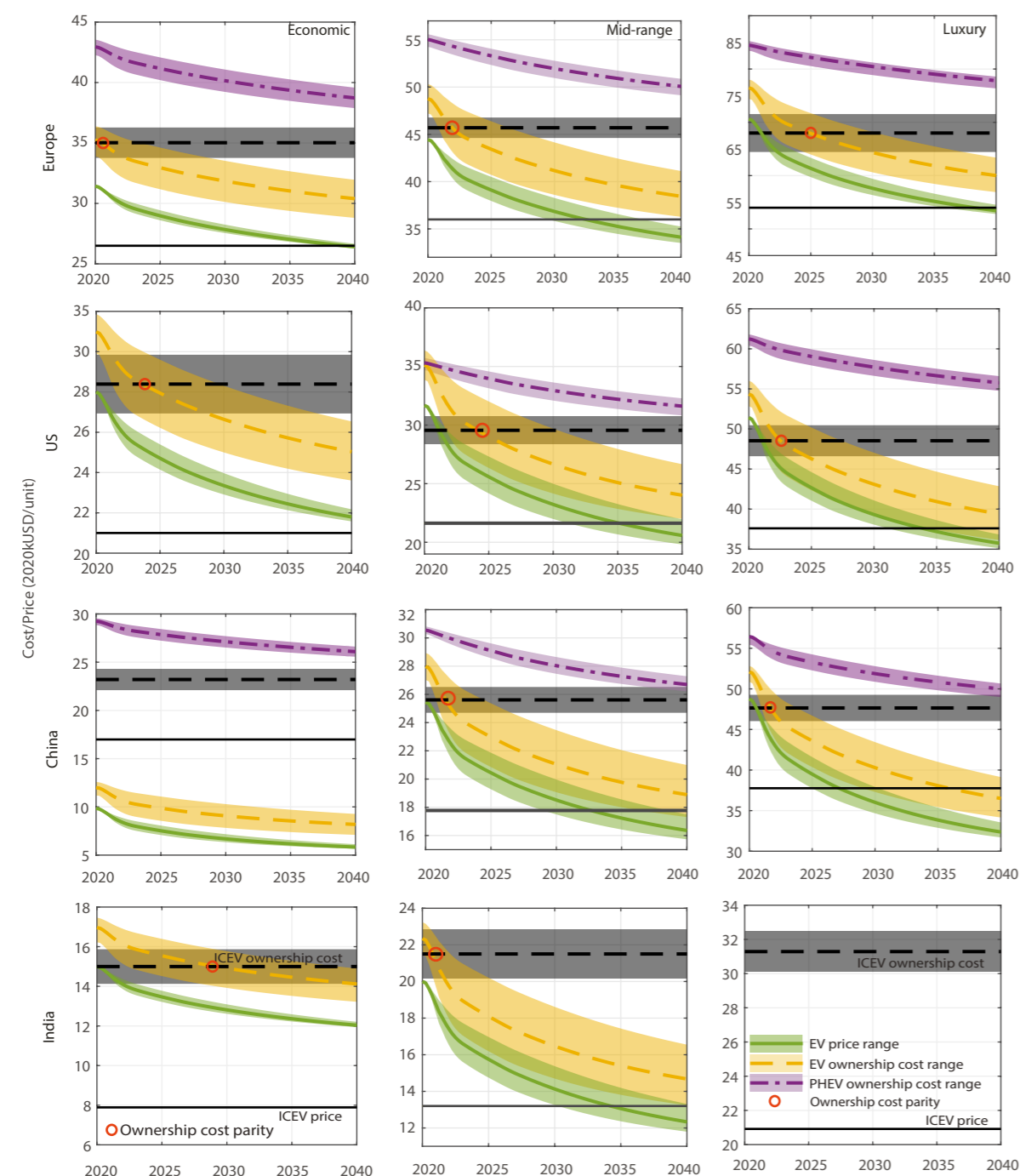
¹⁵⁷ Lutsey, N and Nicholas, M. (2019). Update on Electric Vehicle Costs in the United States through 2030.

¹⁵⁸ Lam, A. and Mercure, J-F (2022). Evidence for a Global Electric Vehicle Tipping Point. GSI Working paper series number 2022/01. https://www.exeter.ac.uk/media/universityofexeter/globalsystemsinsitute/documents/Lam_et_al_Evidence_for_a_global_EV_TP.pdf

¹⁵⁹ Cost parity does not happen for all EV models at the same time because this depends on the model size and specification. “Initial cost parity” is triggered when cost parity is first reached for some vehicle models, in a given market.

Figure 43 shows the projected EV ownership costs and prices, according to the combined Rogers-Wright law (on diffusion and experience curves), against ICEVs in all four major car markets until the policy horizon of 2050 for three different segments, given observed trends, existing uncertainties and assuming that current policy frameworks are maintained.

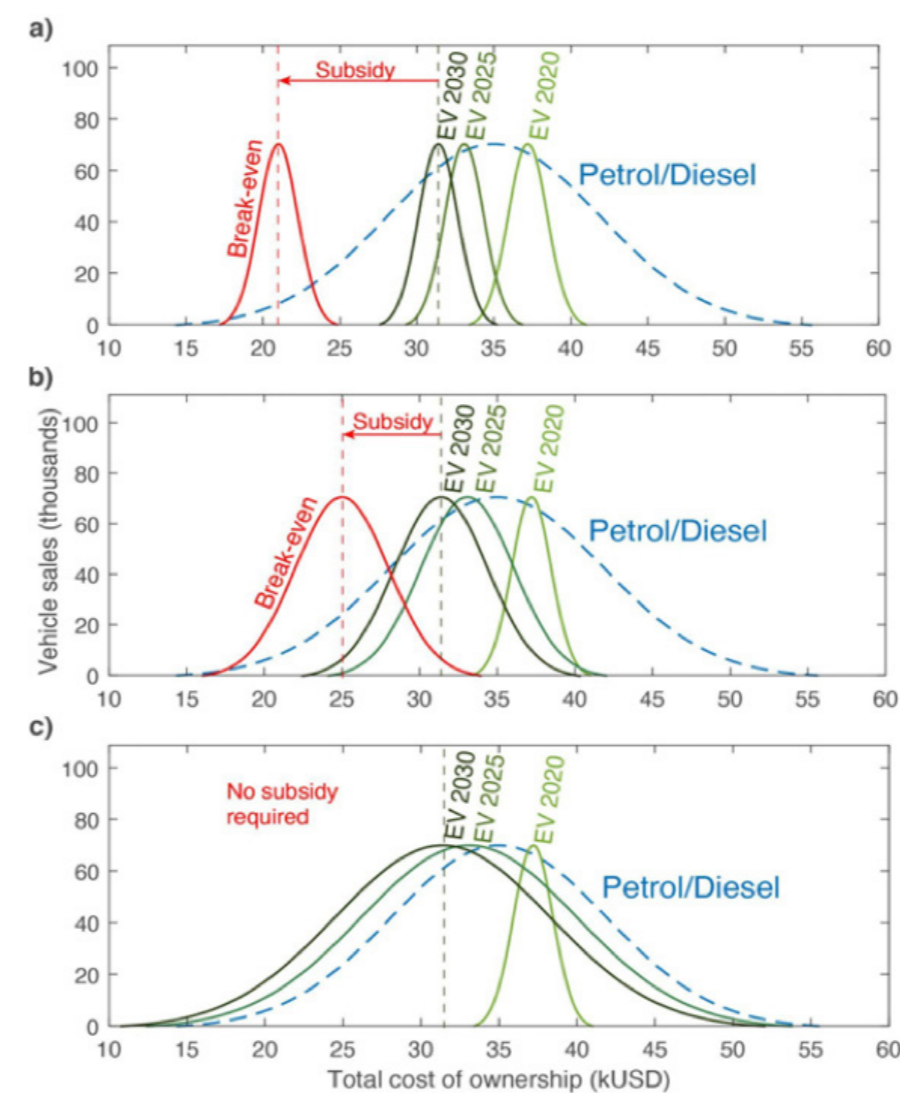
Figure 43: Trajectory of total ownership costs (dashed lines) and prices (solid lines) of BEVs/PHEVs/ICEVs (median and 95 per cent confidence range learning rates).¹⁶⁰



Battery electric vehicles (BEVs) begin to reach cost parity within 2022-2025 for all segments. For Europe, the US and China, cars at the lower end of the price range reach cost parity the earliest, with both prices and ownership costs for BEVs already lower than ICEVs in China. For a mid-range or luxury car, ownership costs of BEVs can achieve parity with ICEVs between 2023 and 2025 in China, India, Europe and the US (Figure 43). However, plug-in hybrid electric vehicles (PHEVs) never achieve cost parity with ICEVs and are absent in India. This is because PHEVs are on average more expensive to own than BEVs (consuming fuel as well as electricity) and cost more to purchase than ICEVs (having a battery and electric drivetrain as well as a motor). Also, cost reductions for BEVs, which have larger batteries than PHEVs, are steeper.

BEV purchase price parity is likely to be achieved later than ownership cost parity, and could occur in the 2028-2035 timeframe. In some cases (e.g. the low-cost segment of the market in India), purchase price parity is not achieved before 2040 based on existing data, because the few BEV models that are available remain a lot more expensive than the comparable ICEVs. To convince consumers to switch to BEVs 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 (see Figure 44). Alternatively, supply-side policies such as ZEV mandates could increase model variety on the market and reduce the need for subsidies.

