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Resources

The Road Ahead

Where Will the Transportation Sector Go Next?

POWERSHIFTING

Can States Take the Steering Wheel?

State governments may get in the driver's seat

CARS IN CHARGE

Electric Vehicle Charging Stations

How much, and who benefits?

BATTERY MATTERS

Critical Mineral Supply Chains

Who in the world has market power?

FLIGHT RISKS

Sustainable Aviation Fuels

Key considerations for policymakers


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A Note from RFF's President

A Cleaner Transportation Sector Remains a Focal Point

An important lever to achieve our mission at Resources for the Future (RFF) has always been direct policy engagement. As you can imagine, unprecedented changes to federal policy in 2025 will require us to adapt our own engagement moving forward. However, key stakeholders continue to turn to RFF for clarity and guidance as the world moves forward. Consequently, I am proud to reiterate that RFF, just like it has been for nearly 75 years, will continue to be an objective voice on policy decisions at all levels of government. Our mission has and always will be to bring rigorous, nonpartisan economic research to current and future environmental, energy, and natural resource decisions.

This *Resources* magazine issue focuses on RFF's Transportation Program, which covers one sector of the economy in which we are seeing the policy landscape shift. Our emphasis on this sector stems from the fact that transportation consumes the majority of petroleum used in the United States, is the largest source of greenhouse gas emissions in the country, and contributes significantly to local air pollution. Meanwhile, the general public tends to be particularly sensitive to the price of gasoline. Substantive policy changes over the last several years have centered on these issues, with RFF providing research that informs how policies can be both economically viable and environmentally sound.

In this issue of *Resources*, you'll read more about what policy actions may look like among US states as the federal government steps away from climate change commitments. We also analyze prices at public charging stations for electric vehicles, along with the critical mineral supply chain and its relationship to China. These are just a sample of the insights from our Transportation Program.

Even before impending policy changes get announced or implemented by the new federal administration, we still face big questions, such as: What are the policy challenges associated with accessing and meeting the demand for the critical minerals on which many transportation technologies rely? How do we tackle the future of lower-emissions aviation or medium- and heavy-duty vehicle fleets? Throughout the evolving and uncertain policy landscape of 2025, we remain committed to answering these and other key questions.

RFF will continue to be an honest and objective partner as policymakers debate environmental and energy solutions, including those related to transportation. We look forward to working with you all in having critical conversations about these economic decisions and finding shared areas of breakthrough. Thank you, as always, for your support and partnership.

Sincerely,

Billy Pizer

Billy Pizer
President and CEO, Resources for the Future

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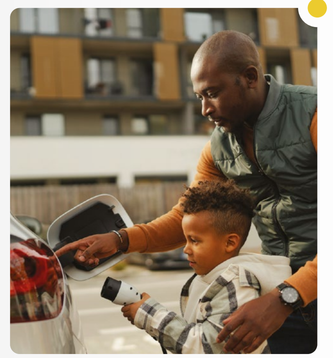
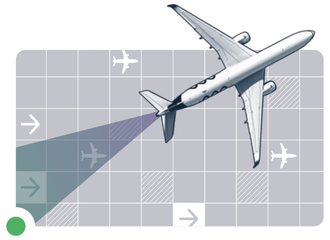
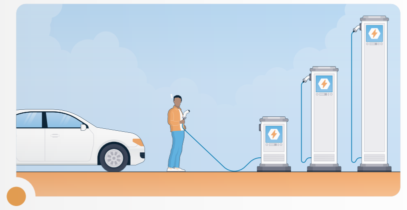
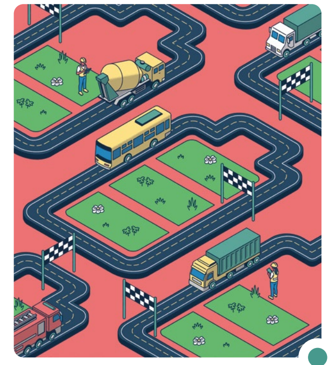








CAN STATES TAKE THE STEERING WHEEL?

Federal policy for the transportation sector will change with the new Trump administration—including what happens to the incentives and regulations related to increasing electric vehicle supply and demand. As a result, state governments may find themselves in the driver's seat to effectively steer transportation policy toward decarbonization goals.

TEXT Beia Spiller, Joshua Linn, and Nafisa Lohawala

ILLUSTRATION James Round

Demand for light-duty electric vehicles (EVs) has risen to about 10 percent of new vehicle sales nationwide, with California and a few other states far exceeding that average. Though part of this success has been due to improvements in EV manufacturing and quality, along with reduced battery costs, policies at the state and federal levels have played an important role. Effectively decarbonizing the transportation sector has relied on a whole-of-government approach, with various state and federal policies supporting one another to help move the needle toward increased EV adoption, particularly for passenger vehicles.

Given a recent decline in federal and monetary support for the EV transition, states will need to ramp up their own spending and strengthen their policies if they want to ensure continued advancement of EV adoption.

Three major types of policies have helped boost EV adoption to date: vehicle emissions standards, federal and state subsidies for vehicles and charging stations, and state-level EV mandates. These policies reinforce one another, working to simultaneously encourage EV manufacturing and increase demand by subsidizing vehicle purchases and expanding charging infrastructure. This policy complementarity means that weakening or removing one is likely to make the others less effective.

Resources for the Future (RFF) research has demonstrated that California's EV mandate (the Advanced Clean Cars rule) helped the federal government increase the stringency of fuel efficiency standards. Without the mandate, manufacturers would have felt less pressure to make and sell EVs. Likewise, other RFF research has demonstrated that subsidies for public charging stations and EV purchases can reinforce one another in a positive feedback loop.

On January 20, 2025, President Donald Trump released an executive order titled Unleashing American Energy, which put a spotlight on actions that the administration may take to weaken vehicle electrification policies, potentially including the following:

- Halting the release of funds that were allocated in the Infrastructure Investment and Jobs Act for investments in charging stations through the National Electric Vehicle Infrastructure Formula Program and the Charging and Fueling Infrastructure Grant Program. Jointly, these programs represented an investment of $7.5 billion.
- Revisiting and loosening vehicle emissions standards, which had placed strong pressure on manufacturers to increase EV production.
- Eliminating the federal waiver that allowed California (and, subsequently, other states) to adopt an EV mandate.

Eliminating tax credits for EV purchases and battery manufacturing also may be in the works, though not included in recent executive orders. The tax credits would have cost the federal government $390 billion by 2028, according to estimates from the Massachusetts Institute of Technology—an order of magnitude larger than originally estimated by the Congressional Budget Office.

Cutting subsidies for public charging stations and certain EV purchases presumably would require congressional action, but the administration might try to weaken federal standards or revoke the waiver unilaterally. Already, the administration has moved forward on blocking the release of funds from the National Electric Vehicle Infrastructure Formula Program and temporarily paused the electric school bus subsidy program.

