ELECTRIC VEHICLES WILL SOON LEAD GLOBAL AUTO MARKETS, BUT TOO SLOW TO HIT CLIMATE GOALS WITHOUT NEW POLICY

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EXECUTIVE SUMMARY

Electric vehicles (EVs) are increasingly considered the obvious technological successor to internal combustion engines (ICEs), and EV sales are growing exponentially, faster than projected.[1]

Six major incumbent automakers, including Volvo, General Motors, Mercedes-Benz, and Ford, have released specific plans and timetables for shifting to only zero-emission vehicle (ZEV) sales, and most automakers have announced at least some ZEV sales targets.[2] [ii] By 2021, automakers had developed more than 450 commercially available models—five times more than in 2015—and new models are on the way, boosted by more than half a trillion dollars in planned EV supply-chain investments.[3]

Policy support is also growing apace with consumer interest and automaker commitments. Major markets are increasingly covered by 100 percent ZEV sales targets, such as the European Union's and California's pledges to complete the transition by 2035.[4]

The last decade has seen a revolution in EV economics due to rapid battery innovation, causing the price of EV batteries to plunge by 89 percent in real terms.[5] As a result, today, in

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[ii] In this report, "zero-emission vehicle" refers to either EVs or hydrogen fuel cell electric drive vehicles. "Electric vehicle" refers to vehicles drawing on batteries for energy, either all-electric or plug-in hybrid vehicles. EVs' technological maturity and cost advantages mean they are expected to emerge as the dominant technology for reaching carbon neutral on-road vehicles, despite eligibility of hydrogen-fueled vehicles.

many places, total lifetime costs for EVs are less than for a comparable ICE vehicle due to EV savings on fuel and maintenance.[6] While EVs remain somewhat more expensive to purchase, the magnitude of up-front cost differences is shrinking. Within several years, most EVs are expected to cost less than comparable ICE cars.[7]

Such trends in sales and consumer sentiment, manufacturer investments, policy commitments, and economics have put transportation electrification in the fast lane, but is the ZEV transition on pace to be fast enough to meet climate goals? On that question, this report focuses on passenger vehicles and draws mainly on the International Energy Agency's (IEA) *Net Zero by 2050* study, which charts a path to energy carbon neutrality by mid-century, based on a 2035 timetable for completing the transition to zero-emission passenger vehicles (cars, SUVs, and vans).[8] A similarly paced transition for passenger vehicles is represented in BloombergNEF's mid-century carbon neutrality modeling, with passenger ZEVs capturing 100 percent of sales in 2038.[9]

While ZEVs are primed to take over global auto markets, success at a speed consistent with climate goals is not guaranteed without additional policy support. Solar and wind technology case studies illustrate the peril of insufficient policy support, particularly technologies with valuable social benefits that are insufficiently valued by markets, leading to the risk of deferred deployment and innovation.[10] Solar and wind technology case studies also provide reason for optimism that learning curve effects mean innovation and cost improvements will continue with greater EV deployment.[11]

Policy Recommendations

We recommend policymakers aim for ZEV shares of new passenger vehicles to reach 60 percent by 2030 and 100 percent by 2035, and still earlier in leading markets, based on IEA and BloombergNEF modeling. These goals are ambitious but achievable considering technological and market trends.

A policy roadmap to reach 100 percent ZEV sales is just as important as appropriately ambitious timelines for completing the transition. This report highlights new vehicle sales performance standards as a foundational avenue to accelerate EV sales consistent with achieving climate goals.

New vehicle sales performance standards for decarbonization come in two varieties, ZEV sales and tailpipe greenhouse gas (GHG) emissions, both setting compliance requirements for vehicle manufacturers. Tailpipe standard approach is broader, setting GHG emissions requirements for all vehicles sold, creating an incentive for ZEV sales as they help offset higher emitting ICE vehicles. EU and United States federal policy use the tailpipe approach. ZEV standards set direct requirements for automakers to sell a steadily increasing percentage of ZEVs. Where possible, we recommend using both tailpipe and ZEV standards as is done in China and California.

New vehicle sales standards are critical but must be embedded within a portfolio of policies to support a fast enough ZEV transition, including consumer incentives, expansion of charging infrastructure, and bolster supply chain adequacy.

Considering buyers’ sensitivity to up-front cost differences, consumer incentives for EV purchases will be critical in coming years. By decade’s end most EVs will cost less than comparable ICE vehicles[12] but today new EVs typically have a higher sticker price without consumer incentives.

Policies to spur public charging infrastructure investment, whether through public funding or by inducing private investments, are also essential. Though much EV charging may take place at residences, sufficient public charging availability for convenient, long-distance travel is a precondition to mass adoption.

Policy supporting expanded supply-chain capacity in an environmentally responsible way, including increased critical mineral production, is another priority to support a rapid EV transition. Increasing investment in new critical mineral supplies on every continent provides a measure of confidence about the potential for additional supply.[13] Furthermore, the success of solar in surmounting silicon input constraints in the mid-aughts shows raw material bottlenecks are manageable.[14]

This report has a clear message for transportation policymakers attending the 27th Conference of Parties to the United Nations Framework Convention on Climate Change (COP27) meeting in Egypt.

While the extraordinary tailwinds propelling EV sales create potential for a surprisingly fast transition to EVs dominating the mainstream market, inadequate policy support could detour the EV transition. The urgency of fully leveraging transportation electrification’s decarbonization opportunity, combined with local air quality and public health improvements and economic benefits from EV supply-chain development, means the transition cannot be left to the invisible hand of the market.

We urge policymakers to support rapid EV deployment with smart, agile policies like those outlined in this report.

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INTRODUCTION

EV sales are surging and have emerged as a consensus favorite to become the new king of the road thanks to factors including consumer sentiment, automaker investments in ramping up EV supply, and government policies.

EVs have already entered the mainstream in the EU and China, capturing well over 20 percent of new car sales. BloombergNEF recently found that when individual markets pass a 5 percent EV sales threshold, as in the U.S. and 18 other nations, sales reach a mass adoption stage.[15]

Such empirical data and research insights from past technology transitions indicate the switch to EVs could happen surprisingly quickly, but success is hardly guaranteed. Current momentum could falter if market forces are left to manage the transition. The history of clean technologies shows transitions are not guaranteed. Solar power has fallen nearly 90 percent in cost since 2010, but these gains only followed policy interventions[16] after the technology languished out of commercial reach for decades.

The 2020s will be remembered as the decade EVs became the predominant automotive technology, but withdrawing policy support too early could delay the transition compared to what is possible. Considering the urgency of quickly reducing GHG emissions, the valuable public health benefits resulting from reduced fossil fuel combustion, and increasingly favorable economics, policy is clearly needed to optimize the transportation electrification revolution.

EVS PROMISING ROLE AS A DECARBONIZATION DRIVER

The Electrification Pathway to Motor Vehicle Carbon Neutrality

EVs are an example of electrification, whereby fuel use from carbon-intensive sources switches to electrical energy. All-electric vehicles draw energy from batteries and have no tailpipes or direct emissions from vehicle operation. Meanwhile, the GHG emissions associated with generating and delivering electricity are falling faster than any other major source of emissions.

In most places, EVs already offer a GHG emissions advantage even in locations with more carbon-intensive electricity grids. Consider the U.S., where 97 percent of people live in places where connecting an EV to the local electricity grid reduces emissions.[17] The U.S. also exemplifies the global trend of improving carbon intensity in electricity generation, with the sector’s technology mix falling from 45 percent coal in 2009 to 23 percent in 2019, while renewables increased from 2 percent to 9 percent.

Transportation is currently responsible for about 15 percent of total global GHG emissions.[18] Considering carbon dioxide emissions from energy alone, transportation’s share of the global total rises to 25 percent, and has grown at a faster rate than other energy end uses for decades.[19] Road vehicles are the source of 75 percent of transportation sector GHG emissions.

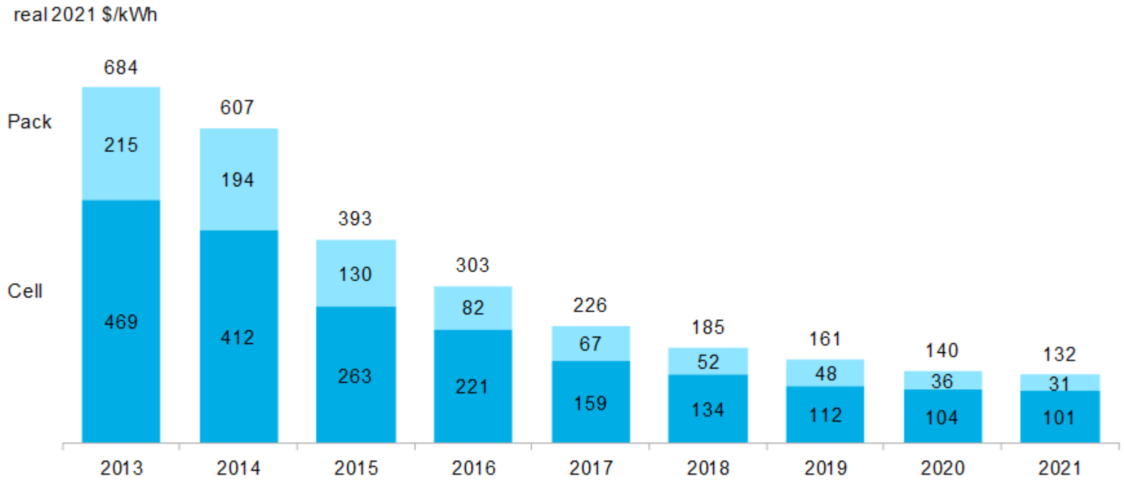
EV decarbonization benefits are already observable in global trends. Global GHG emissions from fossil energy combustion are set to increase by 1 percent in 2022, compared to 6 percent in 2021.[20] The IEA is unequivocal in crediting transportation electrification as one cause of the faster-than-expected improvement, stating, "Thanks to record deployment of renewables and EVs, the CO_2 intensity of the world's energy supply is improving again."[21]

The IEA's *Net Zero by 2050* pathways depends upon reaching 100 percent ZEV sales by 2035 for light-duty passenger vehicles.[22] A similarly paced transition for passenger vehicles is required in BloombergNEF's analysis of the most favorable path to mid-century carbon neutrality, with ZEVs capturing 93 percent of the passenger vehicle market in 2035, growing to 100 percent in 2038.[23] The transportation sector findings of *Net Zero by 2050* directly inform this report's recommendations, providing the basis for the recommendation that policy design aim for a full transition to ZEVs no later than 2035.

Battery Innovation Has Changed EV Economics, Delivering Affordability

Rapid innovation and falling battery prices have changed the economics of EVs because batteries are the main driver of purchase price differences between EVs and ICE vehicles. Figure 1 illustrates the 89 percent reduction in real cost of a volume-weighted market average price for EV battery storage, graphing annual average price from 2010 to 2021.[24] Thanks to battery learning curve effects and the fuel and maintenance savings EVs generate over time, total lifetime costs for EVs are often less than for a comparable ICE vehicle.[25]

Figure 1. EV battery prices have fallen rapidly (89 percent reduction from 2010 to 2021)



Source: BloombergNEF[26]

One challenge in EV-to-ICE cost comparison is accounting for the large share of Tesla vehicles in overall EV sales. Tesla's early dominance skewed EV sales toward the market's luxury segment. As a result, use of unadjusted-sales-volume-weighted average comparisons of EVs to conventional cars leads to mismatched luxury levels, with the EV estimate including a higher share of luxury vehicle amenities.

A 2020 Consumer Reports study provides a textbook example of how to avoid the potential risk of apples-to-oranges comparisons in EV cost analysis. The analysis compares lifetime costs for EVs to the best-selling ICE vehicles in class, showing net savings averaging $8,800 per vehicle, ranging from $3,000 to $17,600 per EV-ICE best-in-class pairing.[27] These findings are based on a standard methodology that discounts the value of future fuel and maintenance savings as part of the study's net present value calculation of ownership cost.[28]

Lifetime cost, accounting for 15 years or more of operational savings, is an appropriate frame of reference for evaluating EV costs, considering the intergenerational policy choices climate change necessitates. Another common perspective is private cost of ownership, netting costs and benefits over an average ownership period, referring to the time between vehicle purchase and resale. For example, in the U.S., six years is a typical length of ownership assumption.[29]

The operational cost advantage for EVs is not fully reflected in the shorter time horizon included in ownership cost assessments. Still, EVs have already surpassed the milestone of better ownership affordability in some places. In the U.S., three ownership cost analyses find many EVs now cost less to own than comparable ICE cars when factoring in consumer incentives.[30] A recent International Council on Clean Transportation (ICCT) study, comparing a generic 300 miles all-electric car to a similar ICE vehicle, excluding vehicle incentives, finds EVs are on the cusp of reaching private ownership cost parity, and should surpass this milestone in 2024.[31,iii]

The last affordability hurdle for EVs is purchase price. The magnitude of up-front cost differences for EVs compared to conventional cars is shrinking. For several more years, however, there is a risk that up-front cost differences could be a barrier to adoption, necessitating policy interventions discussed under Policy Recommendations. Ultimately, trends in battery innovation and cost, further analyzed under the first part of the Additional Tailwinds section, promise that EVs will surpass the milestone of beating ICE cars on purchase price, too.

Public Health Co-Benefits

Policies supporting EV deployment have valuable public health benefits due to reducing fossil fuel combustion. In some places, such as China, air quality and public health will be the most significant policy impact.[32] Despite recent adoption of stronger vehicle emissions standards in most major

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[iii] To see the crossover point, refer to the study's Figure 7, which shows EV ownership's net present value of costs and benefits becoming positive in 2024.

vehicle markets, the transportation sector remains a major contributor to the air pollution disease burden globally.

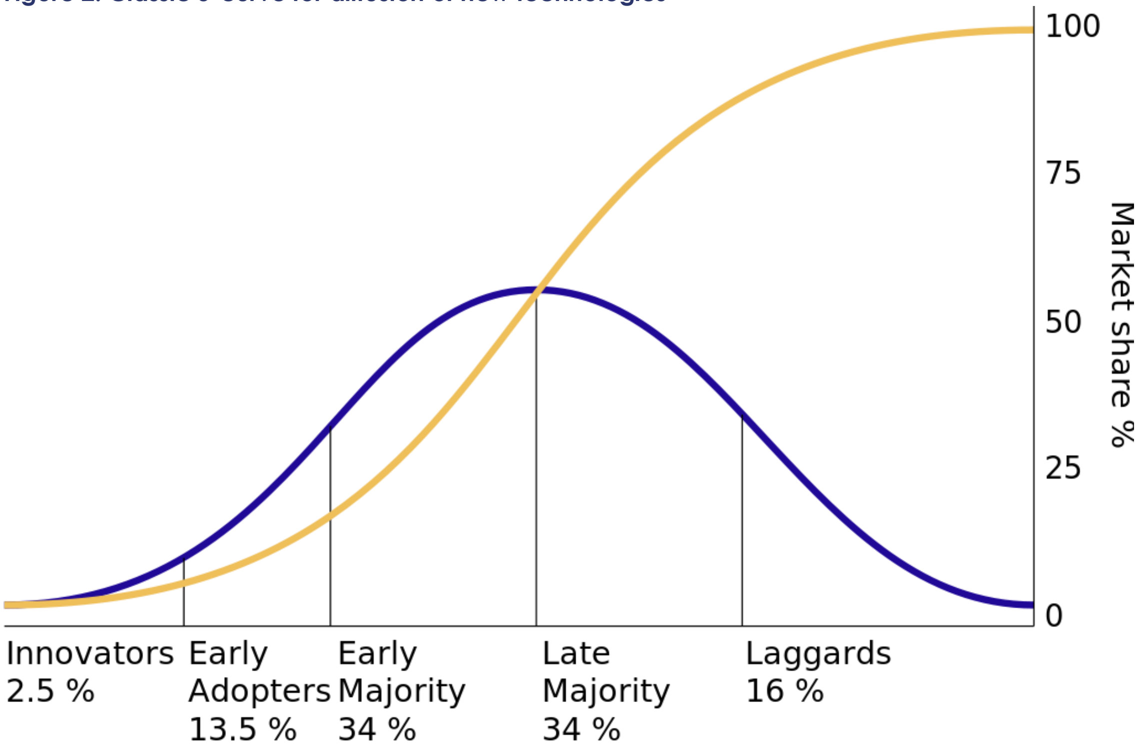
A 2019 ICCT report is the most current global snapshot of health effects from transportation. It found motor vehicle tailpipe emissions were responsible for 385,000 premature deaths in 2015.[33] The ICCT's work is based on a downscaling of total premature mortality from pollution due to fossil fuel combustion, which was estimated at 3.8 million globally in 2015.