Figure 44: Relationship between model variety and the breakeven subsidy in 2025 and in 2030. The red curve represents the subsidy required for an EV to cost less than most of the comparable ICEV models in every cost category in the market. This breakeven subsidy reduces as costs decline with rising diversity, for (a) constant BEV variety, (b) doubled BEV variety and (c) BEV variety matching the current variety of petrol/diesel vehicles. In (a), the subsidy required to narrow the cost difference is larger than in (b) and (c) because there are a significant number of less costly ICEV models on the market. When the diversity of EVs reaches that of the ICEVs (in c), it becomes possible for consumers to purchase a comparable EV model without subsidies.

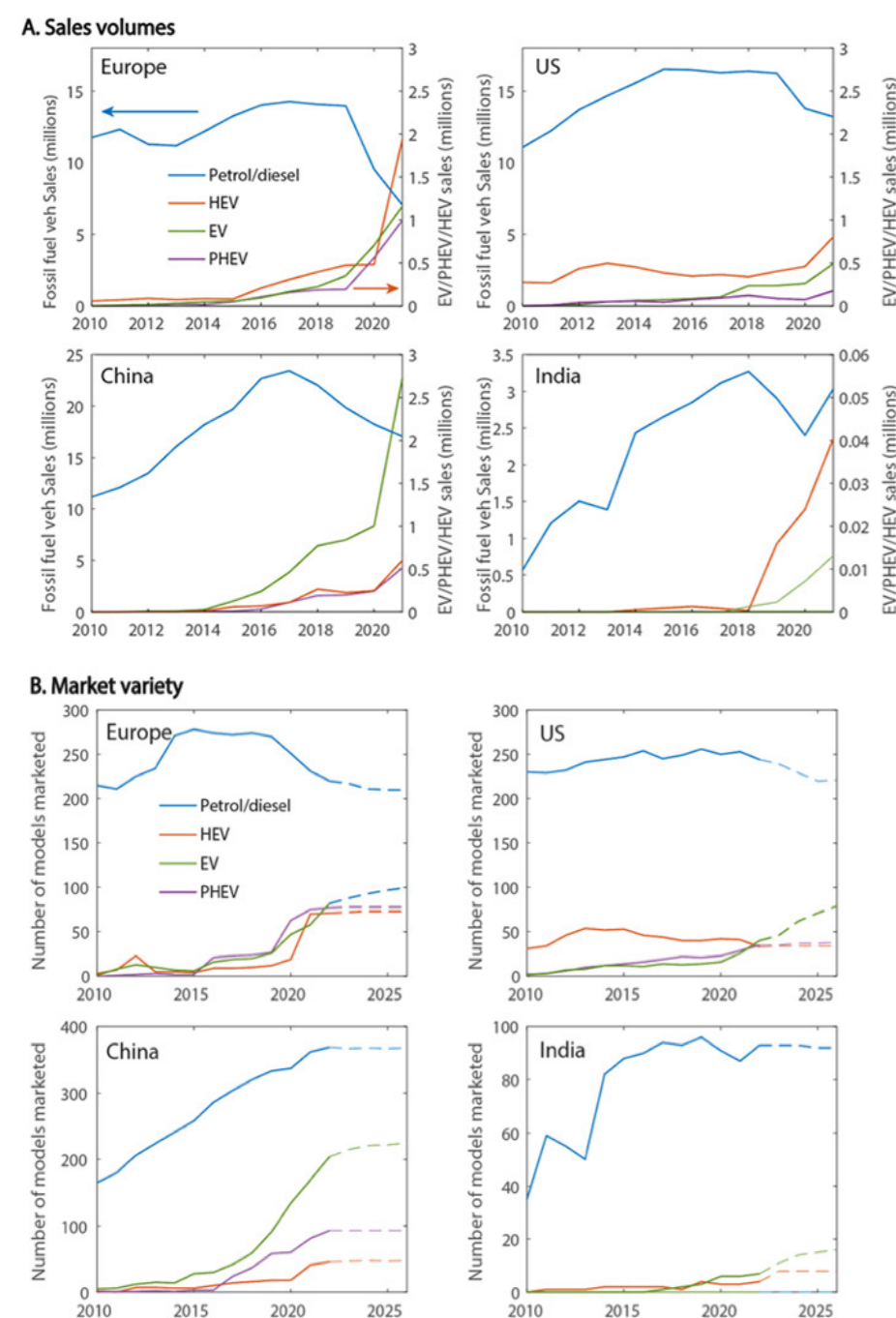


¹⁶⁰ Lam, A., Mercure, J-F (2022). Evidence for a global electric vehicle tipping point. GSI Working paper series number 2022/01. https://www.exeter.ac.uk/media/universityofexeter/globalsystemsstitute/documents/Lam_et_al_Evidence_for_a_global_EV_TP.pdf

In the leading markets, more EV models becoming available has made EVs more attractive to consumers. We observe rapidly rising sales and an increase in variety for both BEVs and PHEVs. BEVs have recently far outpaced PHEVs in their growth, with the latter stagnating in 2019-2021. Crucially, EV sales have been entirely unaffected by the COVID-19 pandemic. While EV sales are still lagging in developing countries such as India, where only a few models are available (Figure 45), sales of electric two and three-wheeler

vehicles have been consistently on the rise. The variety of EVs will need to continue to increase in all markets to ensure a successful and cost-effective transition. Targeting EV purchase incentives at popular ICEV segments where EV models are lacking could help to increase the variety of EVs available. In the case where very few EVs are available in the market, it may also be helpful to develop a trade policy conducive to increasing imports, or to strengthen the EV supply chain domestically.

Figure 45: Evolution of vehicle markets and prices. Price distribution time series for conventional petrol/diesel vehicles, BEVs and PHEVs in Europe, the US, China and India.¹⁶¹



Individual policies to support EV deployment

The nearness of EVs to achieving cost parity does not guarantee a transition to electric mobility that is compatible with a country's economic, industrial or climate change goals. We analysed the effectiveness of four of the main policy instruments for supporting the deployment of EVs: EV subsidy, vehicle tax, vehicle efficiency regulation and EV mandate. We compared outcomes in terms of cost effectiveness of EV deployment; cost effectiveness of emissions reduction; and cost reduction of EVs achieved over the period. We also compared the macroeconomic impacts of fast and slow transition scenarios, in terms of economy-wide energy consumption, GDP, imports and employment.

For the purpose of comparison, we defined individual policy instruments as follows:

- Subsidies:** 'Subsidy current' is an EV purchase subsidy at its current level in the specified market. 'Subsidy cost parity' is an EV purchase subsidy set at the level required to achieve ownership cost parity with an equivalent ICE vehicle in the year 2022. 'Subsidy high' is a subsidy at 150 per cent of the baseline/2020 level. 'Subsidy very high' is a subsidy at 200 per cent of the baseline/2020 level.
- Taxes:** 'Tax cost parity' is a tax on ICE vehicles set at the level required to achieve ownership cost parity with an equivalent EV in the specified market in the year 2022. 'Tax high' is a tax at 150 per cent of the baseline/2020 level. 'Tax very high' is a tax at 200 per cent of the baseline/2020 level.
- Regulations:** 'Regulation slow' is an efficiency regulation that requires the carbon intensity of new vehicles, measured in carbon emissions per kilometre, to reduce linearly from its level in 2022 to 50 per cent of that level by 2035. 'Regulation fast' requires the carbon intensity of new vehicles to reduce linearly from its level in 2022 to zero by 2035.
- Mandates:** 'Mandate slow' requires 50 per cent of new vehicles to be zero emission by 2035. 'Mandate fast' requires all new vehicles to be zero emission by 2035.

Figures 46 and 47 compare the effectiveness and cost of these individual policy instruments for promoting the deployment of EVs in Europe, US, China and India.

The results indicate:

- In terms of pure effectiveness at driving the transition to electric vehicles, mandates are the most effective policy in all four regions.** This is not surprising: mandates are designed to ensure a shift to the new technology. Efficiency regulations, even when they have equivalent stringency (requiring a full shift of new vehicle sales to zero-emission technology by the same date), may achieve less of a shift to electric vehicles on the road, because at least for some period they can be complied with through sales of more efficient petrol or diesel cars.
- Subsidies and taxes, when used without the support of regulations or mandates, are relatively ineffective.** Increasing their level beyond that required to achieve cost parity between EVs and ICE vehicles has relatively little additional effect on deployment. This is because the tax or subsidy at cost parity level is not necessarily enough for many consumers to favour EVs, especially in the absence of what are perceived as comparable models or sufficient numbers of charging stations. Without regulations or mandates pushing the pace of diffusion, too few consumers are aware of, or have access to, the new technologies and therefore few will take advantage of the fiscal incentive until diffusion levels are higher.
- Regulations are generally more cost-effective than financial incentives, for driving the transition to electric vehicles.** This is due to a combination of factors. Regulations and mandates achieve a larger shift to EVs by acting decisively on supply and imposing hard requirements that manufacturers have to meet. In contrast, financial incentives – which focus on narrowing the cost differences – encourage a change in behaviour by consumers but do not require it, and the diverse preferences of consumers mean that some will remain unpersuaded. At the same time, the cost of regulations and mandates (more vehicles bought with higher purchase price) is offset by the lower operating costs of EVs and more efficient ICE vehicles. In China, the cost of regulation is negative because the ownership costs for EVs are already lower than those of ICEVs. An exception to the rule is seen in Europe, where regulations have already been in place for some time and the EV market is relatively mature and varied. In this context, subsidies can be cost-effective.

¹⁶¹ Lam, A., Mercure, J-F (2022). Evidence for a Global Electric Vehicle Tipping Point. GSI Working paper series number 2022/01. https://www.exeter.ac.uk/media/universityofexeter/globalsystemsinsitute/documents/Lam_et_al_Evidence_for_a_global_EV_TP.pdf

● **In all cases, taxes are far less cost-effective than subsidies.** This is because to achieve the same effect of cost parity between EVs and ICEVs, an EV subsidy only has to be applied to the small

share of the market currently accounted for by EV sales, whereas a tax must be applied to the far larger share of the market made up by ICEV sales.