These policy changes are likely to affect both the supply and demand of EVs. Automakers that have invested heavily in EVs may choose to stay committed, but some may scale back expansion plans or shift their focus to hybrid and gasoline vehicles, especially if EV demand declines. On the demand side, high-income consumers and fleets owned by large corporations like Amazon, which see EV investments as profitable, are likely to remain active in the EV market. However, price-sensitive buyers are more likely to delay EV adoption in the absence of federal incentives.

If Federal Policy Gets Scaled Back, Can States Act Independently to Achieve Their Own Goals for Electric Vehicle Adoption?

California has strong decarbonization goals for the transportation sector and has implemented a variety of policies that push forward EV adoption. In December 2024, California approved a $1.4-billion investment in charging stations statewide, which could replace the funds for infrastructure that would have come from the federal government. However, other states are fully reliant on federal funding. Given local budget shortfalls in California, and with its ongoing fire disasters, how much the state can afford to subsidize EVs remains an open question. Furthermore, California also has implemented its own emissions standards, which are part of the Advanced Clean Cars rule. However, if the waiver is rescinded, California (and others that followed the state's lead) will no longer be able to set its own emissions requirements for vehicles.

> “Reducing federal support creates a challenge for ensuring a robust supply of electric vehicles and public charging stations nationwide.”

> “Given their limited resources, states will need to focus on finding the most cost-efficient policies to boost demand and to incentivize innovation and investment on the supply side.”

Beia Spiller is a fellow and director of the Transportation Program, **Joshua Linn** is a senior fellow, and **Nafisa Lohawala** is a fellow at Resources for the Future.

Reducing federal support creates a challenge for ensuring a robust supply of EVs and public charging stations nationwide. Uncertainty about federal emissions standards and federal policies for EV charging hampers investment decisions for manufacturing, such as building new facilities for vehicle and battery production. Similarly, investors in charging stations will want some level of certainty regarding future demand so they can make informed investments. For states to achieve their goals, they will have to find policies that can provide some certainty for auto manufacturers and charging-station investors.

Moreover, states will be working against market forces. Vehicle manufacturers already have begun revisiting and scaling back their EV commitments. For example, General Motors in July 2024 backed out of its plan to manufacture a million EVs by the end of 2025. Similarly, the Alliance for Automotive Innovation penned a letter to Trump in November 2024, asking for a “stable and predictable regulatory environment” with standards that are “reasonable and achievable” and “aligned with current market realities.” The letter intimates a request for a reduction in stringency, given seemingly unfavorable market conditions. The slowdown in the growth rate of EV adoption in 2024 contributed to manufacturer concerns about the profitability of EV investments.

If States Can, Then How?

To meet ambitious goals that address climate change and EVs in the absence of federal support, state governments will have to revisit both the scope of their policies and the magnitude of their investments for transitioning to EVs. Given their limited resources, states will need to focus on finding the most cost-efficient policies to boost demand and to incentivize innovation and investment on the supply side.

For states with ambitious decarbonization goals and limited budgets, identifying and implementing policies that also maximize the broader benefits for economic and social well-being in the energy transition also would be valuable. (See page 18 in this magazine for more on the topic.) Because public support for federal EV policy has waned over the years, a more decentralized policy approach may be viewed more favorably and would allow states to chart their own decarbonization pathways.

Underlying these pending policy decisions, of course, is rigorous evidence. Timely research, including work that facilitates a better understanding of the barriers to EV adoption and how to overcome those barriers, can help guide states in identifying the most cost-effective suite of policies. One interesting example is the use of restructured registration fees to encourage electric truck adoption, as proposed by economist James Sallee. Understanding the price tag that's involved for a state to achieve its EV goals without any federal support is an open question which also can benefit from more research.

Importantly, investments in EVs have broader implications above and beyond the fuel that powers the vehicle. Research has shown that growth in the EV fleet can drive job creation; for example, through an increase in EV manufacturing, a boost in battery manufacturing, and the workforce deployment required for the maintenance and operation of EVs and charging stations. Indeed, the letter to Trump from the Alliance for Automotive Innovation asked for the continuance of EV tax credits due to the benefits that have accrued in terms of increased manufacturing and job creation. Of course, reducing sales of new gasoline vehicles would reduce employment at certain production facilities and possibly for auto mechanics, as well. Thus, the effects on national and regional employment of slowing EV adoption still are unclear. Furthermore, charging stations placed in urban settings can have positive economic spillovers to neighboring businesses and can help improve outcomes such as affordability, accessibility, and broader economic growth for local communities if investments are made carefully.

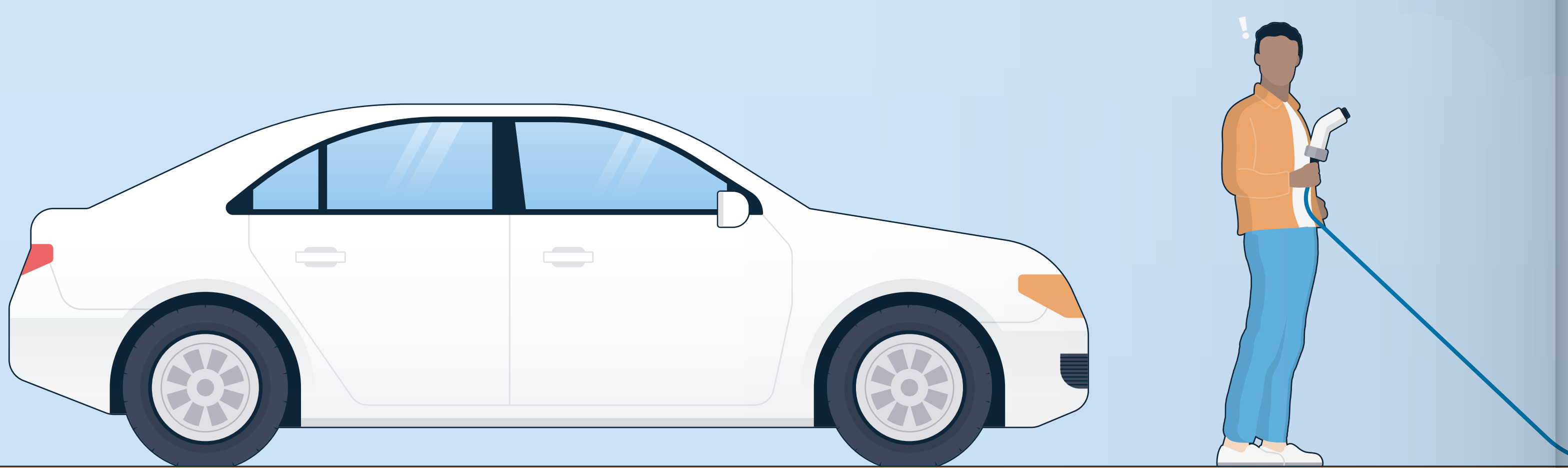
Researchers at RFF will continue to track the quickly evolving world of federal and state policies in the EV space to provide relevant evidence of the trade-offs and possible outcomes for vehicle fleets among states and nationally. ■