Other research on the health damage due to overall fossil fuel combustion points to broadly similar impacts, bolstering the ICCT's transportation burden estimate. Research published in the *Proceedings of the National Academy of Sciences* found a similar global total, estimating 3.6 million premature deaths occurred in 2019 due to the burning of fossil fuels.[34]

Technology Tipping Points

The modern interdisciplinary science of technology transformations can be traced to Everett Rogers' *Diffusion of Innovations*, first published in 1962 and still foundational 60 years later.[35]

Figure 2. Classic S-curve for diffusion of new technologies



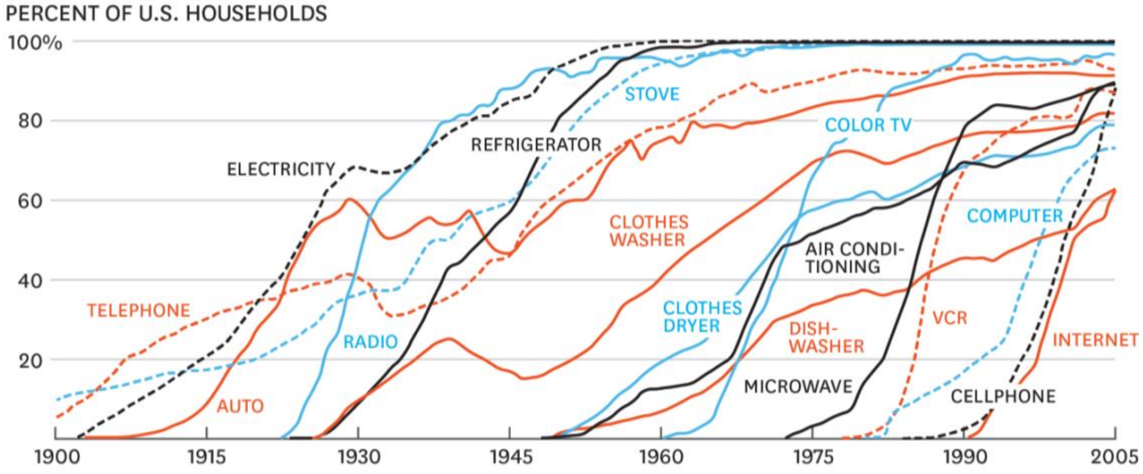
Source: Rogers[36]

Rogers identified a common pattern by which new technologies displace outdated ones. In the early phases of technological change, uptake is slow because of behavioral and systemic factors. Behavioral factors include people's familiarity with the incumbent technology and initial resistance to change due to risk aversion. Systemic factors are economic and technological circumstances that create disincentives to diverge from the incumbent technology. For example, the existing network of petroleum-fueling systems creates a systemic barrier to transportation electrification.

Eventually new technologies reach an inflection point—the onset of what Rogers labeled the "early majority" stage of adoption, characterized by fast exponential growth. Later, the rate of adoption decelerates as those most inclined to embrace the new technology do so. In the last stages of a technological transition, only people or businesses most resistant to a new technology remain, whom Rogers called "laggards," responsible for further deceleration of diffusion in its final stage.

These five phases are shown in Figure 2, above, which also illustrates why such technology diffusion graphs are often called S-curves: The yellow line graphing cumulative adoption traces a curve akin to the shape of the letter S. The percentage values noted for different stages are based on Rogers' assumption of a standard normal distribution for the underlying population.

Figure 3. Technology transitions from the telephone to the internet



Source: Harvard Business Review[37]

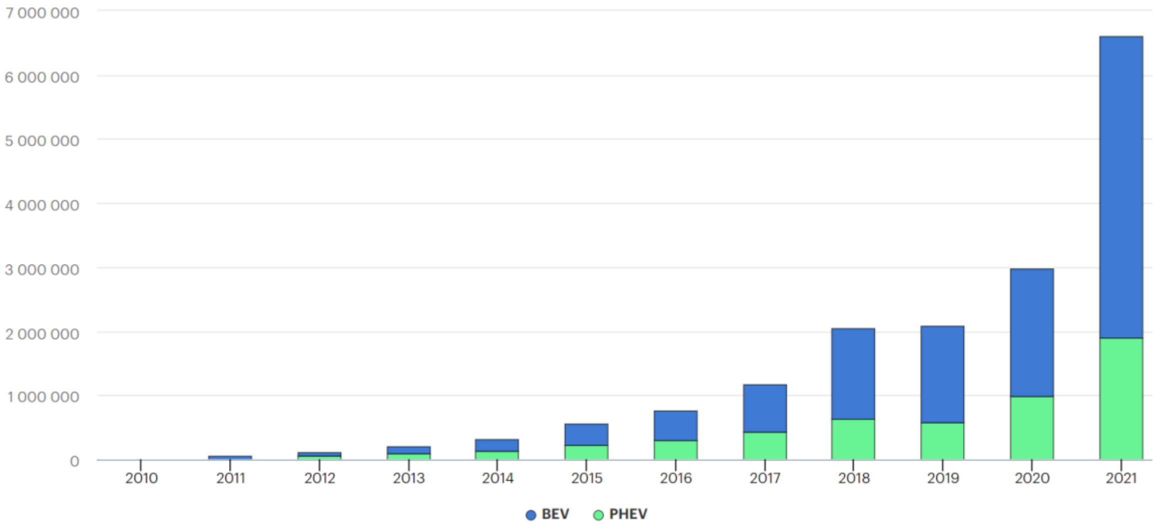
Figure 3 collects 16 technology curves, illustrating the variability introduced by real-world factors, while also effectively illustrating the principle of technology takeoff points and the regularity of S-shaped curves in technology transitions.[38]

EVs Past the Tipping Point

The IEA is not prone to flashy prose but sums up sales trends in EVs with the evocative phrase: "Passenger electric cars are surging in popularity."[39] Indeed, 2021 saw sales more than double from 2020 levels. EV sales are on track for continued growth in 2022 with high confidence based on trends so far. The IEA estimates EVs will account for 13 percent of global car sales in 2022, up from 8.6 percent a year earlier.[40]

China and Europe accounted for more than 85 percent of global EV sales in 2021, with the U.S. the next-largest global contributor at 10 percent (representing about 630,000 EVs sold). That year, EV sales captured a slightly larger sales share in China: 15.4 percent compared to 14.8 percent in Europe. In unit terms, Europe notched 2.3 million EVs sold compared to 3.3 million in China in 2021, lagging in absolute terms, but with a higher level of EV sales per capita. EVs are expected to account for a quarter of new car sales in China in 2022 and reached 29 percent there for the month of September.[41] Norway is the global leader in EVs, topping 80 percent of sales in 2021 and more than 90 percent in some months.

Figure 4. Global passenger EV sales by powertrain: battery electric (BEV) or plug-in hybrid (PHEV)

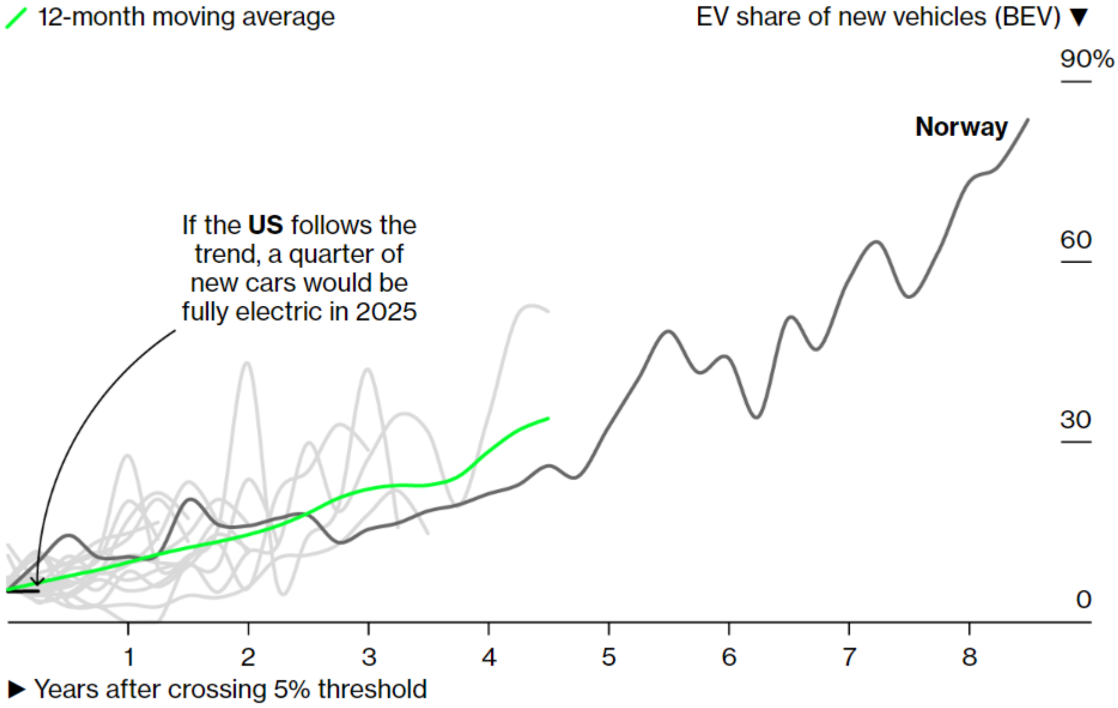


Source: IEA[42]

Considering sales trends in leading markets and using a conceptual framework drawing on the tradition of research discussed in the Technology Tipping Points discussion above, a recent BloombergNEF analysis concludes EV sales are at a takeoff point globally and in the U.S. Analyzing EV sales in 19 leading countries, BloombergNEF identifies a 5 percent EV sales threshold for when exponential growth begins and calculates an international trend—the green-shaded "12-month moving average" curve in Figure 5.

In the fourth quarter of 2021, new car sales in the U.S. and the sum of global new car sales passed the 5 percent threshold, which will jump start faster adoption. Extrapolating based on the aggregate adoption curve, BloombergNEF projects EVs will make up 23 percent of global and U.S. passenger vehicle sales in 2025, and more than 50 percent by 2030.[43]

Figure 5. BloombergNEF's adoption curve after passing the 5 percent EV sales threshold



Source: BloombergNEF[44]

Future EV Sales Forecasts

We draw on the IEA's *Global Electric Vehicle Outlook* for insights into future trends. IEA modeling develops three different forecasts of expected future EV sales, each anchored by different assumptions about how public policy will evolve in the future.

(1) The **Stated Policies Scenario** reflects the effects of implemented transportation policies already established in regulation or specified by law.

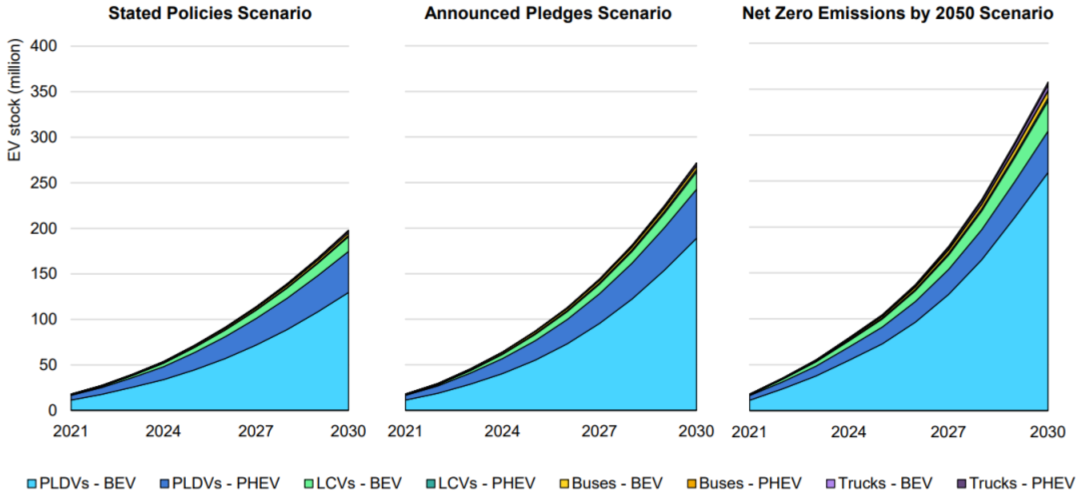
(2) The **Announced Pledges Scenario** includes effects of policy commitments even if these are not yet backed by the force of law or specific implementing policy. For example, this scenario models the expected impacts of 19 countries pledging at COP26 to reach

100 percent zero-emission cars and vans between 2035 and 2040, even in instances where the policies needed to accomplish this goal remain undefined.

(3) The **Net-Zero Emissions by 2050 Scenario**, as has been discussed, achieves energy carbon neutrality by mid-century, offering an even chance of staying under the dangerous 1.5°C threshold for global warming.

The results of EV deployment under the three future policy scenarios are depicted in Figure 6, showing the growth in EV stock, i.e., vehicles on the road, under the three scenarios.

Figure 6. Future EV deployment with differing policy support[iv]



Source: IEA[45]

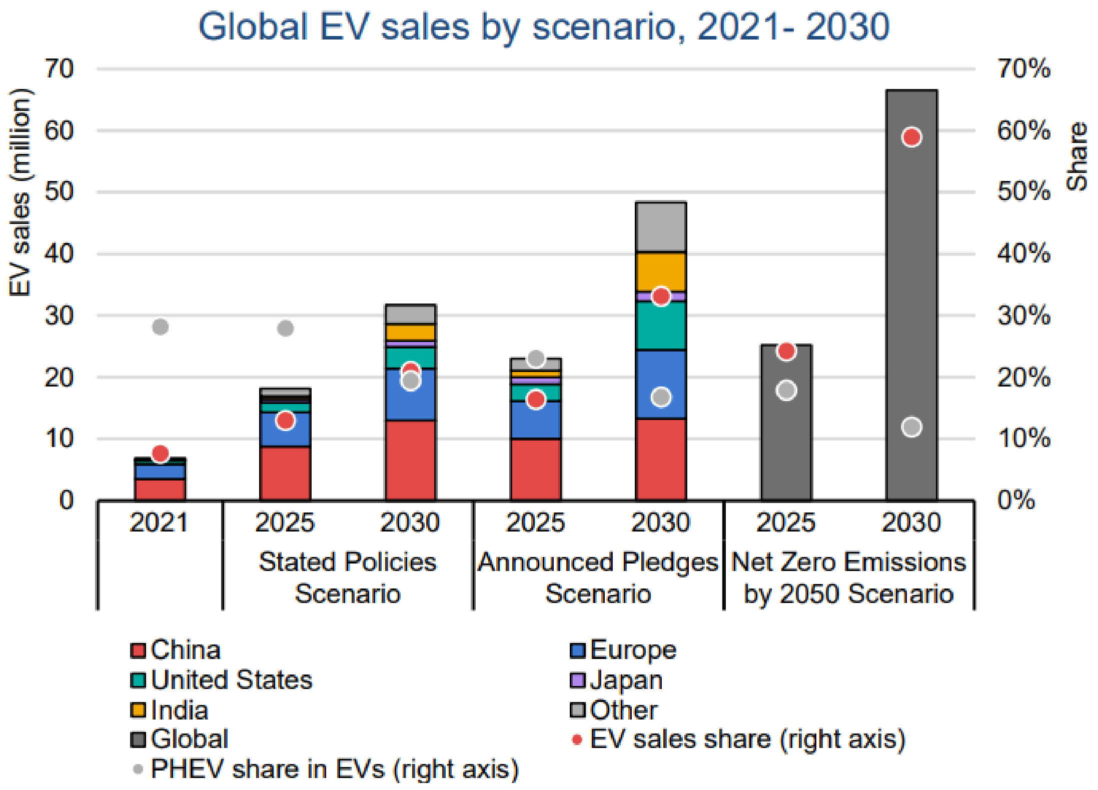
Figure 6 shows passenger EV stock in 2030 reaching 175 million in the Stated Policies Scenario, 240 million in the Announced Pledges Scenario, and 300 million in the Net Zero by 2050 Scenario. The results underline the difference governmental support can make for EVs, with stronger policy causing 50 percent more EV deployment than in the Stated Policies Case.