Figure 46: EV deployment in 2035 and 2050 in major markets resulting from different policies used individually.

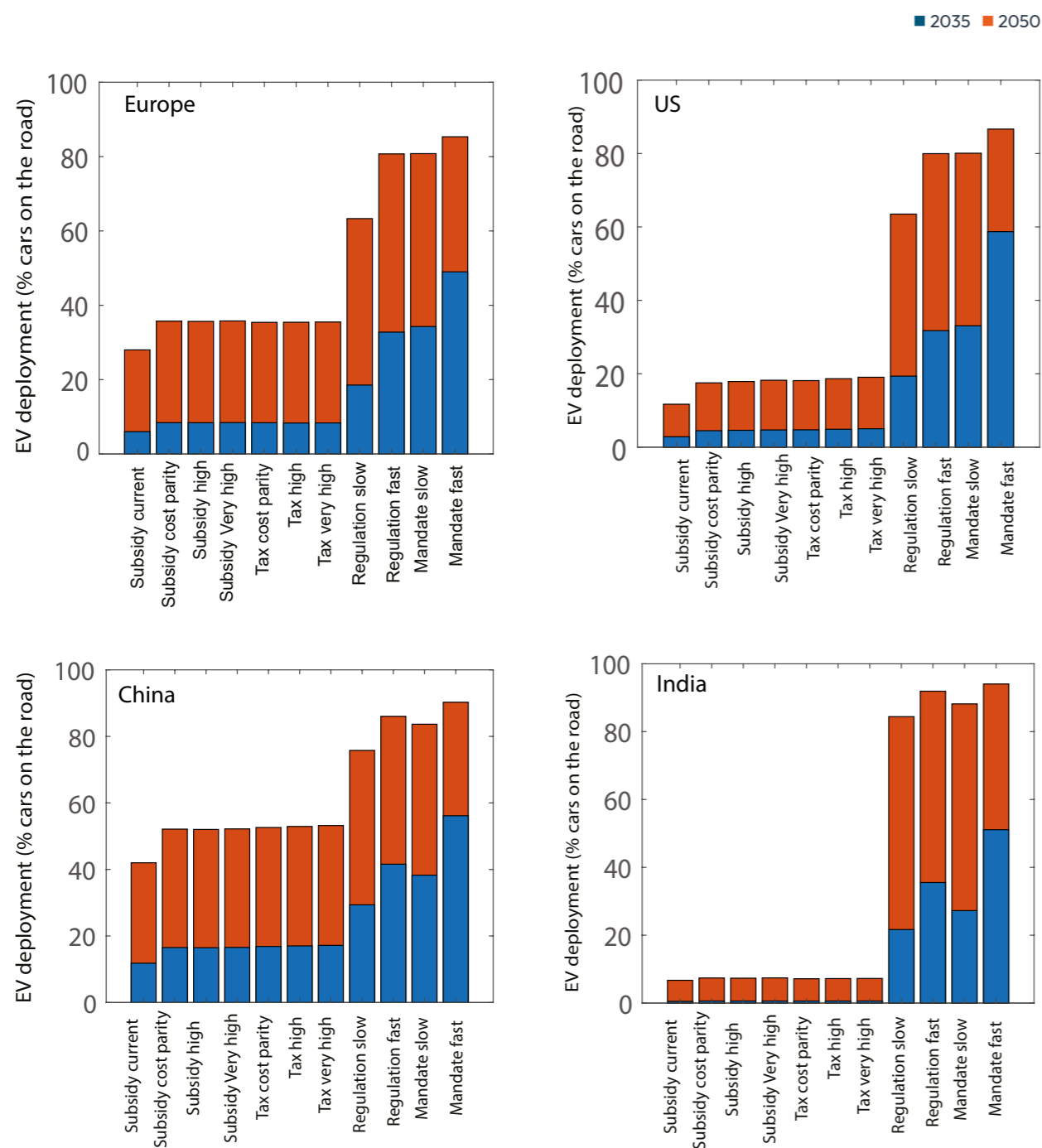


Figure 47: The cost of EV deployment as a result of different policies used individually.

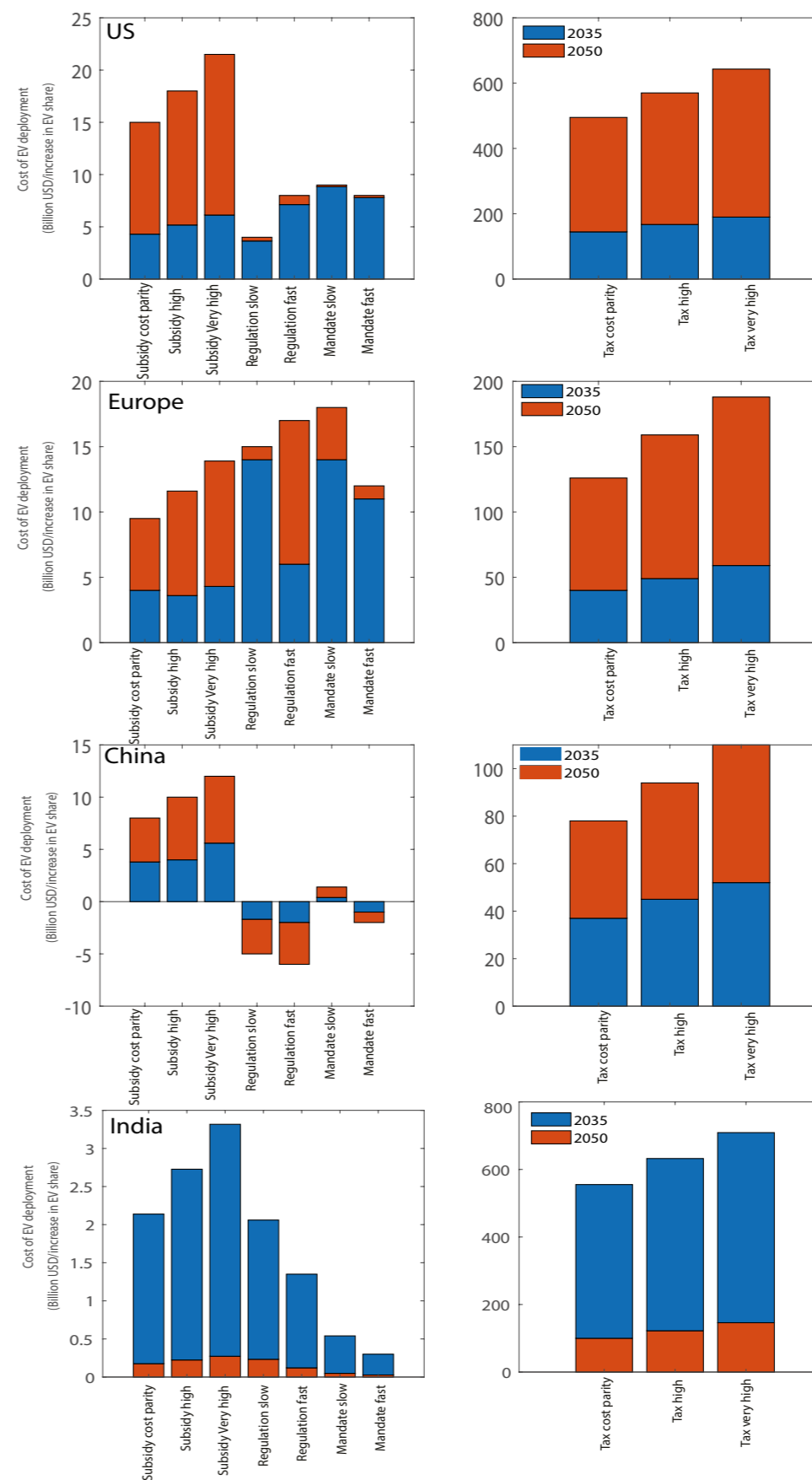


Figure 48 compares the cost effectiveness of the policies in terms of a different outcome: emissions reduction. The overall pattern is similar. Regulations and mandates generally achieve cumulative emissions reductions over the period more cost-effectively than financial incentives. Subsidies achieve emissions reductions more cost effectively than taxes.

Whether the goal is deployment of EVs or reduction of emissions, we find that a fast transition is more

cost effective than a slow transition (Figures 47 and 48). Because the system is highly path-dependent, a fast transition scenario in the short run leads to higher EV diffusion in the long run, and hence it achieves significantly more than a slower transition scenario in terms of EV deployment and CO₂ emissions reductions. Because EVs become cheaper to operate than ICEVs relatively early in the period, a faster transition yields greater overall cost savings.

Figure 48: Cost of CO₂ emissions reduction under different policy assumptions.