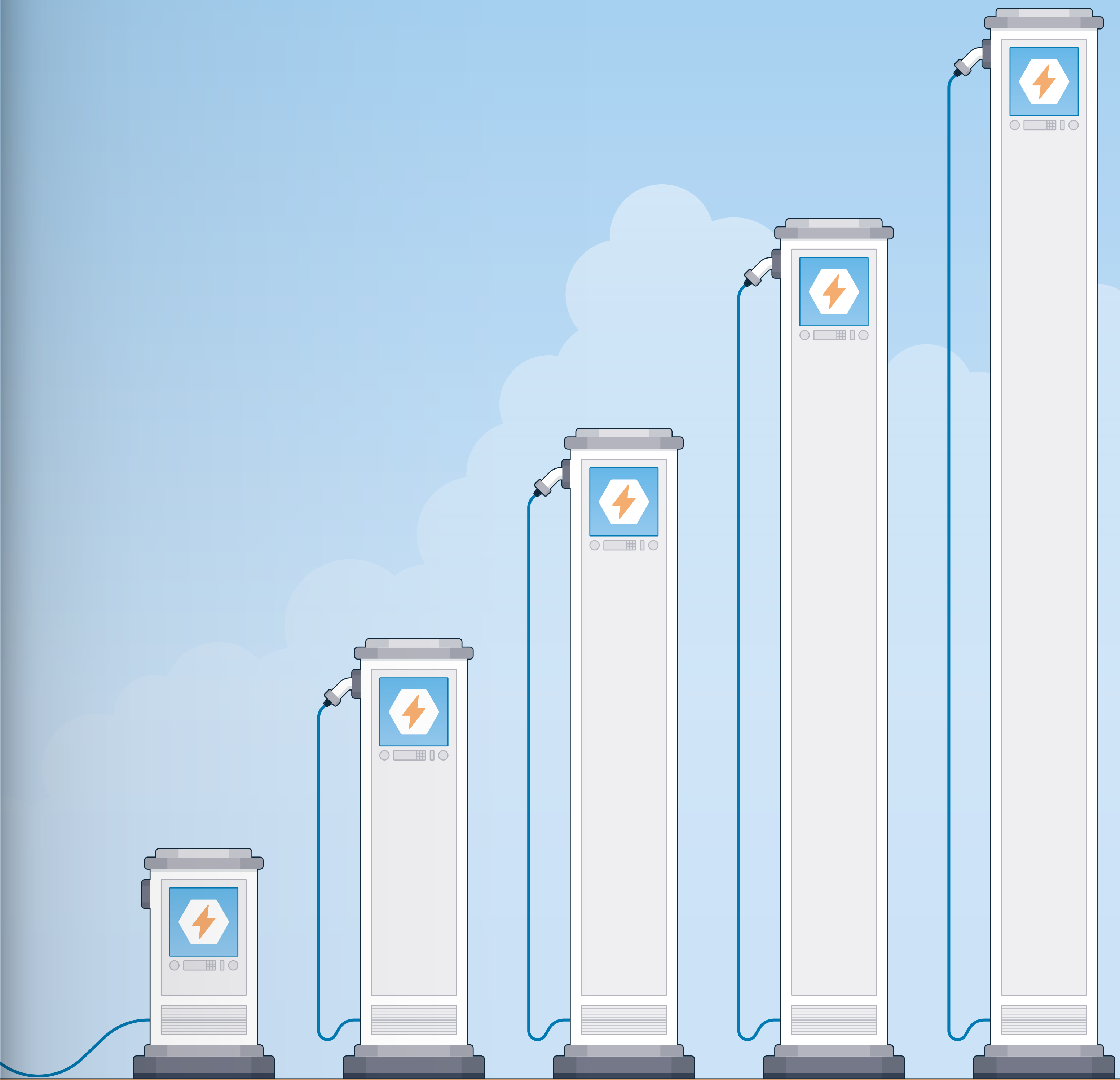
Pain at the (Electric Vehicle) Pump?

Electric vehicle owners would be right to complain that figuring out the cost of car charging can be confusing. Our research addresses this problem head on, so policymakers can take action to avoid "pain at the pump" and ensure that electric vehicle adoption is a good financial decision.

TEXT Beia Spiller, Trenton Marable, and Benjamin Leard

ILLUSTRATION James Round





A cornerstone of advancing electric vehicle (EV) adoption is investment in public charging stations. Charging stations are fundamental for accommodating long-distance travel, including along major highways and at destinations. Though the majority of EV charging currently happens at home and overnight, as EVs become more popular, the share of drivers who are entirely dependent on public chargers (e.g., due to the lack of a home garage) will only increase. The price at the charger therefore will affect the cost of operating an EV, whether for daily use or vacation travel. Because EV adoption generally is promoted as a money-saving opportunity, if the charging prices are high enough, those savings could evaporate, in turn reducing the rates of adoption.

But what exactly are the prices that people find when they charge their EVs in public? That question currently is hard to answer, mainly because prices are not being tracked in a systematic manner. Also, charging operators have choices about how to price their services: flat rates per session, dollars per kilowatt-hour (kWh) consumed, dollars per minute or hour charged, and more. Some operators, such as Tesla, even choose to vary the charging price over the course of the day based on fluctuations in demand. Furthermore, many of these EV charging prices are not available to view online or on a phone app. For prices that actually are listed online, the display format depends on the operator's decision of how to price their services, which produces inconsistency and reduces the ability of drivers to compare prices within and across charging networks.

Given the lack of price transparency and consistency across stations, understanding what price people actually will pay when they access a public charging station becomes important. To that end, we gathered data to evaluate charging prices across the country and how these prices vary across locations. We seek to explore two major lines of inquiry with these data:

How does the cost of public charging compare to the cost of at-home charging?

If the price difference is large (with prices at public chargers outpacing lower costs for home charging), challenges can arise with how benefits and costs get distributed across different types of households—with greater disadvantages for households that don't have access to private charging. Specifically, EV owners who have access to a private garage are more likely to be wealthier, while those who live in multi-unit housing are less likely to have access to at-home charging and more likely to have lower incomes. Thus, higher prices paid at public chargers means that wealthier drivers likely will benefit financially much more from the adoption of an EV.

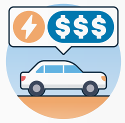
How does the cost of EV charging compare to refueling a gasoline vehicle?