Figure 7 provides additional metrics, including a breakdown of EV deployment by geography and sales shares. EV deployment geography is observable in stacked columns, which indicate more EV sales are expected in China than anywhere else. This result is observable in Figure 7, since the height of the red-shaded band of each column representing EV sales in China is always tallest. European sales, the blue band in each stacked column, are projected to be the second largest.

[iv] PLDV stands for passenger light-duty vehicle, which includes cars, SUVs, and vans. PHEV refers to plug-in hybrid electric vehicles, including both electric and combustion engine powertrains. BEV stands for all-electric vehicles. Note that these EV stock results include not just the passenger vehicles that are the focus of this report but also trucks and buses. EV truck and bus stocks are more than an order of magnitude smaller than passenger EV stocks, which leads to EV deployment—shaded blue—visually dominating results for trucks and buses.

Figure 7 also charts EV sales shares using the right-hand side axis and round markers, colored red for all ZEVs (including both fully electric and plug-in hybrid EVs) and gray for plug-in hybrids alone. The graphic presents snapshots of 2025 and 2030 results, which readers may compare to 2021 empirical data at the far left. Focusing on 2030 results, this analysis forecasts an EV sales share of around 20 percent in the Stated Policies Scenario, more than 30 percent in the Announced Pledges Scenario, and nearly 60 percent in the Net Zero by 2050 Scenario.

Figure 7. EV sales shares and geographic composition forecasts



Source: IEA[46]

Finally, Figure 7 illustrates the expected declining role of plug-in hybrids, which comprised 30 percent of EV sales in 2021. The prevalence of plug-in hybrids falls most precipitously in the Net Zero by 2050 Scenario, with EV sales composed of almost 90 percent all-electric EVs and 10 percent plug-in hybrids in 2030, from 28 percent plug-in hybrids in 2021.

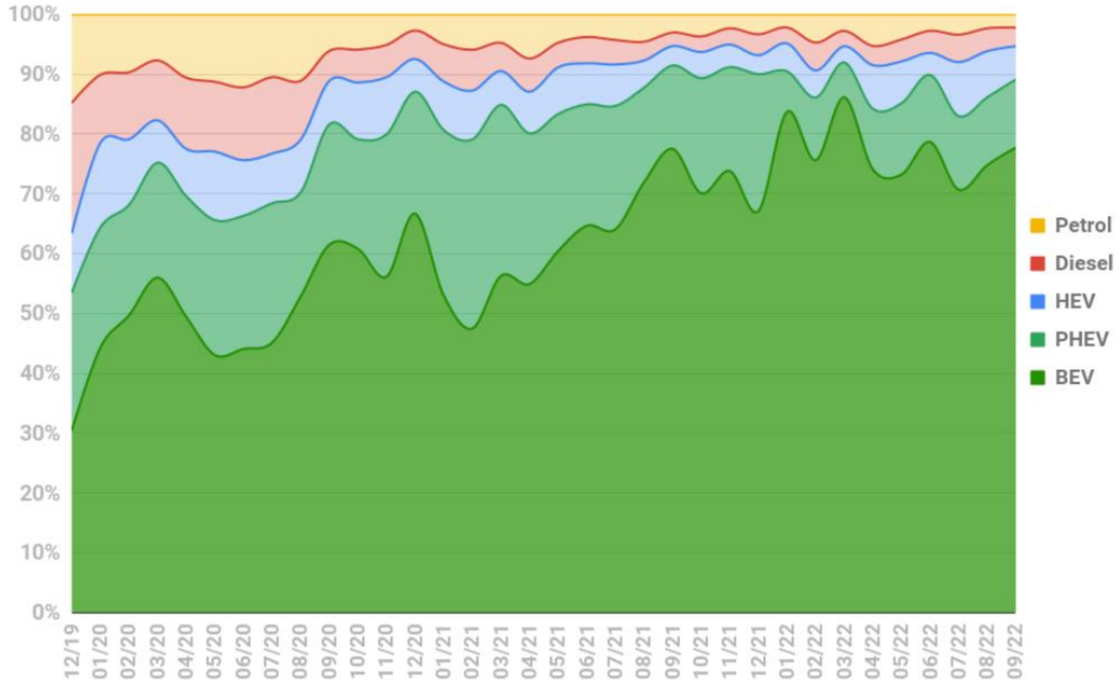
POLICY'S ROLE IN EV UPTAKE SO FAR

"Ambitious policy announcements have been critical in stimulating the electric mobility transition in major vehicle markets," concludes the IEA, in discussing the reasons for EVs' technological and market progress so far.[47] This exploration of policy's role in the rise of EVs so far begins with a Norwegian case study that helps illustrate the role for consumer incentives. Next, we present a brief history of ZEV sales standards. First developed in California, ZEV standards were later embraced in China and were pivotal to Tesla's emergence. Next, we explore a different type of new vehicle policy, tailpipe standards. Some places, such as Europe, are using tailpipe GHG standards as important driver of EV deployment.

A Norwegian Case Study Highlighting Consumer Incentives

Norway has distinguished itself for its vehicle market's rapid shift to EVs, which have captured more than 90 percent of new car sales in recent months and more than 80 percent of annual sales in 2021. Consumer incentives have played a central role in the country's rapid transition, shown in Figure 8.

Figure 8. Technology shares for new passenger vehicles in Norway (monthly sales data)



Source: Holland[48]

Norway provides the strongest financial incentives for EVs of any major country, including completely exempting EV purchases from a 25 percent value-added tax at time of sale. The value-added tax exemption is a powerful monetary advantage, but just one of several financial inducements, including exemption from annual road fees and discounted parking and ferry fares. Norway's electricity is also moderately priced, further bolstering the EV cost advantage.

In addition to showing the power of consumer incentives, Norway's experience demonstrates the value of a multipronged strategy. The nation's policy portfolio has also included developing and investing in a nationwide charging infrastructure network,[49] offering non-monetary benefits[50] such as permission for EVs to drive in bus lanes, and public communication efforts to encourage consumer acceptance.[51]

A Brief History of ZEV Sales Standards

A ZEV sales standard is a performance standard requiring automakers to reach steadily increasing fractions of ZEVs in new vehicle sales over time. The world's largest car market, China's, uses a ZEV sales standard, stemming from decades of dialogue between Chinese and Californian policymakers and researchers. California's efforts were an inspiration for China's, whose "policy is ... a modified version of the California ZEV mandate."[52]

The history of ZEV sales dates to 1990, when the California Air Resources Board adopted the first such policy, which was originally conceived of as a purely local air quality measure.[53] Initially, the state's sectoral decarbonization efforts prioritized tailpipe emissions. In recent years, ZEV sales standards have emerged as the centerpiece of the state's decarbonization strategy. In August 2022, Advanced Clean Cars regulatory updates significantly accelerated ZEV targets, reflecting surging sales. Though this report focuses on passenger vehicles, we note California has also applied ZEV sales standards to commercial vehicles in the 2020 Advanced Clean Trucks policy. In 2022, California's Advanced Clean Fleets policy extended the concept of zero-emission sales requirements to the demand side of the market.[v]

California's ZEV sales standard can be directly linked to Tesla's success. California policy has provided more than two-thirds of total monetary support for Tesla, with the ZEV sales standard responsible for the largest share. ZEV credits add up to an estimated $2.48 billion in monetary support for Tesla out of $3.2 billion from the California program's overall since 2009.[54]

Support delivered by California's ZEV sales standard was not just large, it was also timely. ZEV credits were an early source of cashflow, pushing Tesla into profitability in some quarters. Policy experts and financial analysts alike credit the ZEV policy with drawing Tesla to California and providing cash income at crucial early junctures, without which the company would have likely folded.[55] For example, financial analyst Johnny Ives concludes, "If it wasn't for those credits, Musk wouldn't be the richest person in the world today."[56] A similar view is expressed by Dan Sperling, founding director of the Institute for Transportation Studies at the University of California, Davis,

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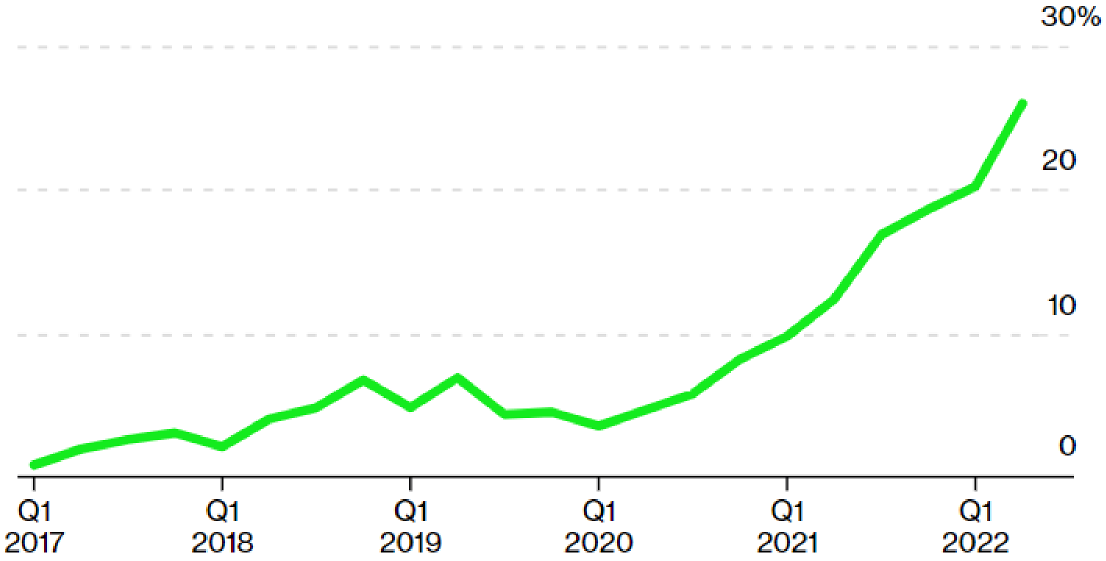
[v] California's Advanced Clean Fleets policy phases in a ZEV purchase requirement for commercial vehicle fleet operators, adopting a novel approach for supporting the demand side of the market in the transition to ZEVs. The policy supports consumer demand for clean commercial vehicles while reducing reliance on publicly expenditures, freeing up government revenue for other investments.

and member of the California Air Resources Board, who states: “Tesla would have gone bankrupt and disappeared without California’s ZEV mandate.”[57]

China has used ZEV sales standards as part of its broader EV policy strategy to great effect. China surpassed 1 million EVs sold in 2017—a level no other single nation has reached. Annual EV sales in China are expected to jump to around 24 percent on average in 2022, equivalent to second quarter sales results, shown in Figure 9.[58] September 2022 sales data show EVs reaching 29 percent of new car sales in China.[59]

Figure 9. EV sales in China reached 24 percent in 2022’s second quarter



Source: BloombergNEF[60]

We should not leave the impression that progress in China’s market is entirely due to its ZEV sales standard. Like Norway and other EV leaders, China also employs a broader portfolio approach. China advanced the state of the art in vehicle registration policy design to encourage EV adoption. Many large cities in China place strict limits on new car registration to reduce traffic congestion and pollution, with some cities establishing quota systems. Beijing distributes these by lottery, while Shanghai uses auctions. Several major cities, including Beijing and Shanghai, encourage EV sales through separate, more favorable quota systems for EVs.

Tailpipe GHG Emissions Standards in Europe and the U.S.

Tailpipe emissions standards that set a declining GHG emissions requirement over time for all vehicle classes are another design option for new vehicle standards to support EV deployment.

Federal policy in the EU and U.S. both employ a tailpipe GHG standard approach.[61] The connection between tailpipe standards and ZEV goals is clearest for the EU, which has proposed a series of standards establishing declining allowable GHG emissions, stepping down to zero in 2035.[62]

POLICY RECOMMENDATIONS

A successful rapid EV transition requires greater long run ambition and a concrete near-term action plan. The following discussion identifies key policy design principles to support transportation electrification at optimal speed and scale, spotlighting the importance of new vehicle sales standards.

More EV Transition Ambition Needed

Growing political and government commitments surround the EV transition, as indicated by two recent global agreements. First, the zero-emission coalition of 19 nations and dozens of automakers established in 2021 at COP26 in Glasgow set a common goal of a 2035-2040 timeframe for completing the transition.[63] Second, in 2022 officials from several of the world's largest new vehicle markets accounting for more than half of global vehicle sales created the Zero Emission Vehicles Transition Council. The Council includes large vehicle markets such as the U.S., Germany, and Japan, but members' commitment to accelerate the global transition to ZEVs does not include a specific timetable.[64]

Even stronger ambition is needed for an EV transition, considering the dwindling potential for Earth's atmosphere to absorb GHG emissions without dangerous consequences.[65]

We urge policymakers to recalibrate EV ambition upwards, aiming for a minimum of 60 percent ZEV sales in 2030, reaching 100 percent ZEV sales by 2035, consistent with the IEA *Net Zero by 2050* modeling for reaching global carbon neutrality by mid-century.

Leading nations—those beyond the 5 percent EV sales takeoff threshold BloombergNEF identifies—should target an even faster EV transition. For these countries, technology and market dynamics suggest the transition to ZEV-only sales should be achievable within a decade. Greater ambition will spur greater learning curve benefits, shortening the timeline for EVs to reach remaining economic milestones, such as purchase price parity.

The recommendation for leading nations to aim for a faster transition to 100 percent EV sales reflects the likelihood that some nations and markets are likely to lag. It is unlikely every market will complete the EV transition by 2035. By extension, putting a net-zero energy future by 2050 in reach requires leaders to do better than the 2035 global average target. Appropriate numerical targets will depend on the particulars of each nation's situation and are beyond the scope of this report.

New Vehicle Sales Standards Are Foundational

We spotlight new vehicles sales standards as the lynchpin of any effective portfolio of EV policies. There are two types of new vehicle standards, targeting either ZEV sales or tailpipe GHG emissions.

Some major car markets are expected to continue to use the tailpipe emissions approach exclusively, such as in Europe. In the U.S., tailpipe standards alone cover sales outside of California or the roughly ten states expected to pursue California's policy, likely to cover about 30-40 percent of national sales.[66]

While acknowledging the validity of the tailpipe approach, we recommend combining both tailpipe and ZEV sales standard for jurisdictions open to it as done by China and in California.

We next identify four design principals for using ZEV sales standards to send a clear signal about the future direction of the vehicle market, unleashing more investment, spurring learning curve effects, speeding emissions reductions, and generating additional economic and social co-benefits.