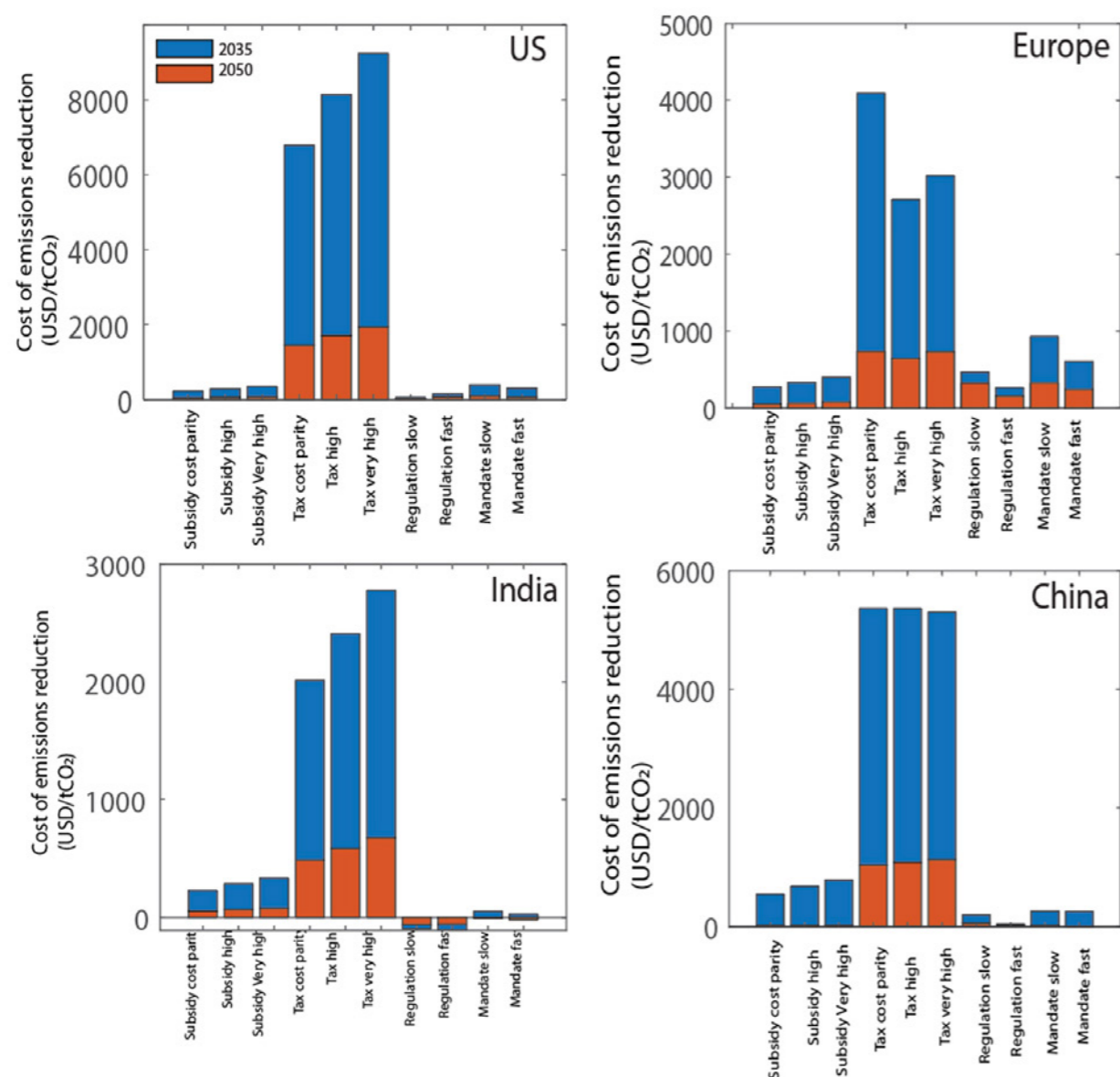
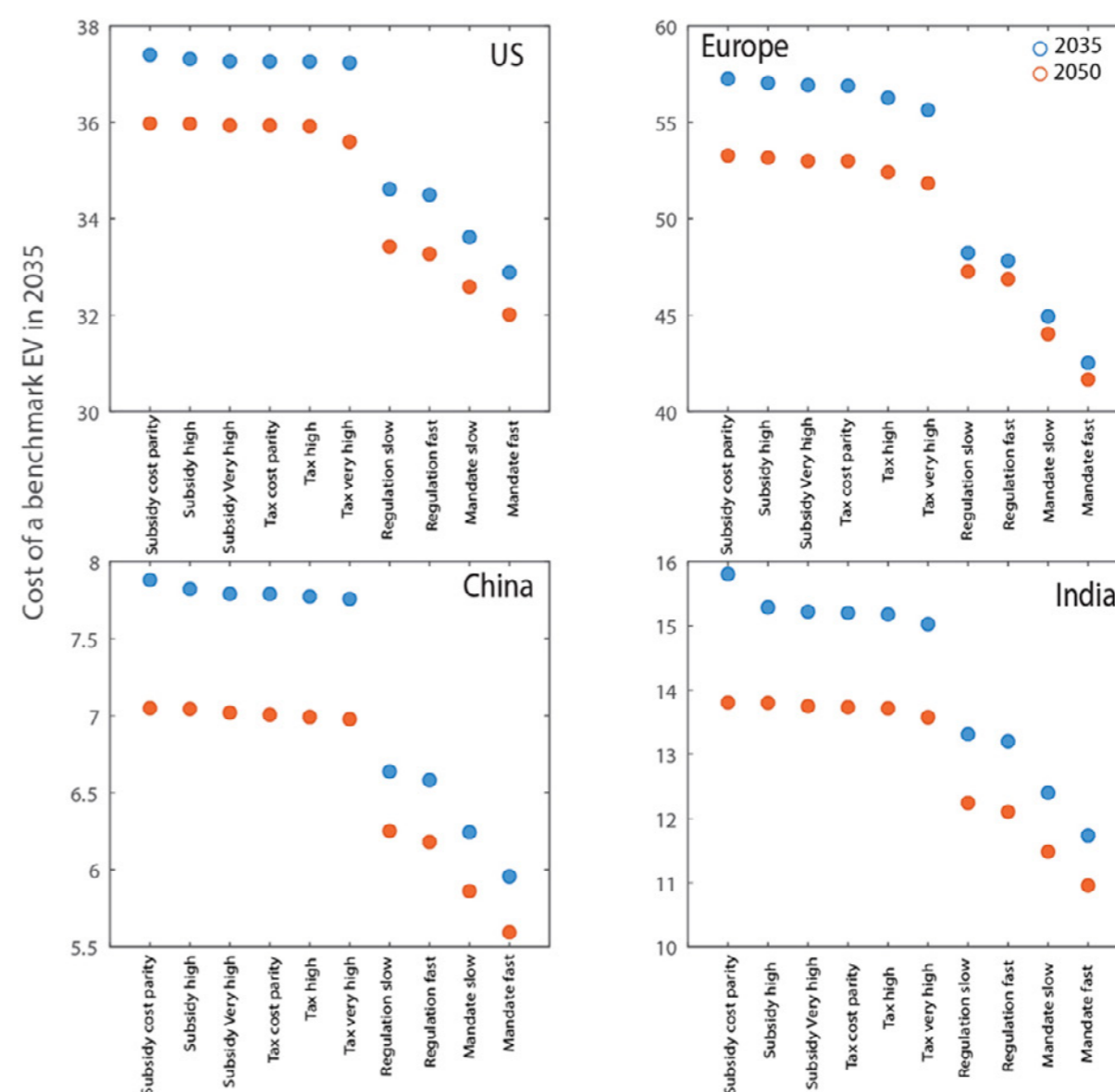


Figure 49 shows the effectiveness of policies in driving down EV costs over time. This happens as deployment drives learning and economies of scale. Regulatory policies are more effective than the financial incentives because they are more effective

in increasing EV deployment. In all cases, the EV mandate drives the greatest cost reductions because it achieves the highest cumulative deployment of EVs (as shown in Figure 45).

Figure 49: Cost of benchmark EV under different policy assumptions.