Many analyses which conclude that EV charging is cheaper than gasoline fueling rely upon the assumption that individuals will charge only at home, though this assumption ignores those EV owners who have no at-home charging opportunities and those who will occasionally charge en route. Quantifying how costs truly compare when EV owners access public charging will be fundamental to understanding how public-charging prices may affect the adoption of EVs, given competition with gasoline.

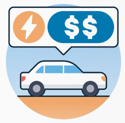
To begin to answer these questions, we gathered a snapshot of public data from the Alternative Fuels Data Center, which lists public pricing at a subset of charging stations across the country, from January 23, 2025. The data list the speed of the charger: either direct current fast chargers (DCFC; much faster than other options, these can almost fully recharge a vehicle in 20 minutes to an hour) or Level 2 chargers (L2; these chargers usually take 4–10 hours to recharge the battery). Because price formats are listed inconsistently, we make assumptions about battery capacity and the time required to recharge, and we convert all listed price formats as $/kWh.

Though a substantial number of chargers are listed as free in the Alternative Fuels Data Center database, station operators may stop offering free charging as demand for EVs grows, and some of these free charging stations may not be fully accessible to the public. Thus, for the purposes of this article, we focus our analyses only on stations that offer positive (non-free) prices when we calculate the cost differential for residential EV charging rates relative to gasoline refueling. By focusing only on positive prices, we can provide a more accurate depiction of how costs compare for current EV drivers who may not be able to access the free public-charging options.

Watts the Difference?



Direct Current Fast Charging
DCFC rapidly recharges EVs in 20–60 minutes, but is the most expensive public charging option available.

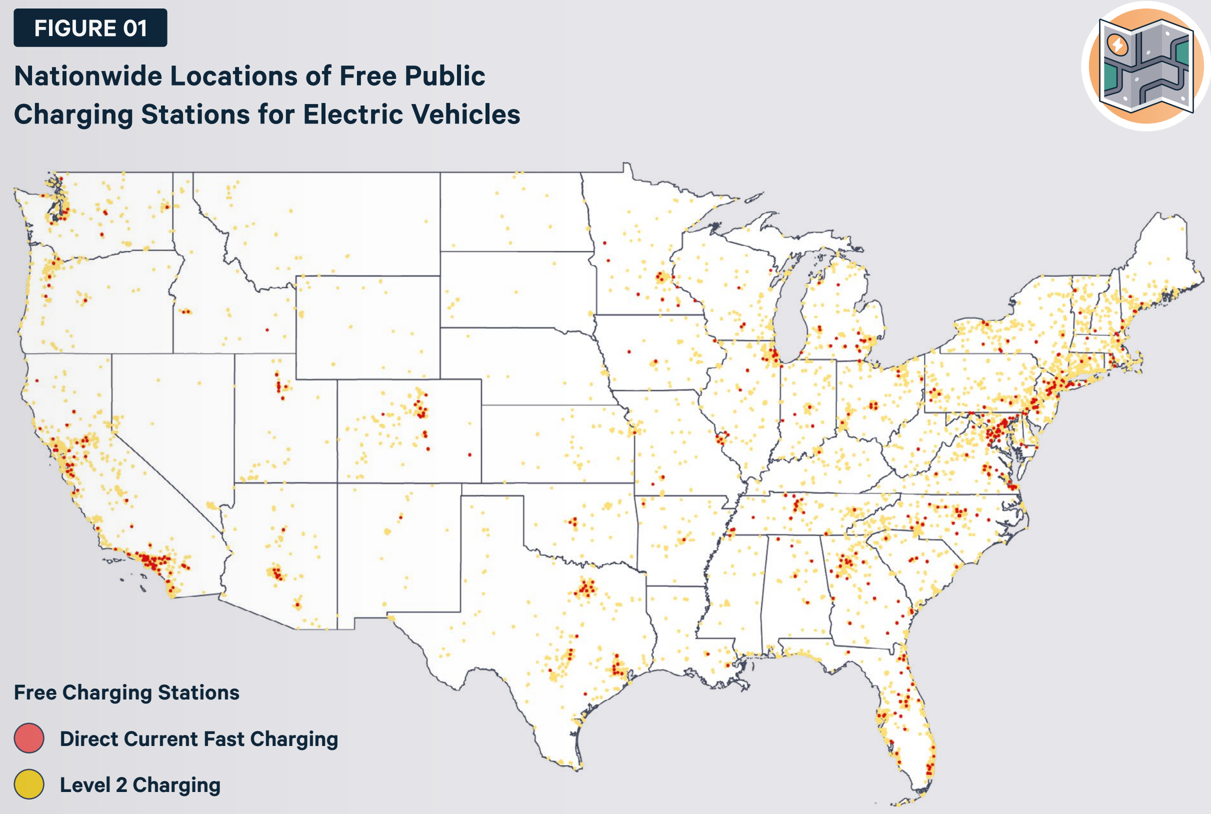


Level 2 Charging
L2 charging takes 4–10 hours, costs less than DCFC, and is common at public stations and home installations.

At-Home Charging
At-home EV charging is the slowest but cheapest option, offering significant annual savings for those with private access.

> **"Given the lack of price transparency and consistency across stations, understanding what price people actually will pay when they access a public charging station becomes important."**

FIGURE 01
Nationwide Locations of Free Public Charging Stations for Electric Vehicles



Did you know?

Most charging happens at home overnight—but not everyone has access, especially in apartments or other multi-unit housing.

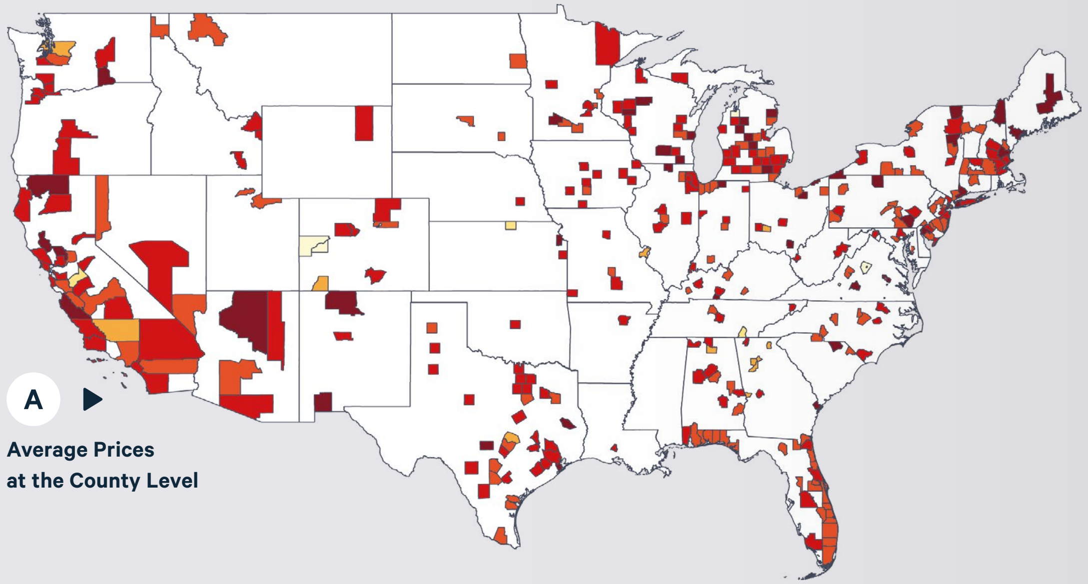
Electric Vehicle Charging Prices Across the Country