1. Set strong new vehicle standards, aiming for at least 60 percent ZEV sales in 2030

   Setting strong new vehicle standards will avoid new investments that entail emissions levels inconsistent with sustainability goals. Once consumers buy a car, they become invested in its continued use. This is the transportation sector equivalent to the technology lock-in and inertia in the energy system resulting from industrial capital stock turnover. The implication is that future decarbonization becomes more difficult if policy fails to discourage investments at odds with reaching carbon neutrality. More optimistically, a new vehicle purchase presents a high-value emissions reduction opportunity for public policy.

2. Employ a technology-neutral approach

   A technology-neutral approach focusing on zero-emission performance has advantages from both policy design and implementation perspectives.

   From the policy design perspective, a technology-neutral approach keeps the focus on performance and the ultimate end goal, i.e., the ability to eliminate tailpipe emissions. By broadly opening the range of solutions, technology-neutral policy design principles support the scope for innovation. In the case of ZEV sales standards, a technology-neutral approach allows EVs and hydrogen fuel cell vehicles to qualify. Though eligible, hydrogen fuel cell vehicles are not expected to seriously challenge EVs, except in a few niche circumstances.[67]

   A technology-neutral, zero-emission performance focus has implementation benefits by leveling the playing field for all technologies. In the absence of a technology-neutral approach, for example if EVs are solely eligible for a policy benefit, technological favoritism questions or concerns are more likely to arise.

3. Include flexibility mechanisms like a ZEV credit trading market, but recognize the need for limits, for example by discounting or disallowing carrying ZEV credits across compliance periods

Including flexibility mechanisms, such as the ZEV credit trading allowed under California's ZEV program, allows companies to pursue more economically efficient decarbonization pathways. Under such an approach, each automaker faces the same ZEV sales requirement, defined as the percentage of ZEVs out of total vehicle sales each year. However, compliance does not require each automaker to meet or exceed the standard. Automakers exceeding a given year's required level of percentage sales are awarded ZEV credits.[vi] Automakers failing to reach the required level must buy credits to make up for underperformance. This approach means the standard will be met on average each year, while allowing EV leaders to go faster.[vii]

Policymakers must also be on guard for excess flexibility, however, which can enervate the policy signal. In California, an unintended large bank of ZEV credits accumulated, inadvertently weakening annual targets, and requiring later adjustments.[68] Policymakers should consider containing the amount of banking of ZEV credits across compliance periods, or disallowing banking over time, to avoid larger-than-intended credit banks, which undermine policy effectiveness.

4. Set a schedule for future updates, anticipating a need for adaptive management

   Given the rapid pace of economic and technological change, policymakers face understandable challenges anticipating the maximum feasible rate of market transformation over decades. In anticipation that future strengthening will be desirable, we recommend establishing a schedule for future updates.

A Portfolio of Policies is Essential

Before exploring other essential parts of an effective EV policy portfolio, we acknowledge that even a broader portfolio of policies aiming to accelerate EV uptake leaves unexplored important swaths within transportation sector decarbonization. Sustainable urban design, including public transit and other transportation system investments, are key to delivering transportation efficiency and providing the mobility options people want, helping people avoid unintended car dependency, and cutting down on unnecessary travel.

Recognizing these bounds, we move on to consider additional policy imperatives to support a rapid, equitable EV transition. Evidence from leading markets points to the importance of several

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[vi] Companies producing only all-electric vehicles, such as Tesla or Rivian, will automatically receive ZEV credits as their sales are 100 percent ZEV

[vii] U.S. national tailpipe emissions standard policy also includes a flexible credit trading mechanism whereby automakers going beyond the minimum for compliance receive marketable CO_2 credits. Further detail available in Department of Transportation, "Corporate Average Fuel Economy Standards for Model Years 2024–2026 Passenger Cars and Light Trucks" (Federal Register Vol. 87, No. 84, May 2, 2022), https://www.govinfo.gov/content/pkg/FR-2022-05-02/pdf/2022-07200.pdf.

reinforcing policies, including consumer incentives, public charging infrastructure investments, support for supply-chain adequacy, and attention to equity considerations:[69]

1. **Provide financial incentives for consumers**

   A ZEV policy portfolio should include consumer incentives. The prototypical example is a rebate or tax credit improving an EV buyer's financial calculus. While electric cars will become less expensive to purchase than comparable ICEs over the next few years, for the time being, the average EV buyer would face higher up-front costs without incentives.[70] These cost differences are offset over time by operating cost savings from reduced fuel and maintenance expenses but provide a drag on EV deployment if left unaddressed.

   Since a new motor vehicle is an expensive purchase, whether electric or gas powered, many buyers borrow to finance their acquisition.[71] As a result, policies that expand access to favorable credit can also be an effective instrument for supporting EV buyers.

2. **Invest in charging infrastructure development**

   Though home charging may account for a large share of charging initially and EV range is steadily improving, broader access to electric charging is widely accepted as a precondition for widespread adoption of EVs.[72]

3. **Support supply-chain development**

   The EV transition will require a sufficiently robust supply of EVs in the local market. "Supply is already a larger constraint on adoption than demand in many countries," concludes BloombergNEF in its *EV Outlook 2022*.[73] Current supply shortfalls for EVs are more rooted in microchip shortages affecting the broader industry and spiking gasoline prices owing to geopolitical instability. Still, there is no doubt that building up critical mineral supply capacity is an essential aspect of EV supply-chain development, considering manufacturing EVs involves more critical minerals.[74] Policy will have to balance the imperative of environmentally and socially responsible development with the goal of encouraging more production.

4. **Promote an equitable transition through policies that broaden access and smooth the path for workers and communities most affected by the transition**

   Equity is integral to EV policy. For economic fairness, a ZEV strategy should include workforce development programs, helping to prepare workers for growing advanced energy industries, and an enhanced social safety net for those unable to successfully transition. A full treatment of the multifaceted intersections between fairness and EV policy is beyond our scope, apart from this brief consideration.

   Though EV owners are diversifying, they have tended to hail from higher-income households, stemming in large part from purchase price differences and early EV model offerings skewing toward luxury vehicles. To increase equitable access, the state of California developed the Clean Cars 4 All program to deliver targeted vehicle incentives. Only moderate- and lower-income households are eligible, and Clean Cars 4 All offers more support to households in the neighborhoods burdened by the heaviest pollution levels, delivering economic and air quality benefits. The program supports buyers of both new and used EVs, with incentives ranging from $5,500 to $9,500, plus up to $2,000 to install a vehicle charger.[75] Energy Innovation® found the program leads to an average savings of 40 percent on transportation costs for households qualifying for the maximum support, comparing used EV ownership costs to those of a comparable gasoline-fueled car.[76]

ADDITIONAL TAILWINDS ACCELERATING VEHICLE ELECTRIFICATION

Evidence shows EVs are primed to take over auto markets faster than many people realize, thanks to factors indicating passage of a technology tipping point. Below, we review the tendency of policy analysis to underestimate learning curve effects and then explore the emerging battery technologies that bolster confidence in continued robust innovation. Two further supply-side trends are profiled: first, the growing availability of EV models across vehicle types and classes, and second, the increasing supply-chain investment commitments. Finally, we cover rising consumer enthusiasm and intrinsic technology and design advantages to complete this section’s overview of economic factors favoring rapid vehicle electrification.

Learning Curves Still Being Underestimated

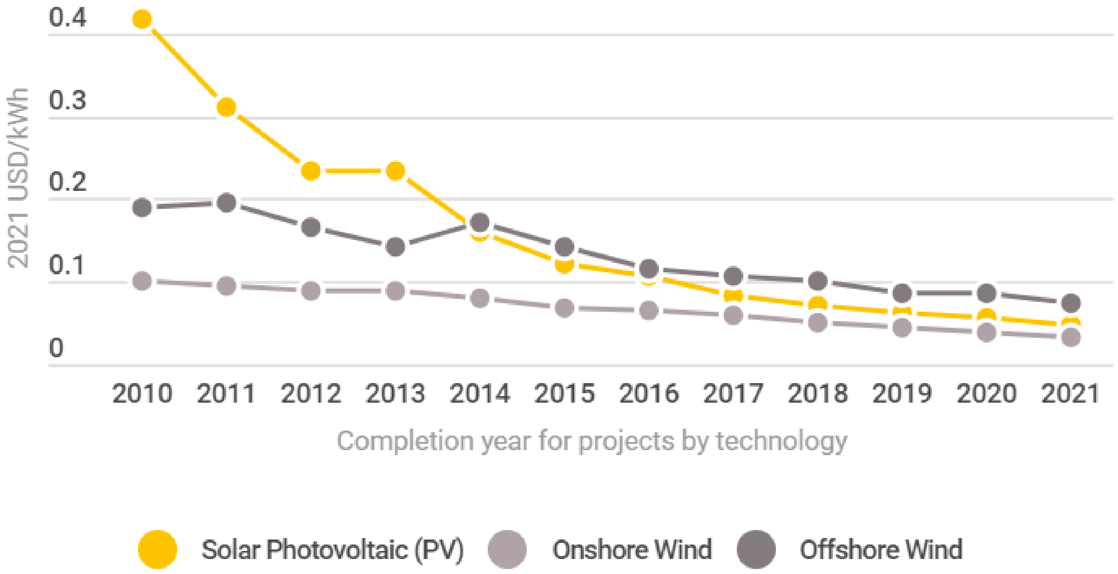
The concept of learning curves is crucial for decarbonization policy design in general, and especially for optimizing EV policy design. Learning curves capture the innovation and cost-lowering effects of economies of scale and learning by doing that come with greater production and experience with an emerging technology. Learning by doing simply refers to the discovery of better approaches, which may improve product design or production methods. Economies of scale reduce per unit production costs by spreading fixed costs of production over greater levels of output. Some factory investments will only be feasible once minimum production thresholds are crossed, creating another source of economies of scale.

Important learning opportunities exist beyond the lab and factory gate, too, in improvements to the application of emerging technology. Learning by doing may improve efficiency of installation and operation. For example, lower installation costs drove 14 percent of overall improvement in solar electricity costs 2010-2021.[77]

Over the last decade, learning curves have produced remarkable effects for solar, wind, energy-efficient LED lighting, and batteries. Figure 10 below illustrates learning curve effects for renewable technologies for electricity generation, focusing on solar PV along with onshore and offshore wind. The global weighted average cost of newly commissioned utility-scale plants declined 88 percent for solar PV, 68 percent for onshore wind, and 60 percent for offshore wind from 2010 to 2021.

These learning curve effects mean that the average cost of renewable electricity has fallen below the average cost of electricity from plants burning coal and natural gas across the globe.[viii,78]

Figure 10. Learning curves for renewables (levelized cost of electricity generation)[ix]



Source: International Renewable Energy Agency (2022)[79]

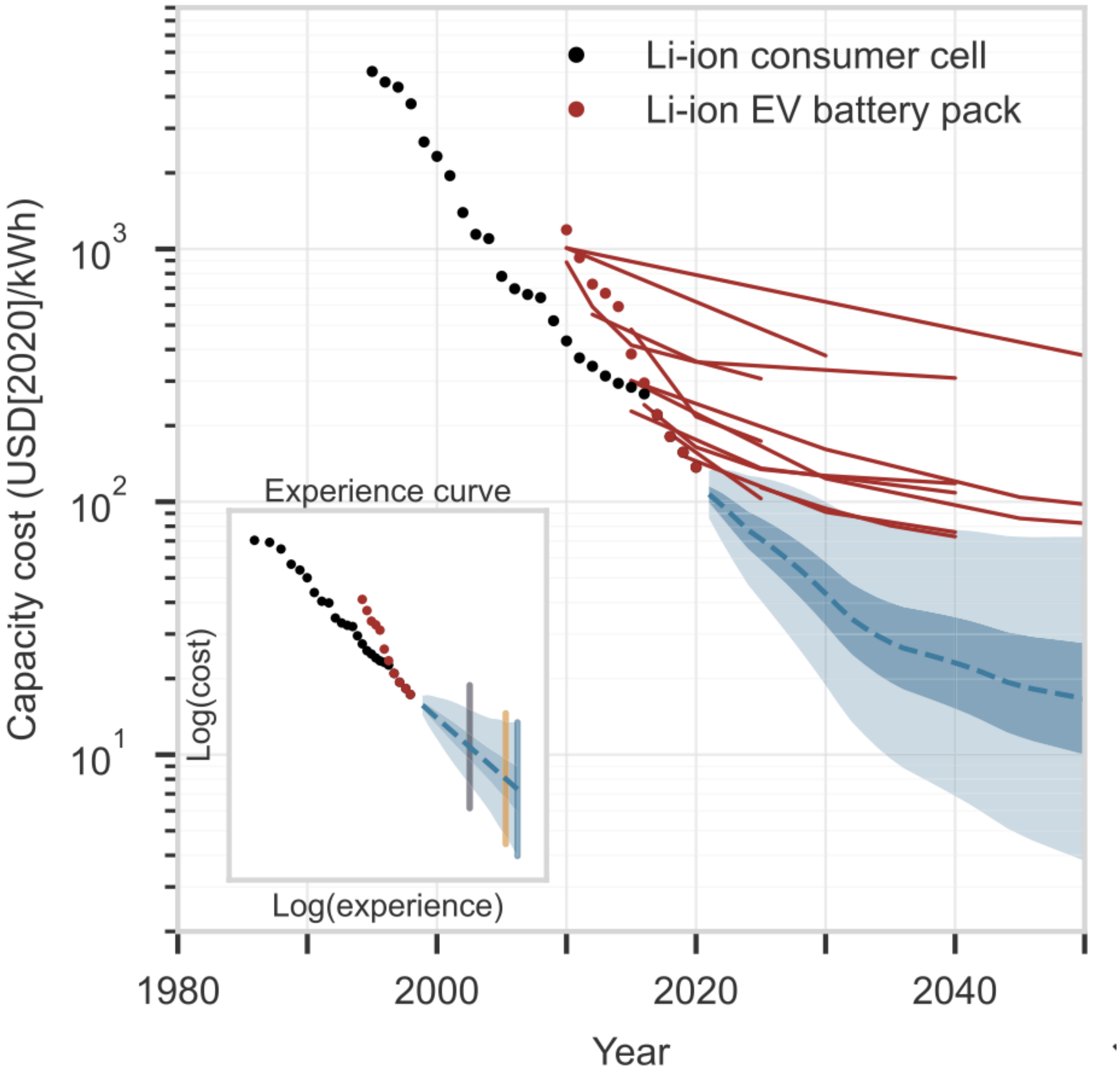
Policymakers should recognize that energy and transportation modelers have almost invariably underestimated future technological progress and associated price benefits for EV batteries as they have for other key decarbonization technologies. Recent, peer-reviewed research by Way et al. shows the persistent underestimation of future innovation for solar PV panels, wind turbines, hydrogen-producing electrolyzers, and batteries.[80]

Figure 11 reproduces Way et al.'s battery learning curve, denoting historical prices for lithium-ion (Li-ion) consumer battery cell prices and Li-ion EV battery packs with black and red data points, respectively, while red line segments trace historical forecasts for the most optimistic scenarios by leading energy-economy modelers such as the IEA.

[viii] See Figure S.2 in International Renewable Energy Agency, "Renewable Power Generation Costs in 2021," July 2022, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Power_Generation_Costs_2021.pdf.

[ix] Levelized cost of electricity is calculated as the ratio of the present value of total construction and operating costs over expected lifetime electricity generation.

Figure 11. Battery electric storage learning curve[x]



Source: Way et al.[81]

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[x] The larger graph charts price over time, a more accessible perspective but one that glosses over the fact that learning curves are properly understood as a function of cumulative production. The smaller inset graph uses cumulative production, instead of time, along the horizontal axis. Another difference relates to units, with the smaller inset graph using the logarithm of price along the vertical axis and the logarithm of cumulative production along the horizontal axis, creating what is known as a "log-log graph." In a log-log graph, a straight-line learning curve effect would represent a constant learning curve effect with increasing cumulative production, an advantage for visual intuition into learning curve effect trends over time.