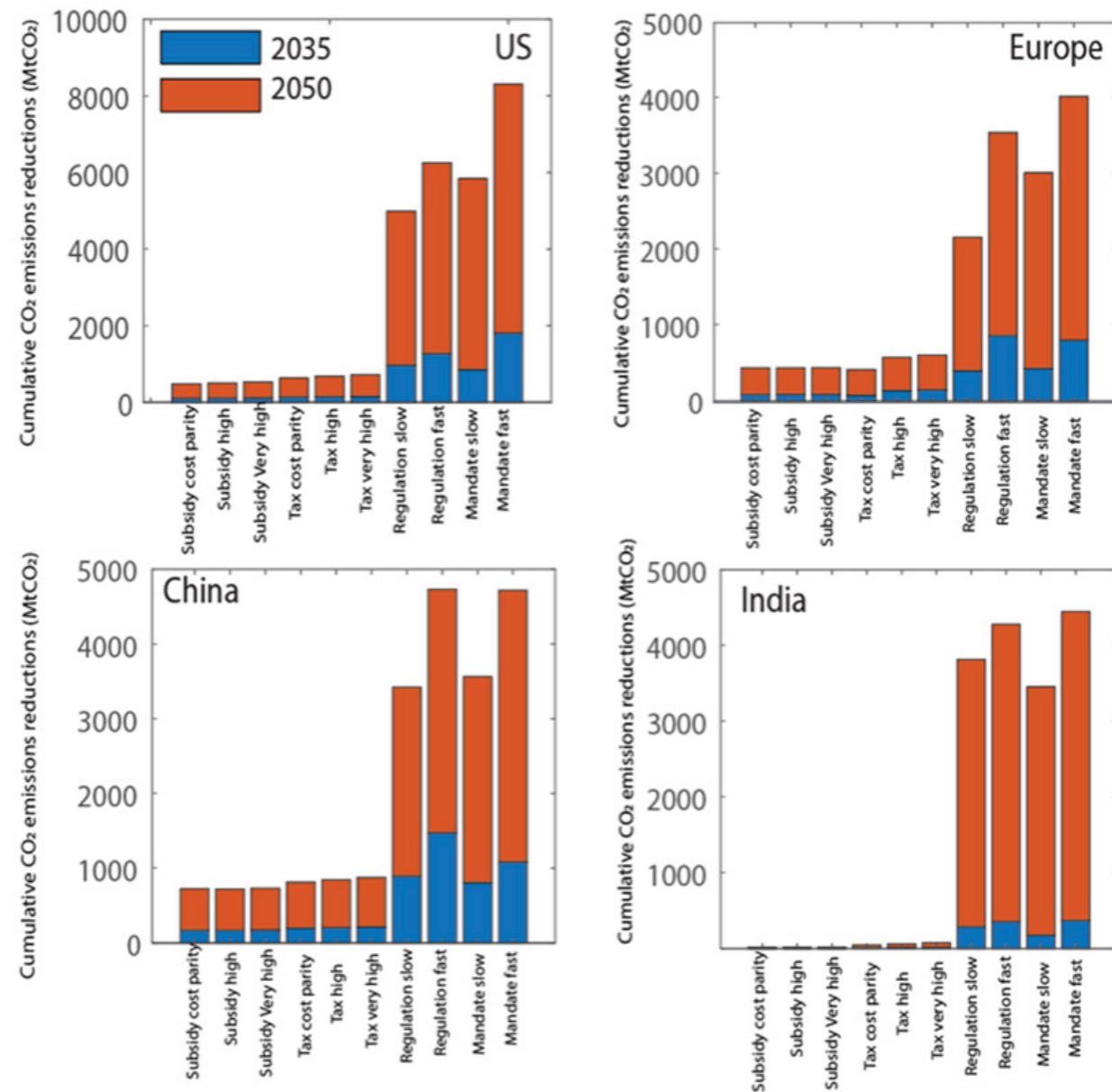
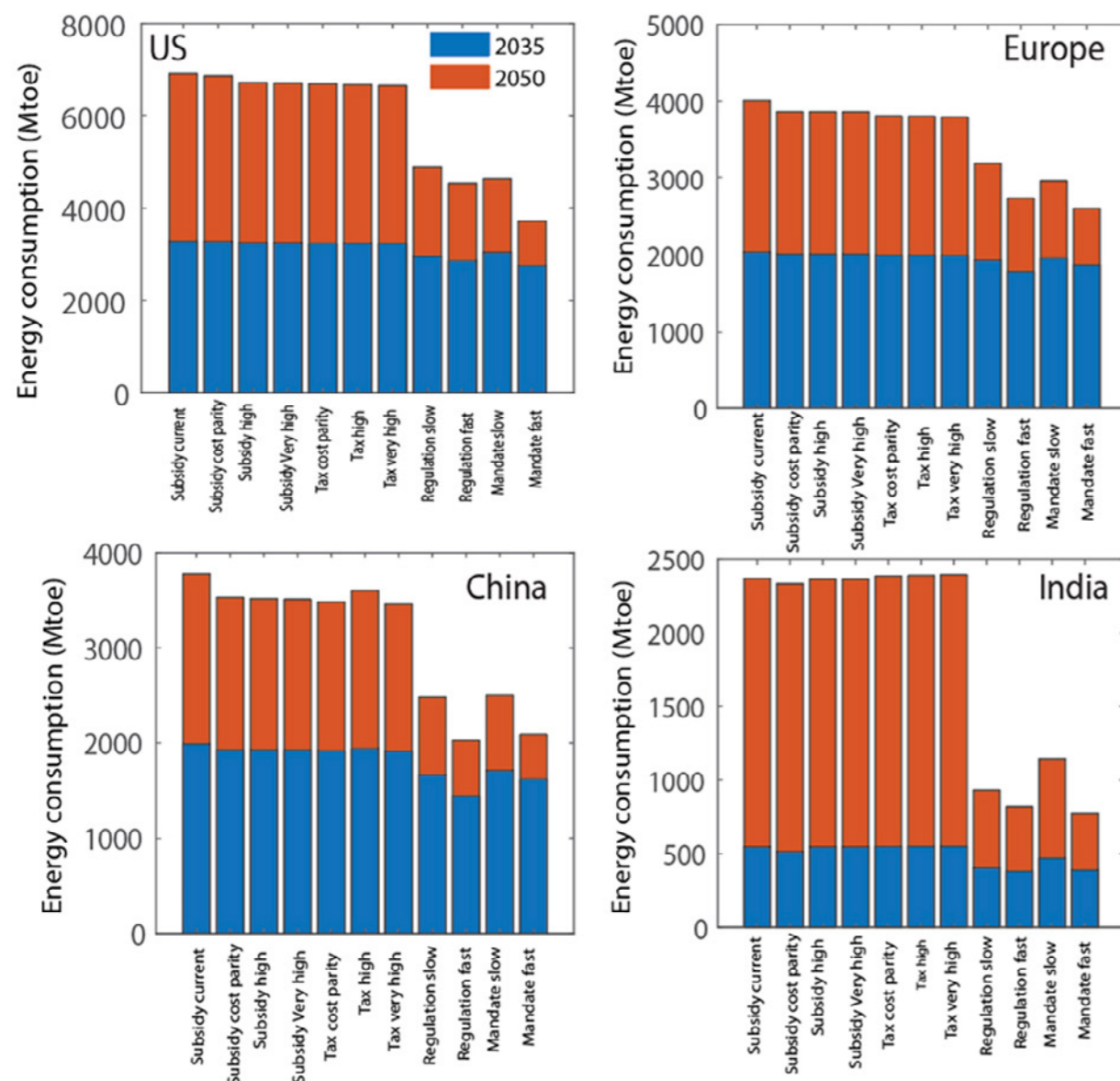


Figures 50 and 51 illustrate the cumulative energy consumption and CO2 emissions reduction under different policy scenarios. Overall, our results indicate that regulations and mandates

are significantly more effective in reducing CO2 emissions than financial incentives and are also more effective at reducing energy consumption.

Figure 50: Cumulative energy consumption under different policy assumptions.

Figure 51: Cumulative CO2 emission reductions under different policy assumptions.



Policy packages to support EV deployment

In reality, individual deployment policies are rarely used in isolation. Typically, there are advantages from implementing different policies simultaneously. However, the effectiveness of policy packages can vary widely.

Figure 52 shows that the combined effectiveness of two policies is generally not equal to the sum of their

individual effectiveness, but can be either smaller (trade-off effect) or larger (reinforcement effect). The strongest reinforcement effects are observed when EV mandates are used together with efficiency regulations; and when EV mandates are used together with road taxes. Trade-offs are observed when efficiency regulations are combined with road taxes or fuel taxes: these combinations achieve less than the sum of their parts.

Figure 52: Policy scenarios to achieve rapid transport decarbonisation under different policy scenarios.¹⁶²