We first explore how prices vary spatially. Free DCFC and L2 charging stations can be found throughout the country (Figure 1). Many of these free charging stations are subsidized by local governments or utilities to promote local EV adoption or as a public good, and some businesses may still offer free charging as an incentive for their customers. However, while charging technically may be free at these charging stations, some may require additional membership or payment for parking and use that is not reported online or in apps. For example, free charging stations may be in a parking garage with paid parking, require a purchase at the host business, or be accessible only by the employees of an office building. Notably, fewer DCFC stations are available for free because the capital costs and operational costs of these stations are much higher than for L2 chargers. Including the existing free DCFC stations in our analysis drops the average price to $0.24/kWh for DCFC chargers and $0.02/kWh for L2 chargers.

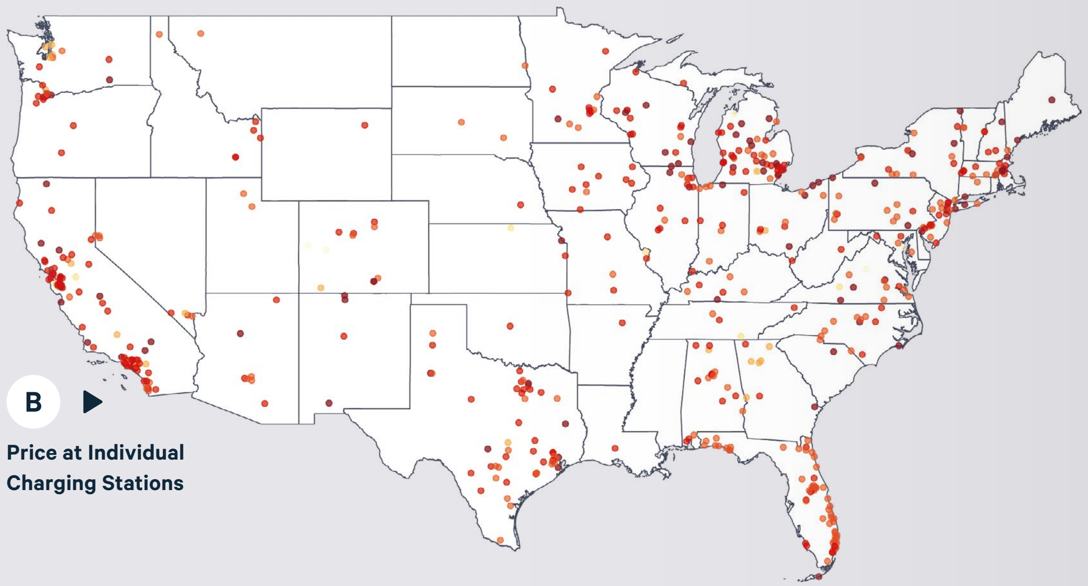
Figures 2 and 3 show prices for a subset of non-free DCFC and L2 charging stations that offer the information to the Alternative Fuels Data Center database, either averaged by county or at the station level. These maps show significant variation across locations, with

FIGURE 02

Price to Charge an Electric Vehicle at Direct Current Fast Charging (DCFC) Stations



A Average Prices at the County Level



B Price at Individual Charging Stations

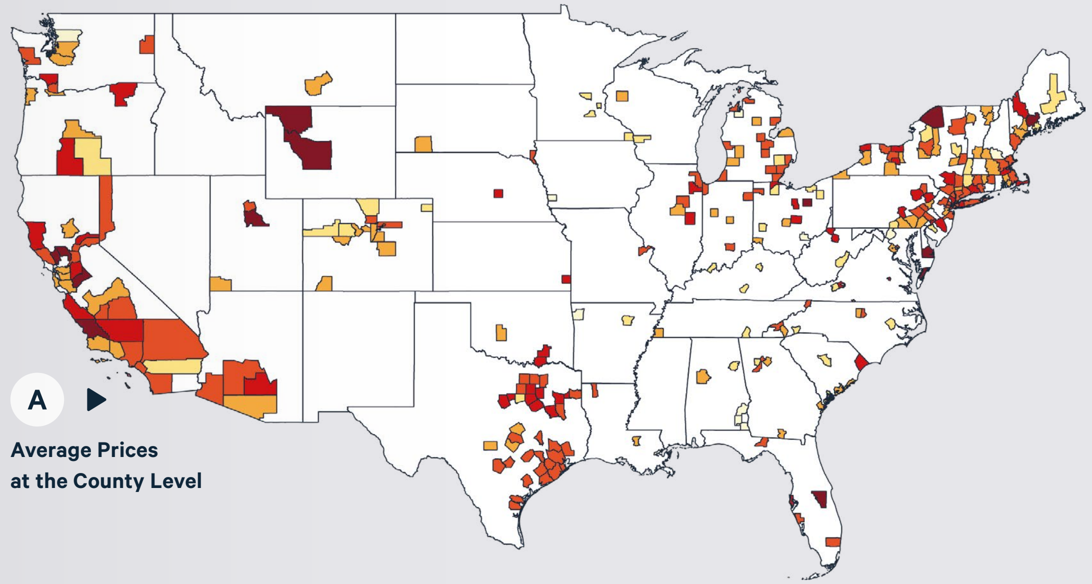
Average Station Price ($/kWh)