This graphing of historical data alongside past forecasts of battery cell and EV battery pack prices reveals the persistent gap between actual and forecasted innovation for batteries.82 We observe this by comparing the steeper trajectory of empirical price reductions to the shallower slope of past forecasts, showing the most optimistic projections for each past forecast. Even compared to these most optimistic projections, actual battery innovation and price improvements exceeded the forecasted pace of technological progress.

New Battery Chemistries

Promising sources of learning curve effects for battery electric storage include emerging, next-generation options as well as more incremental innovation.

Starting with the latter, incremental improvements in current technology are expected from continued learning curve effects. Future investments in battery factories will dwarf those to date, yielding continued economies of scale in production.

Design improvements will also improve material efficiency, yielding lower production costs. For one example, advances in cell-to-pack technology eliminate the need for modules to house cells in the battery pack, simplifying and reducing input demand—a material efficiency benefit.[83]

Advances in cell-to-pack technology have reduced pack deadweight, important because batteries currently make EVs heavier than their conventional counterparts. The average lithium-ion EV battery pack weighs 1,200 pounds. Large battery packs are a drag on energy efficiency and take up significant interior vehicle space. To address this, researchers around the world are pursuing, and regularly achieving, ever-greater energy density—the amount of energy that a given mass of battery material stores.

Cell-to-pack technology has improved the energy density of lithium-ion phosphate batteries, leading to the resurgence of this battery chemistry option, and countering the trend toward nickel-based batteries. Since 2017, nickel-based batteries have captured a growing share of the market. Nickel-based batteries composed more than 90 percent of the EV battery market in 2020. However, lithium-ion phosphate batteries' market share more than doubled in 2021, up from 7 percent of the market in 2020 to 15 percent in 2021, meaning the share for Nickel-based batteries declined to 85 percent.[84] [xi]

A promising innovation aims to solve a hitherto unmanageable chemical reaction, which had previously blocked the substitution of metal electrodes for the conventional graphite. The metal electrodes advance offers a significant leap in the power per weight of next-generation batteries, without sacrificing battery life. The advance was made by Massachusetts Institute of Technology

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[xi] For more detail, see the table entitled, "High-nickel cathode battery chemistries remain dominant though lithium iron phosphate is making a comeback," in IEA, *Global EV Outlook 2022*, May 2022, https://www.iea.org/reports/global-ev-outlook-2022, at 137.

researchers, who estimate it could increase the energy density of lithium-ion batteries by 60 percent, from storing about 260 watt-hours per kilogram to storing roughly 420 watt-hours per kilogram.[85]

Some energy density limitations are unbreachable for current battery technologies. Inventors are addressing these limitations by changing key features of the lithium-ion battery to create an all-solid, or “solid-state,” version, making it possible to shrink the overall battery considerably while maintaining its energy-storage capacity, thereby achieving a higher energy density as well as enhanced safety.[86]

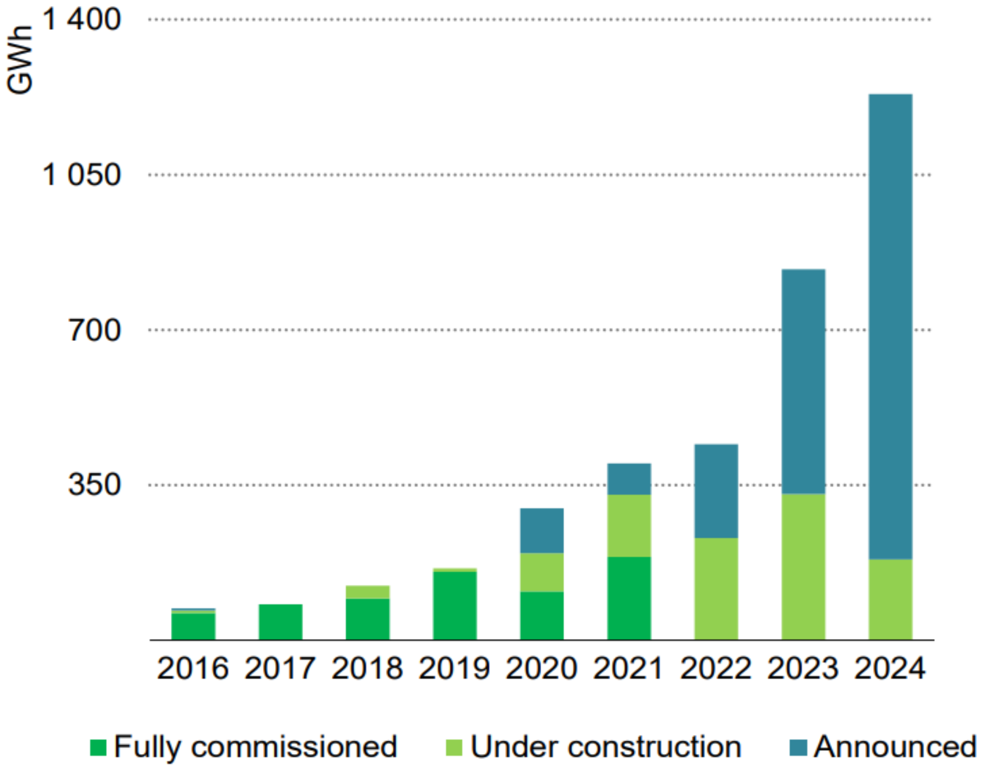
Automaker Investments and Positive Lock-In

Supply-chain investments so far are paying dividends with increasing model availability. The number of electric car models available globally increased by a factor of five from 2015 to 2021, reaching 450 models.[87]

Model availability is greater in the EU and China, but the U.S. market still illustrates rapid expansion of EV offerings. Five years ago, in 2017, manufacturers offered only five electric car models for sale in the U.S.[88] By the end of 2021, consumers could choose from more than 50 models, with expectations that 100 electric car models will be available by January 2023.[89]

Supply-chain investments offer further insights into EV supply chain scaling up, and investment is growing rapidly. An IEA analysis shows investment in EV assembly and parts will jump to $90 billion in 2022, capturing 55 percent of all vehicle-related investment, up from 45 percent in 2021, and 32 percent the year prior.[90] Another recent analysis using a broader accounting of investment, including revenue generated by stock market equity offerings of EV-related companies, finds $183 billion will be invested in the Chinese EV supply chain in 2022 alone.[91]

Figure 12. Battery manufacturing capacity additions

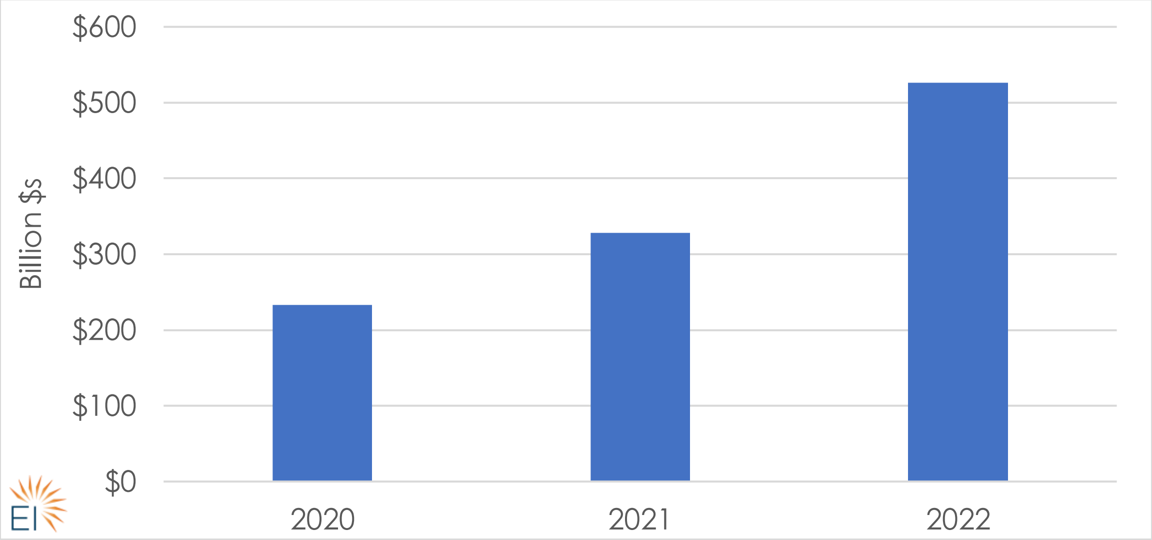


Source: IEA[92]

Battery production stood at just shy of 200 gigawatt-hours in 2019. Factories under construction and announced investments will increase production capacity by six times, assuming all projects are successful, as Figure 12 illustrates.[93]

Global planned investment in EVs has doubled in the past two years. In 2022, automakers announced $526 billion in planned EV investment over the next five years, a significant jump over $233 billion in planned investment over the next five years in 2020, charted in Figure 13.[94]

Figure 13. Planned EV investments looking five years forward for major automakers [xii]



Source: Energy Innovation® graphic with data from AlixPartners[95]

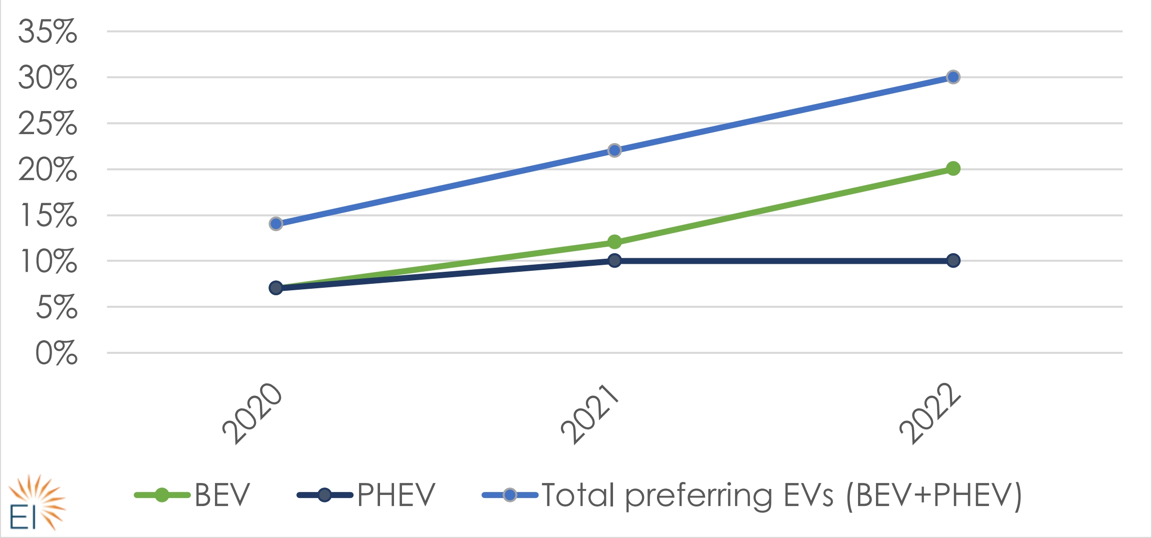
The EV transition is garnering a large amount of investment and an increasing share of industry investment. Whether considering IEA's estimate of $90 billion in EV-related spending in 2020 or the $105 billion average annual implied by AlixPartners' assessment of automakers' future five-year plans, current investment levels appear equal to the challenge. Rapid electrification under the IEA's Net Zero by 2050 Scenario requires $315 billion invested from 2021 to 2025 ($63 billion annually) and $675 billion from 2026 to 2030 ($135 billion annually).[96] Comparing these to 2020 actual investments of $90-$135 billion shows current investment appears to be running above current need, and even approaching the higher levels required later in the 2020s under the IEA's Net Zero by 2050 Scenario.

Positive Consumer Sentiment

Consumer sentiment toward EVs is increasingly positive, as evidenced by survey data and market behavior. A global survey of vehicle preferences by Ernst and Young shows more and more favorable consumer views of EVs.[97] This survey of prospective new car buyers in 18 countries asked what type of vehicle respondents were most likely to purchase next. The results show the number of likely EV buyers more than doubling from 14 percent in 2020 to 30 percent in 2022, including 37 percent of prospective buyers in China, trends graphed in Figure 14.[98]

[xii] These data represent 2020, 2021, and 2022 total of major automakers' investment plans for the next five years.

Figure 14. Consumer surveys show rapidly increasing EV favorability



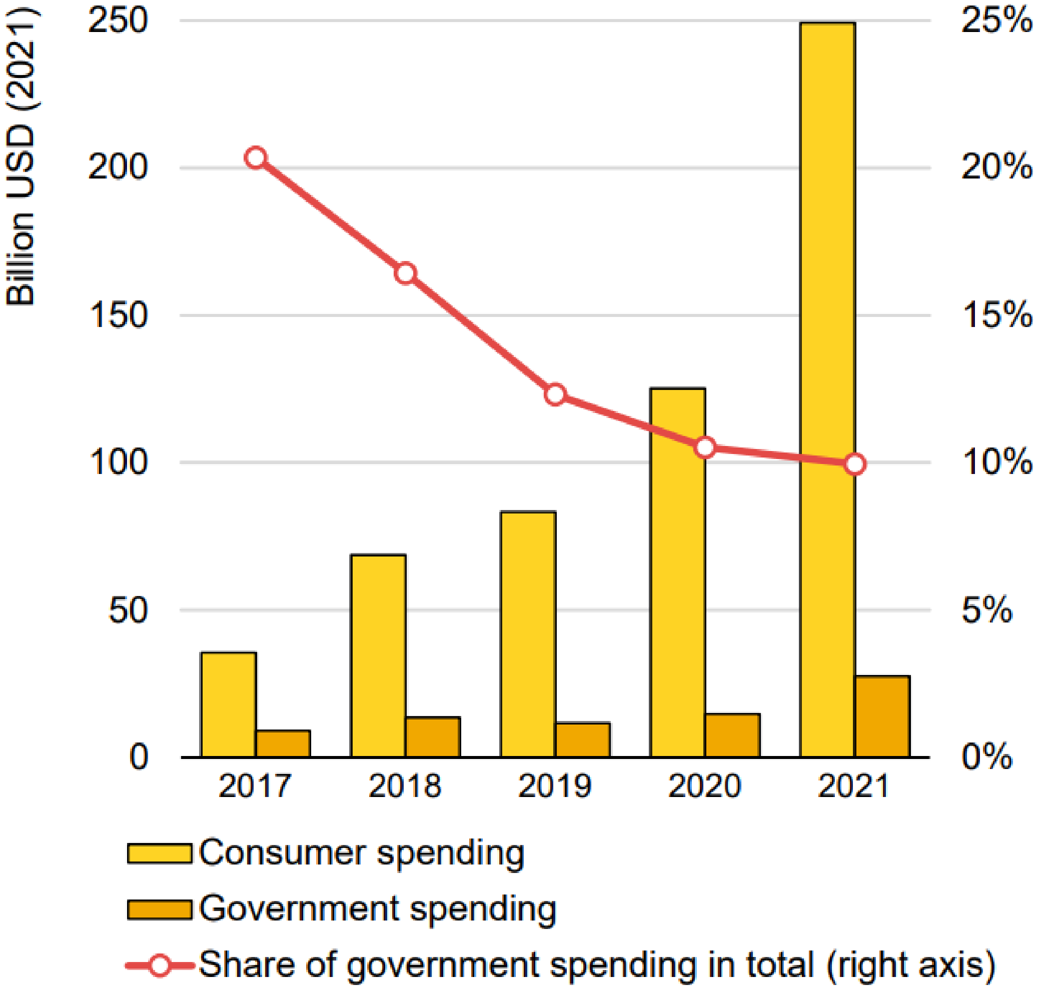
Source: Energy Innovation® graphic with data from Ernst & Young[99]

As of 2022, 37 percent of Chinese consumers expect their next purchase to be an EV.[100] In California, 59 percent of current residents are likely to choose an EV for their next vehicle purchase.[101]

Increasingly positive consumer sentiment is evident in growing willingness to pay for EVs, demonstrated by data showing retail profit margins for EVs exceeding conventional car margins. U.S. data from early 2022 showed an average sale price for a fully electric vehicle was marked up 2.6 percent over the manufacturer's suggested retail price, compared to 1.6 percent for a weighted average of all new car sales.[102]

A final point of evidence demonstrating the positive trend in consumer sentiment tracks the share of EV purchase costs borne by consumers versus the government. From 2017 to 2021, on a global average basis, the share of EV purchase costs paid for by public funds dropped by about half, from 20 to 10 percent, illuminated in Figure 15. The fact that EV purchases have soared even as government support has dropped is proof of increasing consumer demand.