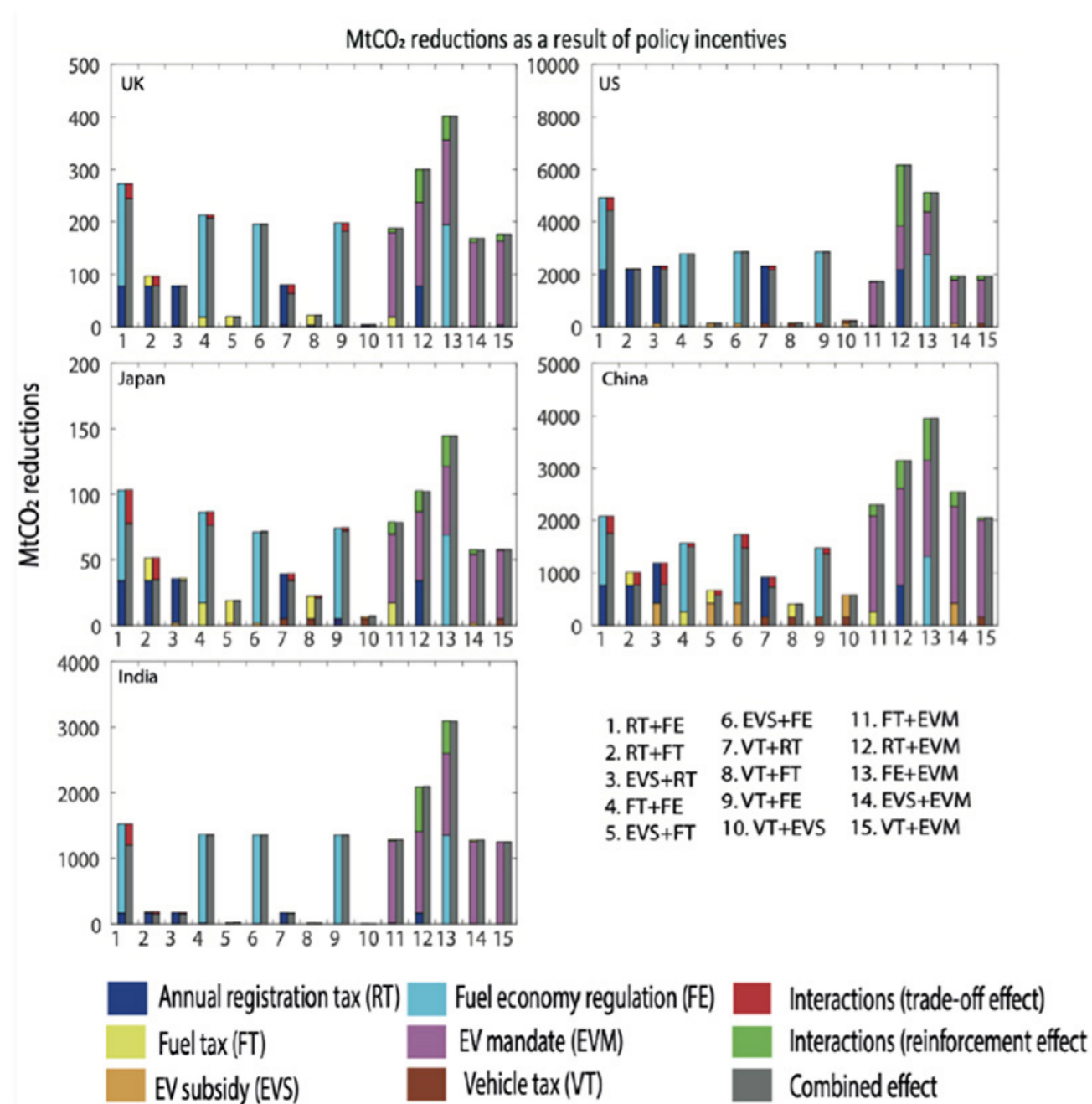
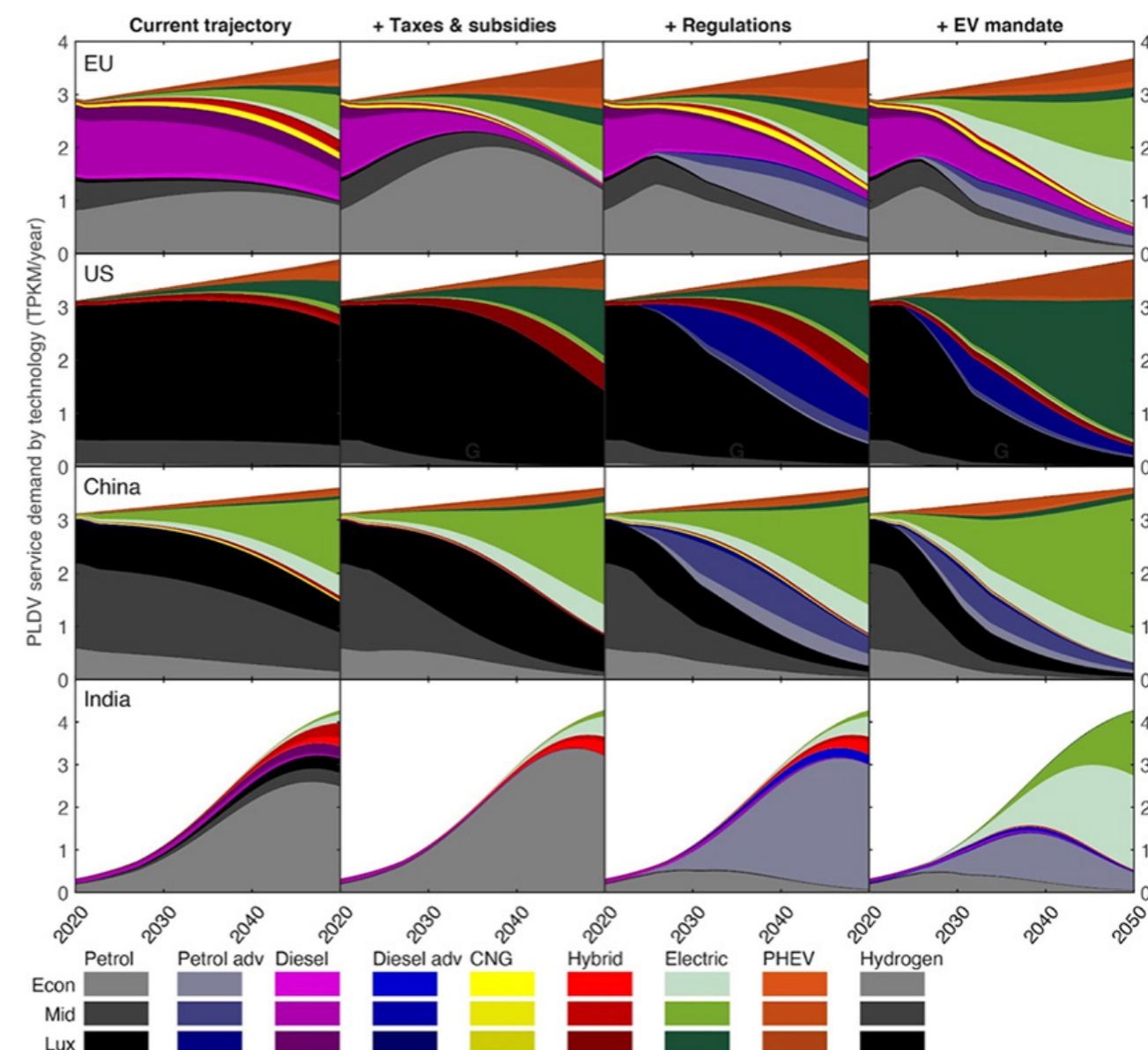


Figure 53 shows the effect of combining more policies in a package, based on simulated scenarios of fleet compositions in the four leading markets. Current trajectory (A) indicates where markets are headed without additional policies. (B) The addition of more stringent road and vehicle taxes and EV subsidies have limited impacts. (C) Fuel economy regulations accelerate conventional vehicle emissions reductions but have limited impacts on the diffusion of EVs. (D) Adding ZEV mandates magnifies substantially

but have limited impacts on the diffusion of EVs. (D) Adding ZEV mandates magnifies substantially the effect of the other policies as it expands their effect across vehicle users. In the current trajectory scenario (Column A), we assume there are no new policy incentives in place. The results show that the transition to 100 per cent EV sales by 2035 will not happen without sustained policy.

Figure 53: 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 ZEV mandates magnifies substantially the effect of the other policies as it expands their effect across vehicle users.¹⁶³



¹⁶² Lam, A. and Mercure, J-F. (2021). Which Policy Mixes are Best for Decarbonising Passenger cars? Simulating interactions among taxes, subsidies and regulations for the United Kingdom, the United States, Japan, China, and India. Energy Research and Social Science 75. <https://doi.org/10.1016/j.erss.2021.101951>

¹⁶³ Lam, A., Mercure, J-F (2022). Evidence for a Global Electric Vehicle Tipping Point. GSI Working paper series number 2022/01. https://www.exeter.ac.uk/media/universityofexeter/globalsystemsinsitute/documents/Lam_et_al_Evidence_for_a_global_EV_TP.pdf

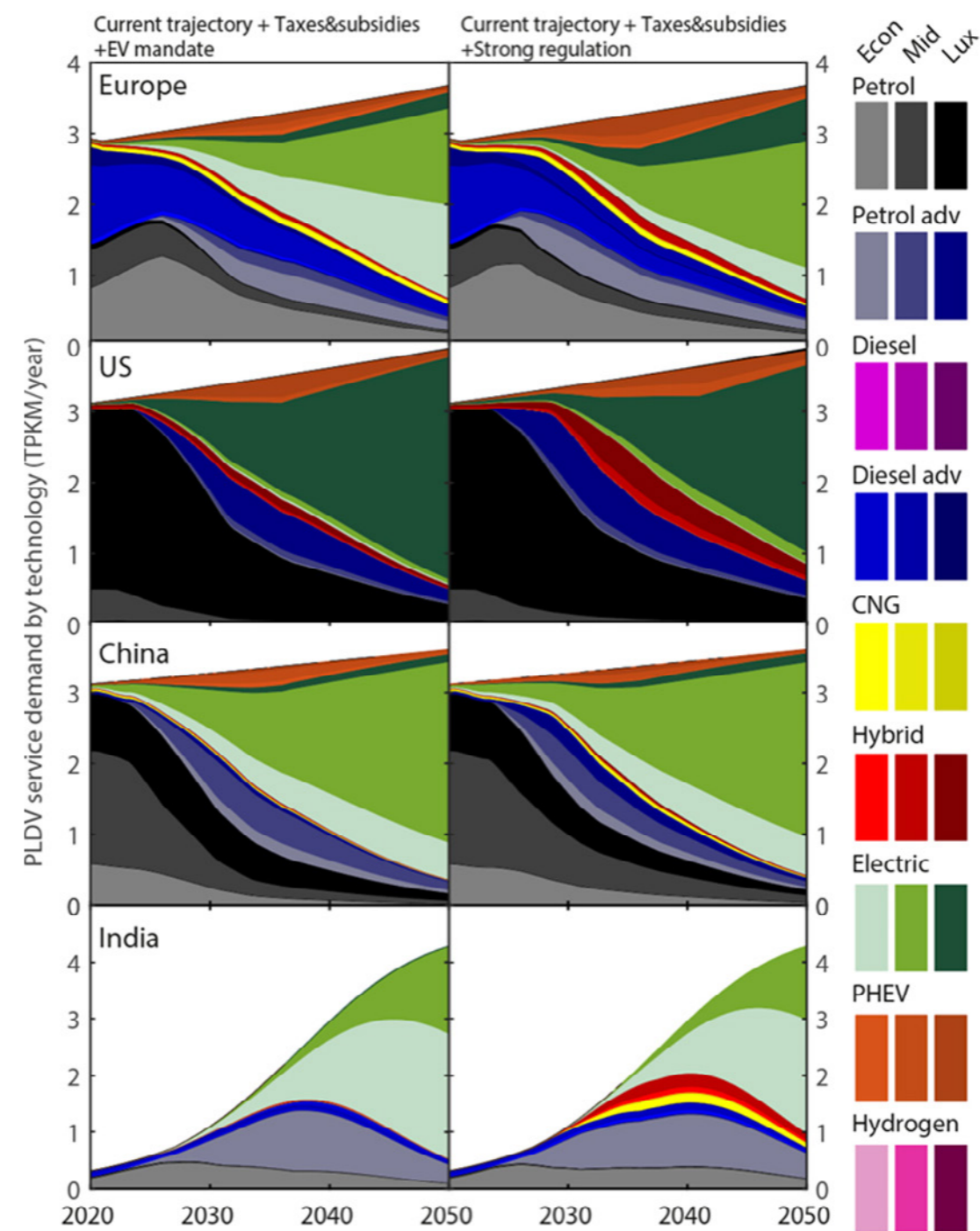
Financial incentives that achieve cost parity between EVs and fossil fuel cars can help, as discussed above. We demonstrate that it is possible to achieve this without putting financial pressure on the government by considering a revenue-neutral feebate. Table 10 shows the BEV subsidies required to break cost parity with different segments of ICEVs in the leading markets in 2023. Subsidies are funded through taxes applied to ICEVs at the point of purchase. With the range of subsidies on fossil fuel cars listed in Table 10, the incentive structure can create a revenue-neutral mechanism to fund BEV subsidies that bridge the cost gaps between ICEVs and EVs in 2023 in Europe, the US and India. The Chinese government is no longer providing subsidies to buyers of EVs so EV subsidy in China is not considered here. Because EVs are currently only a small share of the market, a small tax on each fossil fuel vehicle sold is enough to fund a high subsidy on each new EV.