kWh = kilowatt-hour

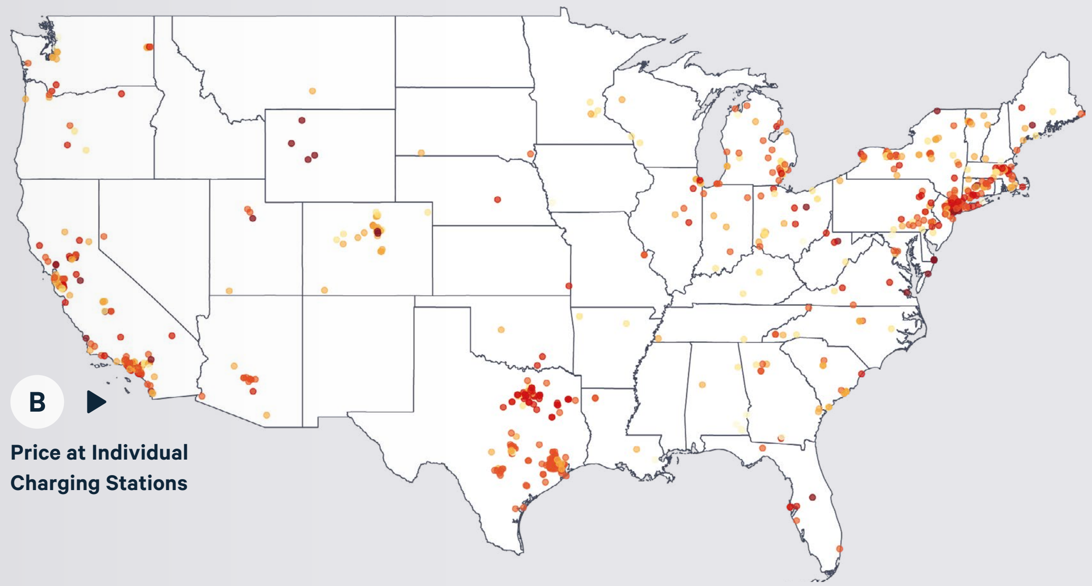
Cheaper ← 0.00–0.09 · 0.10–0.19 · 0.20–0.29 · 0.30–0.39 · 0.40–0.49 · 0.50+ → Costlier

FIGURE 03

Price to Charge an Electric Vehicle at Level 2 (L2) Charging Stations



A Average Prices at the County Level



B Price at Individual Charging Stations

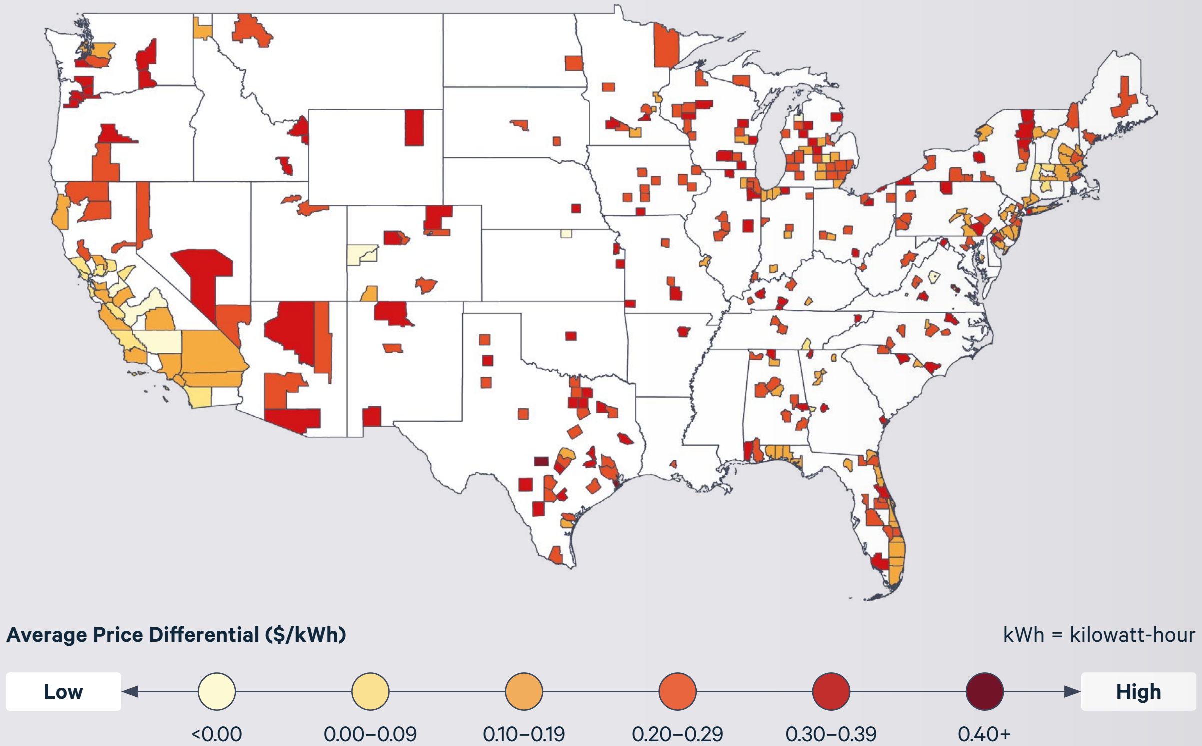
Average Station Price ($/kWh)

kWh = kilowatt-hour

Cheaper ← 0.00–0.09 · 0.10–0.19 · 0.20–0.29 · 0.30–0.39 · 0.40–0.49 · 0.50+ → Costlier

FIGURE 04

County-Level Average Price Differential for Public Direct Current Fast Charging (DCFC) Relative to At-Home Charging



prices varying from just a few cents to over $1/kWh for DCFC, and to over $0.40/kWh for L2. Excluding free stations, the average price to charge an EV is $0.43/kWh for DCFC chargers and $0.30/kWh for L2 chargers.

Comparing Prices for Public and Private Charging

We now look at how these prices for public EV charging compare to residential electricity rates, which represent the price of at-home charging. We utilized data from the US Energy Information Administration, which provides electricity prices at the level of electric service providers, to calculate prices at the county level. Our analysis ignores the fact that home pricing may be subject to much lower overnight rates through time-of-use off-peak pricing. We calculate average price differentials as the difference between the average $/kWh rate at a public station and the average $/kWh rate for at-home charging. Figures 4 and 5 show significant variation across the country, with lower price differentials found in California and some parts of New York State.