Figure 15. Consumer and government share of EV purchase expenditures



Source: IEA[103]

Superior Product

EVs offer superior acceleration, owing to their ability to instantly deliver peak torque even from a complete standstill. Typical street driving, as opposed to highway travel, frequently involves acceleration from a standstill, making this an important advantage. Though the industry is still scaling up, one EV—the Tesla Model S—is already the fastest car in the world, measured by time to reach 60 miles per hour.[104] EVs' performance advantage leads to headlines in mainstream media such as the following example from *Barron's*, a financial news outlet: "EVs Can Turn Anyone into Race Car Drivers—Including Me."[105]

Electric motors are also inherently more energy efficient than ICEs, which suffer losses to waste heat. Conventional cars only convert 12 to 30 percent of the energy stored in gasoline to power at the wheels, compared to more than 77 percent converted for electrical energy in the case of an EV.[106]

EVs also have the advantage of simplicity. Combustion engines are complicated, with many moving parts, resulting in more wear-and-tear problems and breakdowns. EVs have far fewer moving parts, making them more reliable.[107] And less complicated machines are easier to produce, providing an inherent manufacturing advantage for EVs.[xiii]

Another intrinsic advantage for EVs is that their powertrain provides much greater freedom in vehicle design, with benefits for vehicle quality and manufacturing efficiency.[108] A four-wheeled EV can have one, two, three, or four motors. Multiple motors can work in tandem or power up each of the four wheels independently. This gives manufacturers the ability to offer multiple power options while only having to engineer, design, and build a few motor types.

Automakers are only starting to take advantage of EV design flexibility. One innovation in the works involves integrating an EV's battery into the structure of the car so that the cells can serve the dual purpose of powering the vehicle and serving as its skeleton.[109]

The Challenges Ahead section of this report considers the importance of continued improvement in EV charging convenience. Refueling conventional cars currently takes less time than recharging a comparable EV. While acknowledging this EV disadvantage, we note a countervailing advantage for EVs: Owners are mostly able to charge their vehicles at home, avoiding trips to the gas station. Research on the Norwegian experience found EV charging preferable to the conventional petroleum fueling experience, with EV owners specifically identifying the benefit of charging EVs at home and calling charging comparatively "easier" and "more comfortable."[xiv,110]

[xiii] Reduced labor input needs for EVs also increase the importance of workforce policies to help train workers and provide a social safety net.

[xiv] Research found: "EV drivers perceived the charging process as easier than filling their car 'the traditional way' at petrol stations. One of the Nissan Leaf drivers said that he was glad he did not have to worry about filling at the station, stating that 'electric cars are easier for me; they are actually more comfortable than petrol cars because I can charge at home.' Several interviewees confirmed this and pointed to how home charging in particular made EVs more convenient in everyday life than a traditional petrol or diesel-fueled car." Lina Ingeborgrud and Marianne Ryghaug, "The Role of Practical, Cognitive and Symbolic Factors in the Successful Implementation of Battery Electric Vehicles in Norway," *Transportation Research Part A: Policy and Practice* 130 (December 1, 2019): 507–16, https://doi.org/10.1016/j.tra.2019.09.045, at 511.

CHALLENGES AHEAD

Achieving the EV transition at optimal speed will require a realistic perspective on the challenge. First, we acknowledge the difficulty of achieving a 100 percent transition due to laggards, as the last adopters are referred to in technology transition research. Some slowing in the last stages of a new technology's diffusion is typical. Such concerns may be avoided by focusing on interim timelines, such as the recommended sales target of at least 60 percent ZEVs among new cars sales by 2030. Three additional challenges relate to market failures and other factors creating systemic inertia, EV charging, and building up supply chains for critical minerals.

Market Failures and Systemic Inertia

Considering the increasingly compelling EV economics and market tendencies, some might imagine the invisible hand of the market should determine the pace of transportation electrification. However, absent enabling public policies, transportation decarbonization will be sub-optimally slow due to market failures and imperfections, which together create significant systemic inertia that could slow the EV transition.

IEA's forecasts provide one viewpoint on the difference policy will make for EV deployment. The forecasts show that current policy needs strengthening to get EV deployment on track to achieve net-zero emissions transportation by mid-century. The IEA's *2022 EV Outlook* indicates that existing policy puts EV stock on a trajectory leading to 175 million EVs in 2030, compared to the 300 million EVs envisioned in the Net Zero by 2050 Scenario.[111]

Turning to specific market failures, climate and local public health effects are classic examples of societally important impacts not reflected in market prices, which economic theory refers to as "externalities." Standard economic theory recognizes that externalities produce inefficient outcomes without policy correction. The failure of market prices to account for climate and local air quality benefits are one rationale for continued EV policy support.

Nobel Prize-winning economist Joseph Stiglitz explains further: "The reason that the invisible hand of the market often seems invisible is that it is often not there. Whenever there are 'externalities'—where the action of an individual has impacts on others for which they do not pay, or for which they are not compensated—markets will not work well."[112] Stiglitz also points to the role of unequally distributed information "Recent research has shown that externalities are pervasive, [existing] whenever there is imperfect information or imperfect risk markets—that is, always."[113]

Other market imperfections cause systemic drag or friction that would slow down a transition left to the market alone.[114,xv] For one example, the existing petroleum-fueling network serves as a

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[xv] Yeh and Sperling of the Institute of Transportation Studies at the University of California, Davis, offer the following overview specific to the transportation sector: "There are many market failures and market conditions that riddle the energy system, many of them unique to transportation, that result in consumer and business decisions not in the best

barrier to new transportation technologies. Built up over decades, the existing fueling network provides an almost unsurmountable advantage for the incumbent petroleum-centered system, absent policies supporting the development of vehicle charging networks.

Stiglitz explains further: "The reason that the invisible hand often seems invisible is that it is often not there. Whenever there are 'externalities'—where the action of an individual has impacts on others for which they do not pay, or for which they are not compensated—markets will not work well."[115] Stiglitz identified environmental externalities as an "important" and long understood example, adding: "Recent research has shown that externalities are pervasive, [existing] whenever there is imperfect information or imperfect risk markets—that is, always."[116]

The history of solar and wind electricity generation technologies show how market failures and imperfection, combined with inadequate policy impetus caused unnecessary and costly delay in accrual of learning curve benefits. These cases show that to find commercial success a technology must be actively researched (in early stages) and deployed (in middle and later stages) to realize cost reductions. Delayed innovation and cost improvements are of particular concern for technologies delivering important social benefits not reflected in market prices or otherwise directly signaled to market participants.

In the case of solar photovoltaic (PV) panels, a 1954 breakthrough at Bell Telephone Laboratories opened new possibilities for solar. However, no driver of learning curve effects emerged. So, for many years, solar PV panels were too expensive for commercial use except in very limited circumstances, such as to power satellites.[117]

Wind power has an even longer history, including a surge in popularity in the rural economy of 1920s America, which was undercut in the 1940s with the achievement of nearly universal access to electricity grids.[118]

In the recently published *The Big Fix,* authors Hal Harvey and Justin Gillis offer new insights into the history of these two renewable technologies and how both fell victim to markets that were impervious to their environmental advantages.[119] For both technologies, inadequate policy resulted in deferral of learning curve effects for decades: "[T]he problem in both cases was the same: nobody had the motivation to take on the costly task of pushing these technologies to scale. Compared to digging up black rocks and burning them, the devices were still an extremely expensive way to produce electricity. In essence, they were stuck at the top of the learning curve, not moving down it."[120]

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interest of society. These market conditions include network effects of additional coordination among fuel producers, vehicle manufacturers, and fuel distributors; energy security externalities related to petroleum imports; long time horizons needed for investments in fuel infrastructure; the lack of fuel-on-fuel competition; the diffuse nature of biofuel industries; and the market power of oil companies and OPEC countries. Energy markets are particularly inefficient and ineffective at addressing end use technology efficiency and demand reduction." Sonia Yeh and Daniel Sperling, "Low Carbon Fuel Policy and Analysis," *Energy Policy* 56 (May 1, 2013): 1–4, https://doi.org/10.1016/j.enpol.2013.01.008.

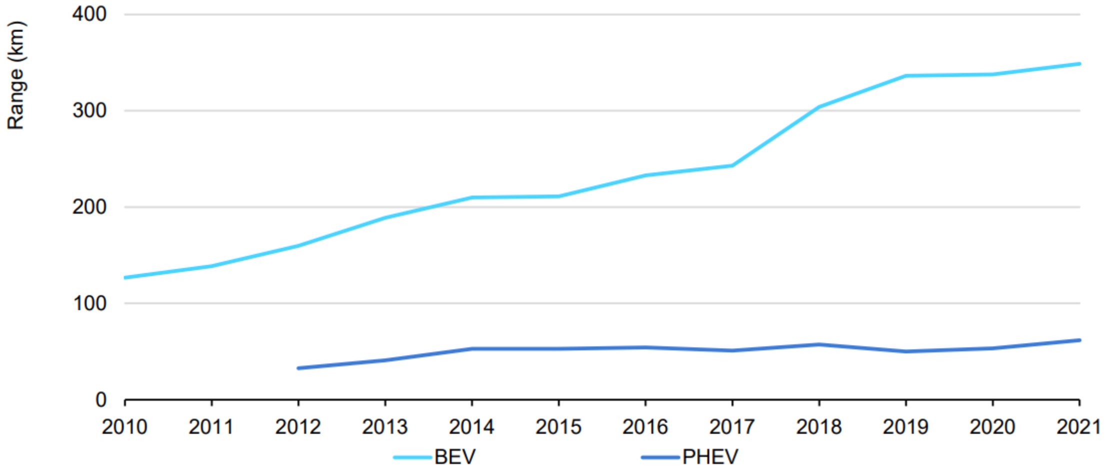
Charging

To support a rapid EV transition, public charging needs to become more convenient and refill time needs to continue to improve, as it is expected. Yet, the challenges associated with charging are easily overstated. For one reason, as discussed, many consumers place a premium on the convenience of electric charging at home.

Moreover, comparison to actual driving habits shows the need for fast or public charging is unlikely to be a concern for most trips. For example, a U.S. survey finds that EVs are well suited to the daily driving habits of most drivers, with 87 percent of drivers travelling less than 100 miles (161 km) daily.[xvi,121] Just 4 percent of car owners reported driving 250 miles (403 km) per day or more on average.

Such daily needs compare favorability to the steadily improving range for EVs. By 2021, an all-electric EV offered an average range of 350 km per charge, as shown in Figure 16. [122]

Figure 16. Increasing range for EVs (annual weighted average by powertrain)



Source: IEA[123]

Taken together, these EV range and daily travel data, as well as the fact that U.S. residents have among the highest levels of per capita vehicles miles traveled globally, suggests that in most places daily driving needs will fall within range for most EVs.

[xvi] Average plug-in hybrid EV range Percentages discussed based on the share of survey respondents providing numerical response, i.e., excluding those refusing to answer (1 percent of respondents) and those answering, "Don't know" (5 percent).

Critical Mineral Supply

Critical mineral supply is another challenge. Though EV fuels are less resource intensive, EVs themselves use more critical minerals than ICE cars. In fact, in general, clean technology production involves greater critical mineral inputs. As a result, clean energy technologies have become the fastest growing segment of demand for most minerals, a trend expected to continue. Growing demand for critical minerals and the many years that typically transpire before a new mineral resource investment leads to production are both reasons for policymakers to attend to critical mineral supply adequacy.

Assessing expected supply from existing mines and projects under construction, the IEA estimates that, by 2030, current plans would meet half of projected lithium and cobalt requirements and 80 percent of copper needs under the IEA's Announced Pledges Scenario (the most ambitious scenario analyzed in *The Role of Critical Minerals in Clean Energy Transitions*).[124]

While several factors lessen critical mineral supply concerns, first, in the spirit of identifying challenges, we discuss typically long completion timelines for new mineral extraction projects. Globally, it can take from four to as long as 20 years for a mine to begin commercial production after an extractable resource is identified through exploration.[125] By way of comparison, battery factories typically take from one to four years to complete.[126] New clarity about the size of future markets and growing government and corporate commitments could speed the project completion process, but other factors could increase the degree of difficulty compared to the past, such as understandable expectations for a higher level of conduct that clearly breaks from irresponsible past practices.

Factors working in favor of future critical mineral supply adequacy include emerging technologies and growing investment in new production capacity. Emerging recycling and less environmentally-costly extraction technologies are also working in favor of supply adequacy, though they are typically not factored into supply forecasts, including the IEA assessment mentioned above, because of the newness of the technology.