We found that adopting subsidies to break cost parity with ICEVs is not enough to make all new vehicles zero emission by 2035 for the reasons stated above (Figure 53, Column B). Resolving the supply problem of BEVs can be accelerated using ZEV mandates or strong efficiency regulations. A number of existing studies^{164 165 166} find that well-designed combinations of policy instruments can lead to a greater rate of transition than may be achieved through the application of any individual instrument. In particular, there is a reinforcement effect between ZEV mandates and other financial incentives (i.e. the presence of two policies offers a larger CO2 mitigation benefit than the sum of the effectiveness of either policy alone).¹⁶⁷

Given that there is a reinforcement effect between the ZEV mandates and other financial incentives, we sequentially add EV subsidies, regulations and ZEV mandates in panels B-C-D in Figure 53. Adding ZEV mandates that guide manufacturers towards supplying specific shares of ZEVs going gradually towards 100 per cent ensures, in tandem with the other policies, that zero emissions at the tailpipe can be achieved by 2050 or earlier.

We compare the results of a gradual tightening of the efficiency regulation that leads towards zero emissions with a ZEV mandate that leads to 100 per cent BEV sales in 2035. As shown in Figure 54, a ZEV mandate leads to more rapid diffusion of BEVs than a gradual tightening of fuel economy regulations. This is because the fuel economy standard is technology-neutral and allows the diffusion of low-emission vehicles such as hybrid electric vehicles (HEVs) and PHEVs. In particular, in countries where the populations of PHEVs and HEVs are much larger than BEVs in the current trajectory scenario (e.g. the US and India), a gradual phase-out of conventional vehicles sees the opportunity for the diffusion of PHEVs and HEVs, due to the strong path dependence of technological diffusion. Meanwhile, a ZEV mandate that requires automakers to produce and sell a certain number of BEVs is a more direct measure for encouraging a rapid diffusion of BEVs. Given BEVs have no tailpipe emissions, more emissions reductions can be achieved with a ZEV mandate when it is combined with a gradual tightening of fuel economy regulation over the simulated period.

Figure 54: Simulations of strong regulations and ZEV mandates. Column A shows simulated scenarios of fleet composition assuming the adoption of ZEV mandates on top of taxes and subsidies. Column B shows the simulated scenarios of fleet composition assuming the adoption of a gradual tightening fuel economy regulation to phase out ICEVs, in addition to taxes and subsidies.¹⁶⁸



¹⁶⁴ Axsen, J. et al. (2020). Crafting strong, integrated policy mixes for deep CO2 mitigation in road transport. *Nature Climate Change* 10: 809–818. <https://doi.org/10.1038/s41558-020-0877-y>

¹⁶⁵ Bhardwaj, C. et al. (2020). Why have Multiple Climate Policies for Light-Duty Vehicles? Policy mix rationales, interactions and research gaps. *Transportation Research Part A: Policy and Practice* 135: 309–326. <https://doi.org/10.1016/j.tra.2020.03.011>

¹⁶⁶ Lam, A and Mercure, J-F. (2021). Which Policy Mixes are Best for Decarbonising Passenger cars? Simulating Interactions Among taxes, Subsidies and Regulations for the United Kingdom, the United States, Japan, China, and India. *Energy Research and Social Science* 75. <https://doi.org/10.1016/j.erss.2021.101951>

¹⁶⁷ Lam, A and Mercure, J-F. (2021). Which policy mixes are best for decarbonising passenger cars? Simulating interactions among taxes, subsidies and regulations for the United Kingdom, the United States, Japan, China, and India. *Energy Research and Social Science* 75. <https://doi.org/10.1016/j.erss.2021.101951>

¹⁶⁸ Lam, A., Mercure, J-F (2022). Evidence for a Global Electric Vehicle Tipping Point. GSI Working paper series number 2022/01. https://www.exeter.ac.uk/media/universityofexeter/globalsystemsinsitute/documents/Lam_et_al_Evidence_for_a_global_EV_TP.pdf

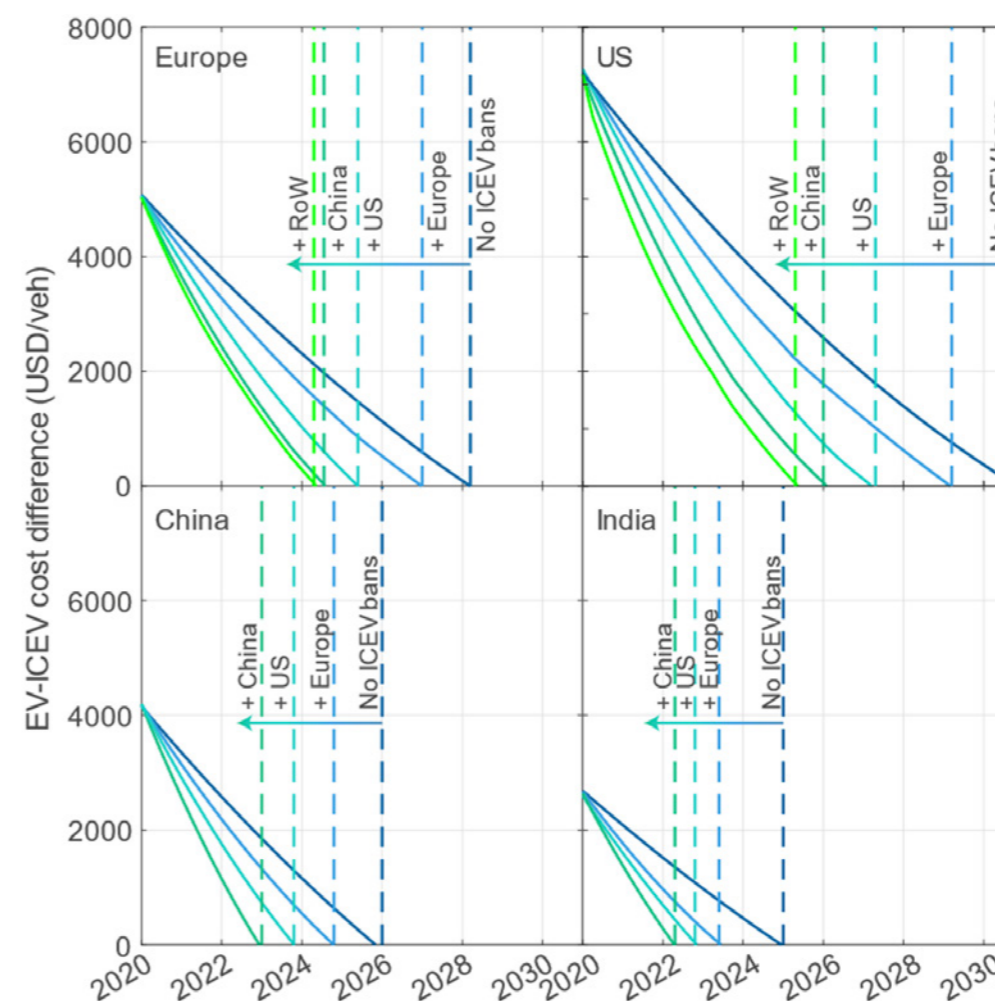
International coordination brings forward BEV cost parity

The Breakthrough Agenda, agreed by 45 countries at COP26 in Glasgow, aims to see countries coordinate their actions to accelerate the development and deployment of clean energy technologies in order to bring down their costs more quickly. Even with recent successes of EV deployment in the leading markets, reaching a trajectory consistent with climate targets requires strong policy action from all countries.

Figure 55 shows the cost differences between BEVs and ICEVs in different scenarios of international cooperation by the leading markets. Assuming that no regions implement strong policies towards all new vehicles being zero emission induces the slowest rate of BEV cost reductions. The adoption of policy frameworks that achieve 100 per cent of new vehicles being zero emission by 2035 in the leading

markets (Europe, the US, China) brings forward the year at which cost parity is achieved by two to five years in Europe, the US and China, significantly increasing the chances of meeting climate targets. In this simulation, we implicitly assumed that the battery and EV production capacity is sufficient to meet the demand for EVs that results from this policy. Meanwhile, BEV adoption in the rest of the world could enable further expansion of production, and drive costs down even further in the leading markets. This coordination gain justifies strong and coordinated action between the major markets, and financial and technical support to promote BEV deployment in developing countries. Due to diminishing returns in price reductions, early policy success has a larger effect on accelerating cost reductions. This suggests that policy action in Europe, China and the US could be particularly important in enabling transitions to ZEVs in the rest of the world.