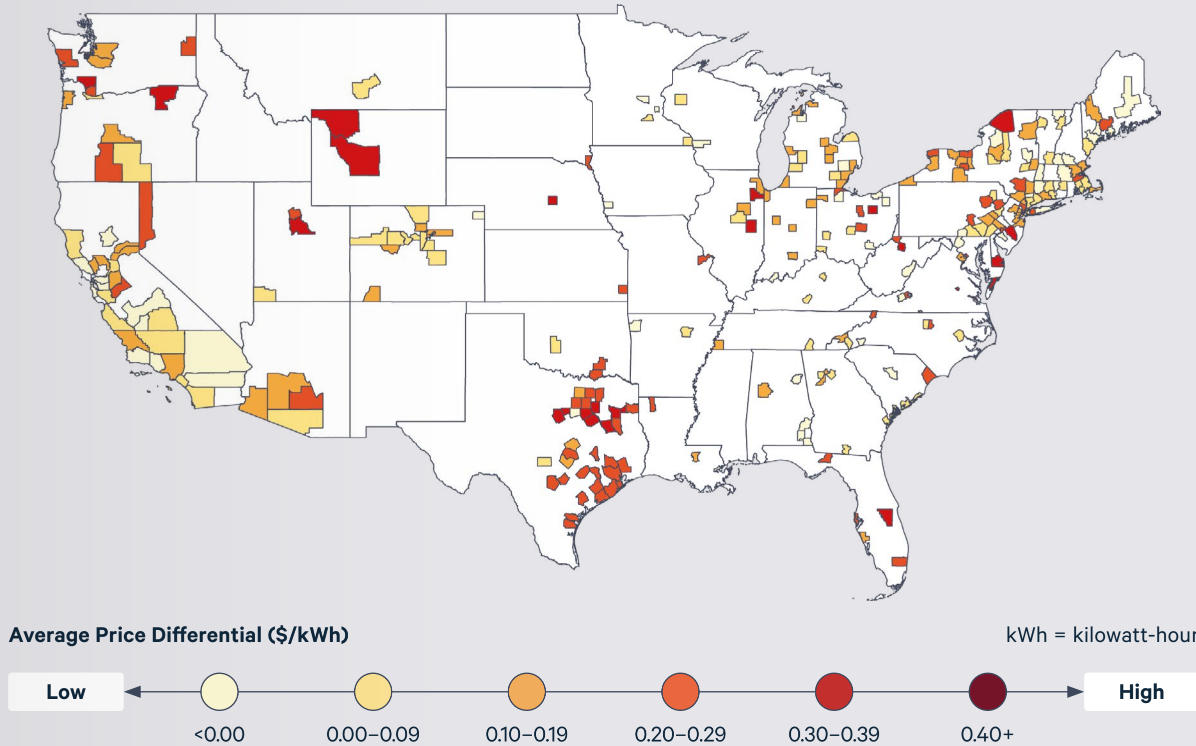
After excluding data from a few stations that offer atypically high prices, we find an average price differential of $0.24/kWh for DCFC and $0.09/kWh for L2 charging relative to at-home charging. Differences in price can be extremely high at some charging stations, such as certain DCFC stations in Warren County, New York ($0.37/kWh); Monroe County, Florida ($0.39/kWh); and Gillespie County, Texas ($0.47/kWh).

Did you know?

Prices at public charging stations can vary significantly—from just a few cents to over $1 per kilowatt-hour.

FIGURE 05

County-Level Average Price Differential for Public Level 2 (L2) Public Charging Relative to At-Home Charging



> **“Given the lack of price transparency and consistency across stations, understanding what price people actually will pay when they access a public charging station becomes important.”**

Comparing the Cost of Electric Vehicle Charging vs. Gasoline Refueling

Finally, we explore the difference in cost between EV charging and gasoline refueling (Table 1). Most EV owners will use some combination of at-home, DCFC, and L2 charging; however, we assume that the driver uses just one of these options when we calculate the average cost of charging an EV.

We find that the average cost of charging an EV can range from $844 to $1,843 per year, depending on whether the charging happens at home, at a DCFC station, or through L2 charging. On the other hand, refueling with gasoline costs an average $1,655 per year. These results imply that EV owners can save an average $811 per year if they charge at home, whereas an EV owner may end up spending $188 more if they charge their EV only at DCFC stations away from home. The amount saved or incurred can vary significantly across locations (Figure 6). (For these calculations, we've used a conservative average EV fuel efficiency of 3 miles/kWh and gasoline vehicle fuel efficiency of 27.2 miles/gallon. The data for average fuel efficiency come from the 2022 National Household Travel Survey conducted by the Federal Highway Administration.)

FIGURE 06

County-Level Average Price Differential for Electric Vehicle Charging Relative to Gasoline Refueling

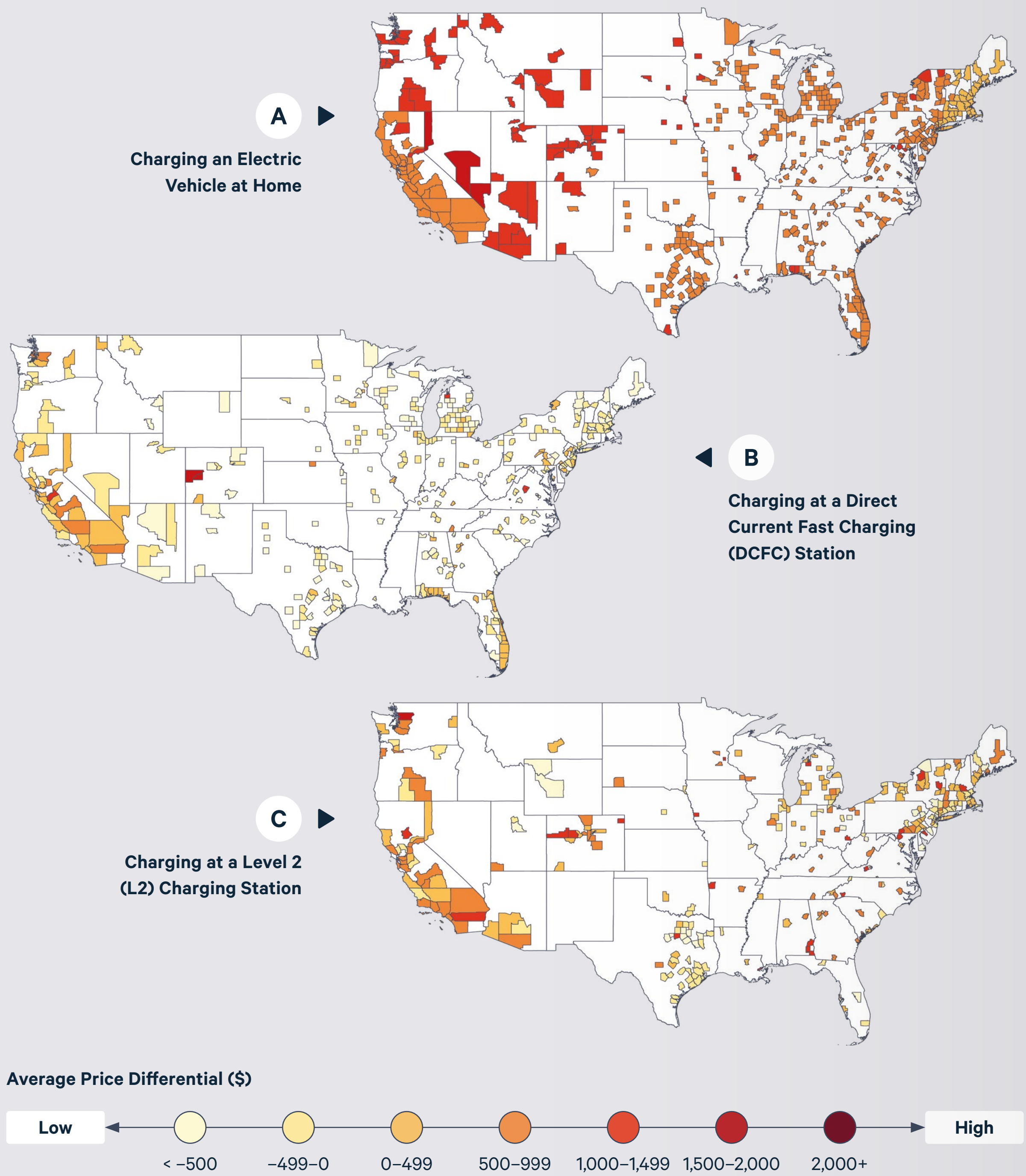


TABLE 01

Costs and Savings Associated with Electric Vehicle Charging, Relative to Refueling a Gasoline-Powered Vehicle