There is also a clear upward trend in investment in new mineral supply projects. Until 2015, annual investment in new capacity for four important critical minerals exceeded $10 billion only once, but it has done so every year since, topping $20 billion in 2016 and 2019 (as shown in the figure graphing announced capital cost for greenfield projects for selected minerals, page 38).[127]

California's "Lithium Valley" provides an example of a potential game changing resource and technology. The briny waters of the state's Salton Sea are estimated to contain one to six million tonnes of lithium, comparable to the largest reserves anywhere.[128] Lithium Valley's potential annual output is estimated at 600,000 tons per year or six times larger than current global output of less than 100,000 tonnes in 2019.[129]

Efforts in the Lithium Valley are developing a new more environmentally-friendly extractive technique compared to conventional hard rock mining and evaporation ponds, "direct lithium extraction." According to a blue ribbon commission appointed by the state: "The environmental impacts of the lithium recovery technologies proposed for use in Imperial County, direct lithium extraction from geothermal brine, have a much lower environmental impact than hard rock mining and evaporation ponds. Direct lithium extraction is a more sustainable and environmentally beneficial approach to lithium recovery in terms of factors such as land use, water use, time to market, and carbon intensity."[130]

Before leaving this topic, we point out differences between the challenge of building the critical mineral supply chain and recent EV supply shortages. EV supply shortfalls in 2021 and 2021 were largely the result of semiconductor shortfalls that more broadly affected auto production and the rapid uptick in EV demand spurred by gasoline price spikes globally. Lithium-related and other input price increases have affected profitability, but short term pressures are expected to lessen. Leading auto industry analysts advise: "While demand-over-supply leverage in the marketplace is driving near-term profitability, it is not sustainable in the long term… Inventory is likely to build once demand and supply are even, eroding pricing power."[131]

Solar Industry Success Overcoming Past Input Supply Bottlenecks

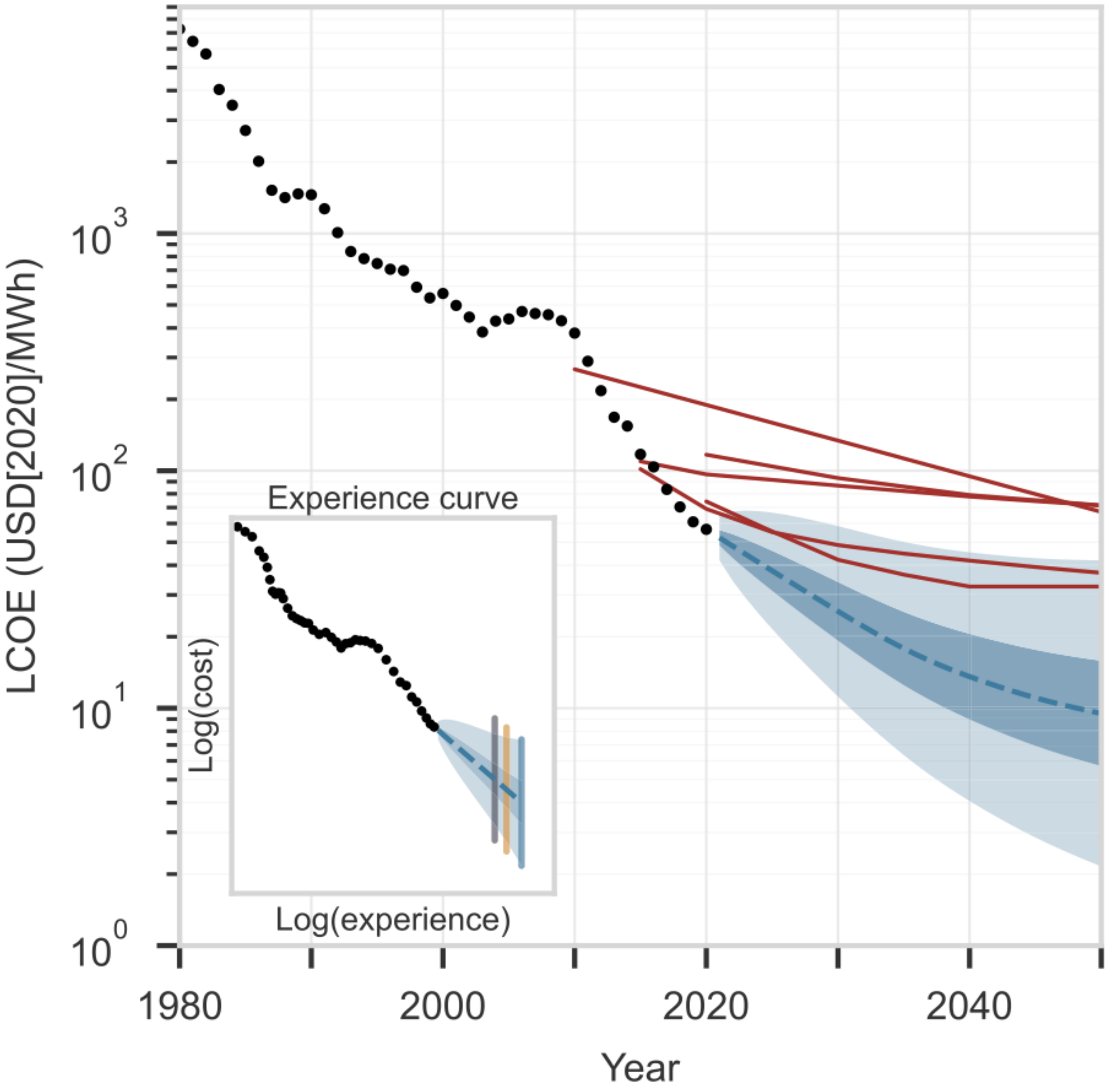
While today's multi-sector challenge of scaling up critical minerals covers a wider array of minerals and greater needs, the solar industry's experience shows that past input supply bottlenecks have been manageable.

Silicon is a key mineral input used in solar PV panels, and as the solar industry ramped up in the mid-aughts, increasing silicon demand created sharply rising prices and raised concerns for the future of the industry. These silicon input price pressures on the cost effectiveness of solar power are evident in Figure 17, which shows slowing learning curve effects in the mid-aughts between the horizontal axis labels denoting the years 2000 and 2010. For a period, the trend shows a reversal of the typical relationship, i.e., rising prices because of rising silicon input prices.

A sense of how the silicon supply situation looked in real time is provided in historical news headlines. A 2005 *Wired* magazine article entitled, "Silicon Shortage Stalls Solar," warned: "A severe shortage of the silicon used in the systems threatens to dampen solar's growth."[132] Two years later, *Greentech Media*'s article, "Silicon Shortage Has Big Impact," began this way: "A shortage of solar-grade silicon still is having a big impact on solar companies, according to a panel of CEOs at the Solar Power 2007 conference in Long Beach, Calif."[133]

Over time, the learning curve reconverged with the longer-term empirical trend. In fact, silicon input prices did more than normalized, going from boom to bust in typical commodity market fashion. Within a few years, a glut of silicon had appeared: "The silicon demand/supply balance [] evolved from a situation of shortage with rocketing sales prices, in the years 2005–2008, to [in 2012 and 2013] an oversupply situation with record low price level for virgin polysilicon."[134]

Figure 17. Solar PV learning curve shows effect of mid-aughts silicon supply constraints[xvii]



Source: Way et al. [135]

The strongest evidence that the silicon supply shortage threat was a mere blip, despite hand-wringing headlines to the contrary, is today's solar industry success. Today, people are building more solar PV power capacity than any other type of power generation technology. In 2020, the

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[xvii] The figure's red line segments show cost projections used by major energy models, which have consistently been too high for several clean technologies. The blue band shows Way et al.'s empirically based probabilistic technology forecast (more detail available in Figure A, page 2065).

IEA concluded solar power plants now offer the “cheapest … electricity in history,” with the technology cheaper than coal and gas in most major countries,” prompting its executive director to say: “I see solar becoming the new king of the world’s electricity markets. Based on today’s policy settings, it is on track to set new records for deployment every year after 2022.”[136]

Today, the solar industry’s leading position seems stronger than ever, and its resolution of raw input constraints proves an adage favored by commodity market traders: “High prices are the best solution for high prices.” In other words, high prices drive supply investments, which will reduce future commodity output prices.

The solar industry’s success in overcoming earlier silicon supply limitations and the substantial attention now being devoted to developing the necessary resources are reasons to expect current input price pressures will moderate within a few years and suggest long-term supply adequacy concerns are manageable.

CONCLUSION

Passenger EVs are a top decarbonization solution primed for scaling up given EVs’ technological maturity, cost effectiveness, and recent progress. EV sales are surging, and consumer surveys point to continued growth. Model availability, battery range, and charging convenience are steadily improving—trends set to continue based on investment commitments, adding up to more than half a trillion dollars for major automakers alone. Government ambition and policy support for transportation electrification are similarly on the upswing. These trends signify a clear trajectory: EVs are on a path to becoming the predominant new motor vehicle technology.

EVs are poised to take over the mainstream market, but market failures and inertia mean the transition to EVs must be managed, not outsourced to the invisible hand. The EV transition will be too slow without support from an effective portfolio of policies. Valuable public health and other co-benefits add to the decarbonization impetus for EV policy support. Though several different policy pathways exist for effectively supporting EV deployment, what is invariant is the importance of new vehicle sales standards, ideally including both broad GHG tailpipe and ZEV sales standards and the need to push for unprecedented speed and scale to fully leverage the EV decarbonization opportunity.

REFERENCES

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[1] Tom Randall, “US Crosses the Electric-Car Tipping Point for Mass Adoption,” *Bloomberg.com*, July 9, 2022, https://www.bloomberg.com/news/articles/2022-07-09/us-electric-car-sales-reach-key-milestone.

[2] Zero Emission Vehicles Coalition, “COP26 Declaration on Accelerating the Transition to 100% Zero Emission Cars and Vans,” 2021, 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.

[3] David Welch, “Carmakers Start to Starve Combustion Models Out of Existence,” *Bloomberg.com*, July 8, 2022, https://www.bloomberg.com/news/articles/2022-07-08/carmakers-start-to-starve-combustion-models-out-of-existence.

[4] International Energy Agency, “Global EV Outlook 2022,” May 2022, https://www.iea.org/reports/global-ev-outlook-2022.

[5] BloombergNEF, “Battery Pack Prices Fall to an Average of $132/KWh, But Rising Commodity Prices Start to Bite,” November 30, 2021, https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/.

[6] Chris Harto, “Electric Vehicle Ownership Costs: Today’s Electric Vehicles Offer Big Savings for Consumers” (Consumer Reports, October 2020), https://advocacy.consumerreports.org/wp-content/uploads/2020/10/EV-Ownership-Cost-Final-Report-1.pdf.

[7] Peter Slowick et al., “Assessment of Light-Duty Electric Vehicle Costs and Consumer Benefits in the United States in the 2022–2035 Time Frame” (International Council on Clean Transportation, October 18, 2022), https://theicct.org/publication/ev-cost-benefits-2035-oct22/.

[8] International Energy Agency, “Net Zero by 2050” (Paris: IEA, 2021), https://www.iea.org/reports/net-zero-by-2050.

[9] BloombergNEF, “New Energy Outlook 2021,” 2021, https://about.bnef.com/new-energy-outlook/.

[10] Hal Harvey and Justin Gillis, *The Big Fix: 7 Practical Steps to Save Our Planet* (New York: Simon & Schuster, 2022), https://www.simonandschuster.com/books/The-Big-Fix/Hal-Harvey/9781982123987.

[11] Rupert Way et al., “Empirically Grounded Technology Forecasts and the Energy Transition,” *Joule*, September 13, 2022, https://doi.org/10.1016/j.joule.2022.08.009.

[12] Slowick et al., “Assessment of Light-Duty Electric Vehicle Costs and Consumer Benefits in the United States.”

[13] International Energy Agency, “The Role of Critical Minerals in Clean Energy Transitions” (Paris: IEA, 2021), https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

[14] Gøran Bye and Bruno Ceccaroli, “Solar Grade Silicon: Technology Status and Industrial Trends,” *Solar Energy Materials and Solar Cells* 130 (November 1, 2014): 634–46, https://doi.org/10.1016/j.solmat.2014.06.019.

[15] Randall, “US Crosses the Electric-Car Tipping Point.”

[16] International Renewable Energy Agency, “Renewable Power Generation Costs in 2021,” July 2022, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Power_Generation_Costs_2021.pdf.

[17] David Reichmuth, “Plug In or Gas Up? Why Driving on Electricity Is Better than Gasoline,” *Union of Concerned Scientists* (blog), June 7, 2021, https://blog.ucsusa.org/dave-reichmuth/plug-in-or-gas-up-why-driving-on-electricity-is-better-than-gasoline/.

[18] International Energy Agency, “Net Zero by 2050.”

[19] Arijit Sen and Josh Miller, “Emissions Reduction Benefits of a Faster, Global Transition to Zero-Emission Vehicles,” Working Paper 15-2022 (International Council on Clean Transportation, March 2022), https://theicct.org/wp-content/uploads/2022/03/Accelerated-ZEV-transition-wp-final.pdf.

[20] International Energy Agency, “Defying Expectations, Carbon Dioxide Emissions from Global Fossil Fuel Combustion Are Set to Grow in 2022 by Only a Fraction of Last Year’s Big Increase,” October 19, 2022, https://www.iea.org/news/defying-expectations-co2-emissions-from-global-fossil-fuel-combustion-are-set-to-grow-in-2022-by-only-a-fraction-of-last-year-s-big-increase.

[21] International Energy Agency, "Carbon Dioxide Emissions Defying Expectations in 2022.”

---

[22] International Energy Agency, “Net Zero by 2050.”

[23] BloombergNEF, “New Energy Outlook 2021.”

[24] BloombergNEF, “Battery Pack Prices Fall.”

[25] Harto, “Electric Vehicle Ownership Costs: Today’s Electric Vehicles Offer Big Savings for Consumers.”

[26] BloombergNEF, “Battery Pack Prices Fall.”

[27] Harto, “Electric Vehicle Ownership Costs: Today’s Electric Vehicles Offer Big Savings for Consumers.”

[28] Harto.

[29] Slowick et al., “Assessment of Light-Duty Electric Vehicle Costs.”

[30] Harto, “Electric Vehicle Ownership Costs”; Orvis, “Most Electric Vehicles Are Cheaper to Own”; Tom Taylor and Josh Rosenberg, “Total Cost of Ownership Analysis: Comparison Between Four of the Most Popular Gasoline Powered Models in the Country and an EV Equivalent for Purchase in 2022” (Washington, DC: Atlas Public Policy, n.d.), https://atlaspolicy.com/wp-content/uploads/2022/01/Total-Cost-of-Ownership-Analysis.pdf.

[31] Slowick et al., “Assessment of Light-Duty Electric Vehicle Costs.”

[32] Xinyu Liang et al., “Air Quality and Health Benefits from Fleet Electrification in China,” *Nature Sustainability* 2, no. 10 (October 2019): 962–71, https://doi.org/10.1038/s41893-019-0398-8.

[33] Susan Anenberg et al., “A Global Snapshot of the Air Pollution-Related Health Impacts of Transportation Sector Emissions in 2010 and 2015” (International Council on Clean Transportation, 2019), https://theicct.org/wp-content/uploads/2021/06/Global_health_impacts_transport_emissions_2010-2015_20190226.pdf.

[34] J. Lelieveld et al., “Effects of Fossil Fuel and Total Anthropogenic Emission Removal on Public Health and Climate,” *Proceedings of the National Academy of Sciences* 116, no. 15 (April 9, 2019): 7192–97, https://doi.org/10.1073/pnas.1819989116.

[35] Everett Rogers, *Diffusion of Innovations*, 5th ed. (New York: Simon & Schuster, 2003).

[36] Rogers, *Diffusion of Innovations*.

[37] Rita Gunther McGrath, “The Pace of Technology Adoption Is Speeding Up,” *Harvard Business Review*, November 25, 2013, https://hbr.org/2013/11/the-pace-of-technology-adoption-is-speeding-up.

[38] McGrath, “The Pace of Technology Adoption Is Speeding Up.”

[39] International Energy Agency, “Global EV Outlook 2022.”

[40] International Energy Agency, “Electric Vehicle Sales Update,” September 27, 2022, https://www.iea.org/fuels-and-technologies/electric-vehicles.

[41] “China’s Electric Trucks May Well Pull Forward Peak Oil Demand,” *Bloomberg.com*, October 11, 2022, https://www.bloomberg.com/news/articles/2022-10-11/china-s-electric-trucks-may-well-pull-forward-peak-oil-demand.

[42] International Energy Agency, “Global EV Outlook 2022.”

[43] Boudway, “More Than Half of US Car Sales Will Be Electric by 2030.”

[44] Ira Boudway, “More Than Half of US Car Sales Will Be Electric by 2030,” *Bloomberg.com*, September 20, 2022, https://www.bloomberg.com/news/articles/2022-09-20/more-than-half-of-us-car-sales-will-be-electric-by-2030.

[45] International Energy Agency, “Global EV Outlook 2022.”

[46] International Energy Agency, “Global EV Outlook 2022.”

[47] International Energy Agency, “Global EV Outlook 2022.”

[48] Maximilian Holland, “Norway’s Plugin Growth Flat In September, BEV Share Up,” *CleanTechnica*, October 4, 2022, https://cleantechnica.com/2022/10/04/norway-bev-share-up/.

[49] Felix Schulz and Johannes Rode, “Public Charging Infrastructure and Electric Vehicles in Norway,” *Energy Policy* 160 (January 1, 2022): 112660, https://doi.org/10.1016/j.enpol.2021.112660.

[50] Erik Figenbaum, “Perspectives on Norway’s Supercharged Electric Vehicle Policy,” *Environmental Innovation and Societal Transitions* 25 (December 1, 2017): 14–34, https://doi.org/10.1016/j.eist.2016.11.002.