Figure 55: International cooperation brings forward cost parity. Analysis of cost parity between ICEVs and BEVs for different scenarios of international cooperation to bring BEV costs down. The more countries join in, the sooner the cost difference between BEVs and ICEVs reaches zero. The impact of adding the 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.¹⁶⁹



¹⁶⁹ Lam, A., Mercure, J-F (2022). Evidence for a Global Electric Vehicle Tipping Point. GSI Working paper series number 2022/01. https://www.exeter.ac.uk/media/universityofexeter/globalsystemsinsititute/documents/Lam_et_al_Evidence_for_a_global_EV_TP.pdf

A fast transition to ZEVs can lead to positive macroeconomic impacts, though this depends on the context

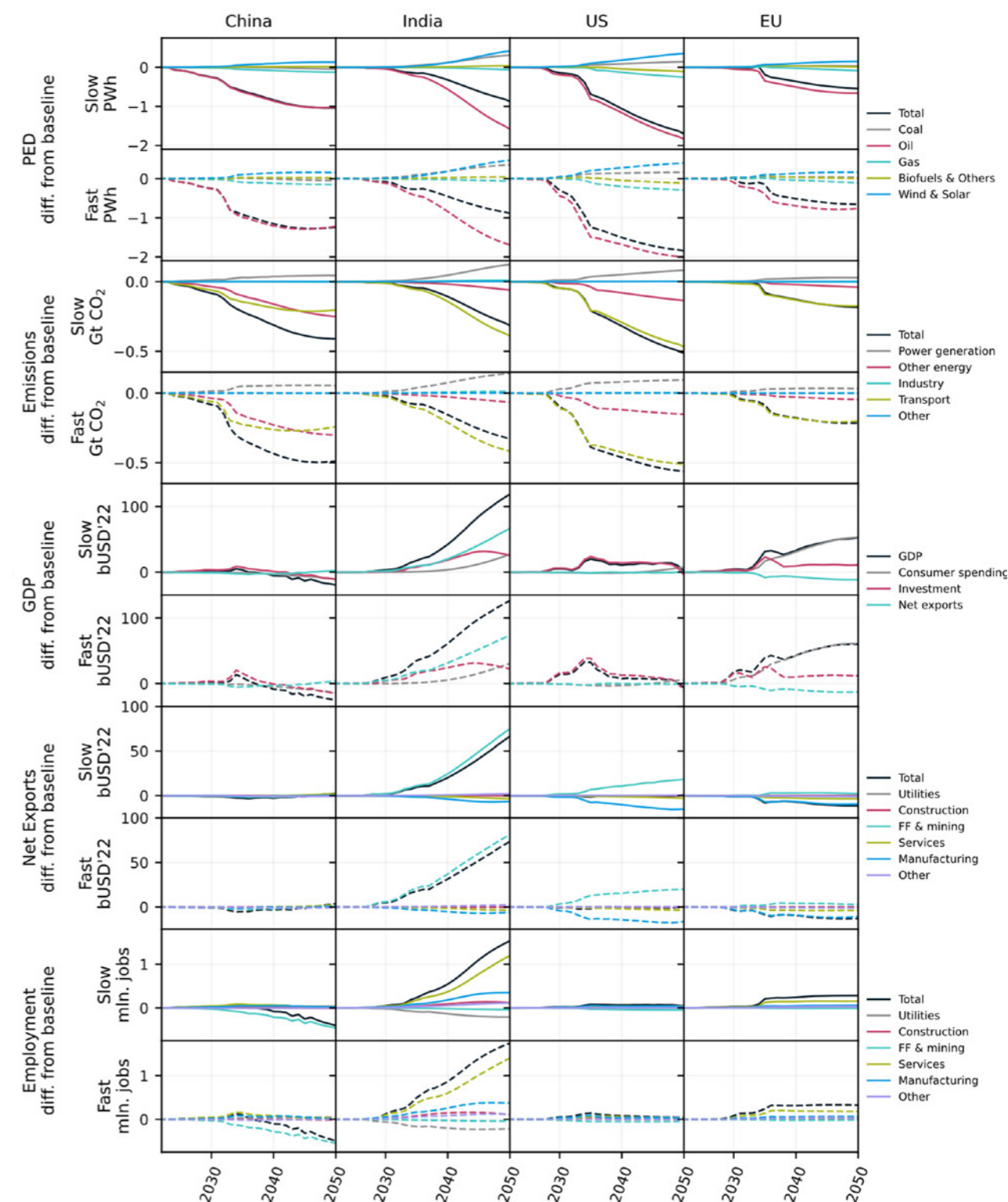
We used the E3ME model to investigate the effects of the transition to EVs and its pace on various macroeconomic indicators. Figure 56 displays the impacts of a slow and fast transition compared with the reference scenario where such transition does not occur. The top row displays the economy-wide differences in primary energy demand of both scenarios compared to the reference. Electrification of the vehicle fleet leads to a large reduction in the demand for oil, which is greater in the fast transition scenario. In China, oil demand in 2035 falls by 8 per cent in the slow transition and by 12 per cent in the fast transition, compared to the baseline scenario in 2035. In India, the equivalent numbers are 4 per cent and 8 per cent. However, the transition also requires additional electricity, which requires various primary energy sources. In all regions we note an increase in demand for electricity, which generally includes a mix of renewable energy and fossil fuels, depending on the local energy mix. This is reflected in power sector emissions, which increase in India and the US; however, this is more than offset by emission reductions in the transport sector and the fuel manufacturing sector (contained in the 'other energy' group). The reason for this is that fossil fuel electricity plants and electricity transmission together are generally more efficient than internal combustion engines of cars in generating movement.

Looking at GDP, we notice subtly different stories for each country. India and the EU show additional growth due to the transition to EVs, and the increase is higher in the fast transition scenario than in the low transition scenario (by US\$126bn2020 for India and by US\$60bn2020 for the EU, compared to the reference scenario in 2050). In contrast, the US and particularly China show lower GDP outcomes when undergoing a fast transition compared to the reference. China is the only region with negative

GDP impacts in the slow transition scenario as well. These results are driven via a combination of changes to consumer spending, industrial investments and net exports. Consumer spending is affected by employment, wages and prices. In China the model shows a large decrease in employment in the fossil fuel and mining sectors (particularly oil and gas) which suppresses consumer spending. Lower consumer spending leads to lower demand and therefore slows down investments, while net exports are also down, despite an interplay of fewer imports of crude oil and fewer exports of refined oil products. The story is the opposite for India. India relies much more heavily on crude oil imports than the other countries and so a decline in oil demand leads to improving the trade balance (expressed as net exports), leaving income to spend domestically, with consequent benefits for GDP and jobs. The US is a large producer of crude oil and refined products, and mainly sees negative impacts due to reduced crude exports. Finally, the EU is not a large producer of crude oil and it has sizeable oil-refining capacities to meet demand within its own market. Hence, the negative trade impacts are lower. Across all countries and scenarios, the bandwidth of relative GDP impacts is relatively small, ranging from approximately -0.1 per cent to +0.6 per cent.

An important limitation of the model is that it does not differentiate between economic activity and jobs generated through the manufacturing of EVs and those generated through the manufacturing of ICEVs. It also does not determine for each country whether EVs are imported or domestically manufactured. This means it does not capture the economic gains or losses that may arise through a country increasing or decreasing its share of global vehicle sales as the sector makes the transition from fossil fuels to EV technology. This may lead to an understatement of the economic benefits of policies that stimulate the growth of EV supply and demand within a country's domestic market.

Figure 56: Impacts of slow and fast transitions compared to the reference on primary energy demand (PED), emissions, GDP, net exports and employment.



Conclusion

With rapidly falling costs of batteries for EVs, cost parity with fossil-fuelled vehicles could be reached in many countries in the near future. Once cost parity is crossed, EVs could deliver substantial cost savings to the economy. Governments have an interest in identifying the policies that can maximise those savings.

An EV subsidy that closes the cost gaps between EVs and ICEVs can make EVs more attractive to consumers and can be made revenue-neutral with only a small tax on ICEVs. However, financial

incentives alone are not sufficient to drive a fast transition when individual preferences vary, and choices are limited. Policy measures such as ZEV mandates and efficiency regulations that increase the supply of ZEVs to the market can be more cost effective individually and can be used together with financial incentives to create highly effective policy packages. The transition towards EVs can be further accelerated through international coordination. The most significant macroeconomic consequence of the transition may be the reduction in oil consumption, which may affect countries positively or negatively depending on their status as an importer or exporter.

Table 10: Revenue-neutral approach to support the transition towards EV. a) EV subsidy required to break cost parity with ICEVs. b) Revenue-neutral tax levels in the leading markets in 2023.

| A. Subsidy required per vehicle in 2023 (US\$) | Europe | US | India |
|--|--------|------|-------|
| EV Low-cost | 0 | 1900 | 1000 |
| EV Mid-range | 1600 | 3000 | 0 |
| EV Luxury | 4800 | 4500 | NA |
| B. Revenue-neutral tax per vehicle in 2023 | Europe | US | India |
| ICEV lower-case | 0 | 90 | 7 |
| ICEV mid-range | 160 | 200 | 0 |
| ICEV luxury | 310 | 260 | NA |



EEIST

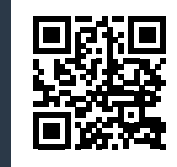
Economics of Energy Innovation and System Transition

The Economics of Energy Innovation and System Transition (EEIST) project develops cutting-edge energy innovation analysis to support government decision making around low-carbon innovation and technological change. By engaging with policymakers and stakeholders in Brazil, China, India, the UK and the EU, the project aims to contribute to the economic development of emerging nations and support sustainable development globally.

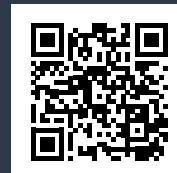
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