[51] Lina Ingeborgrud and Marianne Ryghaug, “The Role of Practical, Cognitive and Symbolic Factors in the Successful Implementation of Battery Electric Vehicles in Norway,” *Transportation Research Part A: Policy and Practice* 130 (December 1, 2019): 507–16, https://doi.org/10.1016/j.tra.2019.09.045.

---

[52] Shikha Rokadiya and Zifei Yang, "Overview of Global Zero-Emission Vehicle Mandate Programs" (International Council on Clean Transportation, 2019), https://theicct.org/sites/default/files/publications/Zero%20Emission%20Vehicle%20Mandate%20Briefing%20v2.pdf.

[53] California Air Resources Board staff, "The Zero Emission Vehicle Regulation Fact Sheet," accessed April 27, 2021, https://ww2.arb.ca.gov/sites/default/files/2019-06/zev_regulation_factsheet_082418_0.pdf.

[54] Dustin Gardiner, "Newsom Says 'There Is No Tesla Without' California. Here's How Much Money It Has Received from the State," *San Francisco Chronicle*, September 28, 2022, sec. Politics, https://www.sfchronicle.com/politics/article/Does-Tesla-owe-all-its-success-to-California-17473046.php.

[55] Gardiner, "Newsom Says 'There is No Tesla Without' California."

[56] Gardiner, "Newsom Says 'There is No Tesla Without' California."

[57] Gardiner, "Newsom says 'There is No Tesla Without' California."

[58] Colin McKerracher, "Electric Vehicles Have China's Massive Middle Market Surrounded," *Bloomberg.com*, August 30, 2022, https://www.bloomberg.com/news/articles/2022-08-30/electric-vehicles-have-china-s-massive-middle-market-surrounded.

[59] McKerracher, "China's Electric Trucks May Well Pull Forward Peak Oil Demand."

[60] McKerracher, "China's Electric Trucks May Well Pull Forward Peak Oil Demand."

[61] Uwe Tietge et al., "Carbon Dioxide Emissions from New Passenger Cars in Europe: Car Manufacturers' Performance in 2020" (International Council on Clean Transportation, August 2021), https://theicct.org/wp-content/uploads/2022/08/co2-new-passenger-cars-europe-aug22.pdf;

Department of Transportation, "Corporate Average Fuel Economy Standards for Model Years 2024–2026 Passenger Cars and Light Trucks" (Federal Register Vol. 87, No. 84, May 2, 2022), https://www.govinfo.gov/content/pkg/FR-2022-05-02/pdf/2022-07200.pdf;

Sara Baldwin, Amanda Myers, and David Wooley, "Accelerating Clean, Electrified Transportation by 2035: Policy Priorities" (Energy Innovation: Policy and Technology, LLC, April 2021), 0, https://energyinnovation.org/wp-content/uploads/2021/04/Energy-Innovation_2035-2.0-Accelerating-Clean-Transportation-Policy-Report.pdf.

[62] Tietge et al., "Carbon Dioxide Emissions from New Passenger Cars in Europe."

[63] Zero Emission Vehicles Coalition, "COP26 Declaration on 100% ZEVs Transition."

[64] "ZEV Transition Council," *International Council on Clean Transportation* (blog), 2022, https://theicct.org/initiatives-partnerships/zev-tc/.

[65] Intergovernmental Panel on Climate Change, "Assessment Report 6 - Synthesis," 2022, https://www.ipcc.ch/report/sixth-assessment-report-cycle/.

[66] Gil Tal, Adam Davis, and Dahlia Garas, "California's Advanced Clean Cars II: Issues and Implications," Working Paper Reference No. UCD-ITS-RR-22-73 (Institute for Transportation Studies, University of California, Davis, May 31, 2022), https://escholarship.org/uc/item/1g05z2x3.

[67] Michael Liebreich, "The Clean Hydrogen Ladder (V4.1)," August 15, 2021, https://www.linkedin.com/pulse/clean-hydrogen-ladder-v40-michael-liebreich/.

[68] David Reichmuth, "Going from Pump to Plug: Adding Up the Savings from Electric Vehicles" (Union of Concerned Scientists, November 2017), https://www.ucsusa.org/sites/default/files/attach/2017/11/cv-report-ev-savings.pdf.

[69] Dale Hall et al., "Decarbonizing Road Transport by 2050: Effective Policies to Accelerate the Transition to Zero-Emission Vehicles" (International Council on Clean Transportation, 2021), https://theicct.org/wp-content/uploads/2021/12/ZEVTC_EffectivePolicies_dec2021.pdf;

Sara Baldwin, Amanda Myers, and David Wooley, "Accelerating Clean, Electrified Transportation by 2035: Policy Priorities" (Energy Innovation: Policy and Technology, LLC, April 2021), https://energyinnovation.org/wp-content/uploads/2021/04/Energy-Innovation_2035-2.0-Accelerating-Clean-Transportation-Policy-Report.pdf;

Kelly L. Fleming Austin L. Brown, "Carbon Neutrality Study 1: Driving Transportation Emissions to Zero in California," 2020, https://doi.org/10.7922/G2222S1B;

California Air Resources Board, "Low-Income Barriers Study, Part B: Overcoming Barriers to Clean Transportation Access for Low-Income Residents," February 21, 2018, https://ww2.arb.ca.gov/sites/default/files/2018-08/sb350_final_guidance_document_022118.pdf.

[70] Slowick et al., "Assessment of Light-Duty Electric Vehicle Costs."

---

[71] Orvis, "Most Electric Vehicles Are Cheaper to Own Off the Lot."

[72] Baldwin, Myers, and Wooley, "Accelerating Clean, Electrified Transportation by 2035."

[73] Colin McKerracher, "EV Outlook 2022" (BloombergNEF, June 2022), https://about.bnef.com/electric-vehicle-outlook/.

[74] International Energy Agency, "The Role of Critical Minerals in Clean Energy Transitions" (Paris: IEA, 2021), https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

[75] Cynthia Shahan, "California Offers up to $9,500 to Purchase Used or New Electric Vehicle, Focus on Lower-Income Motorists," *CleanTechnica*, January 5, 2020, https://cleantechnica.com/2020/01/05/california-offers-up-to-9500-to-purchase-a-used-or-new-electric-vehicle-focus-on-lower-income-motorists/.

[76] Chris Busch, "Used Electric Vehicles Deliver Consumer Savings Over Gas Cars" (Energy Innovation: Policy and Technology, LLC, 2021), https://energyinnovation.org/publication/used-electric-vehicles-deliver-consumer-saving-over-gas-cars/.

[77] International Renewable Energy Agency, "Renewable Power Generation Costs in 2021," July 2022, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Power_Generation_Costs_2021.pdf.

[78] International Renewable Energy Agency, "Renewable Power Generation Costs in 2021."

[79] International Renewable Energy Agency, "Renewable Power Generation Costs in 2021."

[80] Way et al., "Empirically Grounded Technology Forecasts."

[81] Way et al., "Empirically Grounded Technology Forecasts."

[82] Way et al., "Empirically Grounded Technology Forecasts."

[83] International Energy Agency, "Global EV Outlook 2022."

[84] International Energy Agency, "Global EV Outlook 2022."

[85] Weijiang Xue et al., "Ultra-High-Voltage Ni-Rich Layered Cathodes in Practical Li Metal Batteries Enabled by a Sulfonamide-Based Electrolyte," *Nature Energy* 6, no. 5 (May 2021): 495–505, https://doi.org/10.1038/s41560-021-00792-y.

[86] Luhan Ye and Xin Li, "A Dynamic Stability Design Strategy for Lithium Metal Solid State Batteries," *Nature* 593, no. 7858 (May 2021): 218–22, https://doi.org/10.1038/s41586-021-03486-3; Michelle Lewis, "How Solid State EV Batteries Could Cut Emissions by up to 39%," *Electrek* (blog), July 19, 2022, https://electrek.co/2022/07/19/how-solid-state-ev-batteries-could-cut-emissions-by-up-to-39/.

[87] International Energy Agency, "Global EV Outlook 2022."

[88] Sean Tucker, "Electric Vehicle Buying Guide," *Kelley Blue Book* (blog), October 1, 2021, https://www.kbb.com/car-advice/electric-vehicle-buying-guide/.

[89] Tucker, "Electric Vehicle Buying Guide."

[90] International Energy Agency, "World Energy Investment 2022," June 2022, https://www.iea.org/reports/world-energy-investment-2022.

[91] Danny Lee, "CALB's Debut Was Lukewarm, But China Has Buckets of EV Funding," *Bloomberg.com*, October 10, 2022, https://www.bloomberg.com/news/articles/2022-10-10/calb-s-debut-was-lukewarm-but-china-has-buckets-of-ev-funding.

[92] International Energy Agency, "World Energy Investment 2022."

[93] International Energy Agency.

[94] Welch, "Carmakers Start to Starve Combustion Models."

[95] AlixPartners, "2021 AlixPartners Global Automotive Outlook," June 17, 2021, https://www.alixpartners.com/media-center/press-releases/2021-alixpartners-global-automotive-outlook/; AlixPartners, "2022 AlixPartners Global Automotive Outlook," June 22, 2022, https://www.alixpartners.com/media-center/press-releases/2022-alixpartners-global-automotive-outlook/.

[96] International Energy Agency, "Investment Data Explorer," n.d., https://www.iea.org/data-and-statistics/data-tools/investment-data-explorer.

[97] Gaurav Batra, Akshi Goel, and Ankit Khatri, "Ernst & Young Mobility Consumer Index 2022" (Ernst & Young, Global Ltd., 2022), https://assets.ey.com/content/dam/ey-sites/ey-com/sv_se/news/2022/ey-mobility-consumer-index-mci-2022-study.pdf.

[98] Batra, Goel, and Khatri, "Mobility Consumer Index 2022."

---

[99] Batra, Goel, and Khatri, “Mobility Consumer Index 2022.”

[100] Batra, Goel, and Khatri, “Mobility Consumer Index 2022.”

[101] Mark DiCamillo, “Majority Support for the State’s All-Electric Car Mandate - New Vehicle Buying Intentions Align with Views About the Mandate” (Institute for Governmental Studies, University of California, Berkeley, October 7, 2022), https://escholarship.org/uc/item/6fm432sb.

[102] Ira Boudway, “Dealers Are Marking-Up EVs, Too,” *Bloomberg.com*, March 5, 2022, https://www.bloomberg.com/news/articles/2022-03-05/hyundai-kia-price-mark-ups-test-consumers-purchasing-impulses.

[103] International Energy Agency, “Global EV Outlook 2022.”

[104] Jeff Bartlett, “Best and Worst Cars for 0-to-60 Acceleration,” *Consumer Reports* (blog), May 20, 2022, https://www.consumerreports.org/driving/best-and-worst-cars-0-to-60-acceleration-a6528636806/.

[105] Al Root, “EVs Can Turn Anyone into Race Car Drivers—Including Me,” *Barron’s*, October 3, 2022, via MarketWatch edition, https://www.marketwatch.com/articles/evs-tesla-porsche-race-car-drivers-51664750828.

[106] U.S. Environmental Protection Agency, “All-Electric Vehicles,” n.d., http://www.fueleconomy.gov/feg/evtech.shtml.

[107] Harto, “Electric Vehicle Ownership Costs.”

[108] Von Antoine Chatelain, “Elektroautos: Trends in Electric Vehicle Design” (McKinsey, March 21, 2018), https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/what-a-teardown-of-the-latest-electric-vehicles-reveals-about-the-future-of-mass-market-evs/de-de.

[109] Mark Andrews, “A New Approach to Car Batteries Is About to Transform EVs,” *Wired*, August 29, 2022, https://www.wired.com/story/cell-to-chassis-batteries-electric-vehicles/.

[110] Ingeborgrud and Ryghaug, “The Role of Practical, Cognitive and Symbolic Factors.”

[111] International Energy Agency, “Global EV Outlook 2022,” May 2022, https://www.iea.org/reports/global-ev-outlook-2022.

[112] Daniel Altman, “Economist’s View: Q & A Joseph Stiglitz,” *International Herald Tribune*, October 11, 2006, https://www8.gsb.columbia.edu/faculty/jstiglitz/sites/jstiglitz/files/Economist%27s%20View_%20Joseph%20Stiglitz%20Q%20%26%20A.pdf.

[113] Daniel Altman, “Economist’s View: Q & A Joseph Stiglitz,” *International Herald Tribune*, October 11, 2006, https://www8.gsb.columbia.edu/faculty/jstiglitz/sites/jstiglitz/files/Economist%27s%20View_%20Joseph%20Stiglitz%20Q%20%26%20A.pdf.

[114] Sonia Yeh and Daniel Sperling, “Low Carbon Fuel Policy and Analysis,” *Energy Policy* 56 (May 1, 2013): 1–4, https://doi.org/10.1016/j.enpol.2013.01.008.

[115] Daniel Altman, “Economist’s View: Q & A Joseph Stiglitz.”

[116] Daniel Altman, “Economist’s View: Q & A Joseph Stiglitz.”

[117] Harvey and Gillis, *The Big Fix*.

[118] Harvey and Gillis, *The Big Fix*.

[119] Harvey and Gillis, *The Big Fix*.

[120] Harvey and Gillis, *The Big Fix*.

[121] Union of Concerned Scientists, “Electric Vehicle Survey Methodology and Assumptions,” February 2013, https://www.ucsusa.org/sites/default/files/2020-09/UCS-CU-Electric-Vehicle-Survey-Methodology.pdf.

[122] Union of Concerned Scientists, “Electric Vehicle Survey Methodology and Assumptions.”

[123] International Energy Agency, “Global EV Outlook 2022.”

[124] International Energy Agency, “The Role of Critical Minerals in Clean Energy Transitions” (Paris: IEA, 2021), https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

[125] International Energy Agency, “The Role of Critical Minerals in Clean Energy Transitions.”

[126] International Energy Agency, “The Role of Critical Minerals in Clean Energy Transitions.”

[127] International Energy Agency.

[128] Julie Chao, “Quantifying California’s Lithium Valley: Can It Power Our EV Revolution?,” *Lawrence Berkeley National Laboratory News*, February 16, 2022, https://newscenter.lbl.gov/2022/02/16/quantifying-californias-lithium-valley-can-it-power-our-ev-revolution/.

---

[129] Geothermal Technologies Office, “Lithium Valley: Powering Our Clean Energy Transition,” Office of Efficiency & Renewable Energy, U.S. Department of Energy, October 20, 2022, https://www.energy.gov/eere/geothermal/articles/lithium-valley-powering-our-clean-energy-transition; International Energy Agency, “The Role of Critical Minerals in Clean Energy Transitions.”

[130] Blue Ribbon Commission on Lithium Extraction, “Draft Report of the Blue Ribbon Commission on Lithium Extraction in California,” TN# 246170 (California Energy Commission, September 21, 2022), https://efiling.energy.ca.gov/getdocument.aspx?tn=246170.

[131] AlixPartners, “2022 AlixPartners Global Automotive Outlook.”

[132] John Gartner, “Silicon Shortage Stalls Solar,” *Wired*, March 28, 2005, https://www.wired.com/2005/03/silicon-shortage-stalls-solar/.

[133] Jennifer Kho, “Silicon Shortage Has Big Impact,” *GTM Greentech Media*, September 26, 2007, sec. Solar, https://www.greentechmedia.com/articles/read/silicon-shortage-has-big-impact-118.

[134] Bye and Ceccaroli, “Solar Grade Silicon.”

[135] Way et al., “Empirically Grounded Technology Forecasts.”

[136] International Energy Agency, “World Energy Outlook 2020,” accessed October 13, 2020, https://www.iea.org/reports/world-energy-outlook-2020; International Energy Agency, “World Energy Outlook 2020 – Press Release,” IEA, accessed October 13, 2020, https://www.iea.org/reports/world-energy-outlook-2020.