	Direct Current Fast Charging	Level 2 Charging	At-Home Charging	Gasoline Refueling
Cost	$1,843	$1,464	$844	$1,655
Savings	-$188	$191	$811	n/a

Clearly, home charging is the most financially viable option in terms of reducing the costs associated with EV operation. With public EV charging, and in particular DCFC, the cost is much higher and can exceed the costs associated with operating and refueling gasoline vehicles. Though installing an L2 charger in a garage can cost between $800 and $2,000, the benefits accrue quickly, providing a possible one-year payback period if the EV owner otherwise would use DCFC chargers exclusively.

Conclusions

We have shown that charging at public stations can be costly, yet further research would do well to answer some lingering questions.

Do people know what they will pay to charge their car if they purchase an EV?

Fuel economy labels, which are issued by the US Environmental Protection Agency, provide information for car buyers about the cost of EV charging and potential cost savings. But these labels assume a low refueling price; the agency's guidance to vehicle manufacturers regarding fuel economy labels for model years 2025 and 2026 assumes an electricity price of $0.17/kWh, which is about half the likely price for public charging. Whether the potential realization of higher charging costs results in buyer's remorse will be important to understand.

Are EV owners being educated about how costs differ based on where and how they may charge their car?

If sellers do not provide this information to car buyers, a potential outcome may include suboptimal financial decisionmaking about where, when, and at which speed the new owner ends up charging their EV.

What are the biggest contributors to high prices at public charging stations?

Quantifying the role of different policies (e.g., reduced commercial electric tariffs, incentives for market entry, requirements for price transparency and price formatting) in helping to reduce the price of public EV charging can help policymakers understand which policies may facilitate the lowest charging rates. For example, how do underlying commercial electric tariffs affect public charging prices, and what factors can lead to decreased costs for public charging?

Ultimately, does the price of public charging actually matter?

Specifically, are EV owners sensitive to prices at public charging stations? To what extent do EV drivers switch between public and private charging when prices increase? Understanding the degree to which high charging prices reduce demand (or not) will provide charging-station operators with key information to ensure that the stations are profitable and remain in business.

We are in the process of collecting more data for charging prices, charger utilization, and other useful variables, which will allow us to make progress in answering these questions. Unless we see more price transparency, gain a better understanding of the prices that EV owners will pay to recharge their vehicles, and learn how policies will affect these charging prices, "pain at the pump" soon could shift from a gas-station woe to an EV reality. ■

> "Understanding the degree to which high charging prices reduce demand (or not) will provide charging-station operators with key information to ensure that the stations are profitable and remain in business."

Beia Spiller is a fellow and director of the Transportation Program, **Trenton Marable** is a research intern, and **Benjamin Leard** is a university fellow at Resources for the Future.





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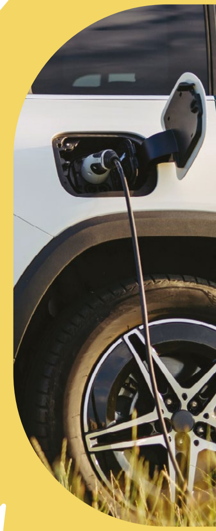
Leveraging Investments in Electric Vehicle Charging Stations to Maximize Public Benefits





TEXT Beia Spiller and Suzanne Russo

As federal funding for electric vehicle infrastructure shifts, US states are left to figure out how to continue such investments themselves—and how to get the most public benefits from those investments.














Electric vehicle (EV) charging stations, the infrastructure that directly supports the adoption of zero-emissions vehicles, have been rolling out over the past few years at an increasing rate. Though primarily led by private investments, this rollout also has been supported more recently by federal and state investments. In 2022, the federal government allocated over $7 billion through the Infrastructure Investment and Jobs Act to support investments in EV infrastructure across the country—both along major road corridors and within cities. However, less than $5 billion has been doled out to states so far, and the future of this current funding stream is unknown: On February 6, 2025, the Trump administration ordered a suspension of all funding for the National Electric Vehicle Infrastructure (NEVI) Formula Program until new guidance for the program is released. Even though some NEVI funds already have been obligated to states, the funds are available on a reimbursement basis, and the status of those reimbursements is unclear due to the executive order.

Several states have supplemented these federal investments with their own funds, too. For example, in early January 2025, California announced an investment of $1.4 billion for charging stations across the state. In February, New York announced a $60-million investment in charging stations.

Because the future of federal investments in charging stations is in flux, US states are facing a future in which they may become the sole provider of support for EV charging infrastructure.

EV owners rely upon a network of charging stations that is well-connected, affordable, and reliable. EV adoption is not widespread, necessitating the public investments that supplement private-sector activities. To date, EV ownership has skewed heavily toward higher-income, higher-educated, white, younger vehicle buyers, and private operators have located their charging stations in neighborhoods where similar characteristics predominate.

Because private-sector investments have led to an uneven distribution of charging stations across the country, a significant portion of government investments have attempted to target funds toward under-resourced neighborhoods. But this new pattern of investment prompts a question: How can these underserved neighborhoods fully benefit from the charging stations, especially if people who live there don't own EVs? In fact, some communities are concerned that these ostensibly positive investments may bring more harm than good, due to potential gentrification, increased traffic congestion, or even increased electricity prices due to a need for grid expansion.

To that end, in a working paper released by RFF in August 2024, RFF researchers and coauthor Rachel Wilwerding explored how states and local governments can work to ensure that these investments in charging stations—particularly those that are made in under-resourced communities—maximize the benefits to surrounding communities. Solutions include expanding access to both EVs and charging stations in underserved communities, maximizing opportunities for economic development, addressing the affordability of public charging services, and incorporating community voices into such planning.

To access their NEVI funding, states were required to complete an infrastructure plan that addressed a multitude of questions around how and where new charging stations would be placed. One section of the plan template, titled "Equity Considerations," required the applying state to describe how it would incorporate community voices into the planning process and to identify how 40 percent of these benefits would accrue to disadvantaged communities, given the Justice40 requirements that were tied to the grants. States also were required to discuss the nature of these benefits, which could include a focus on issues such as accessibility, jobs, mobility, and air quality.

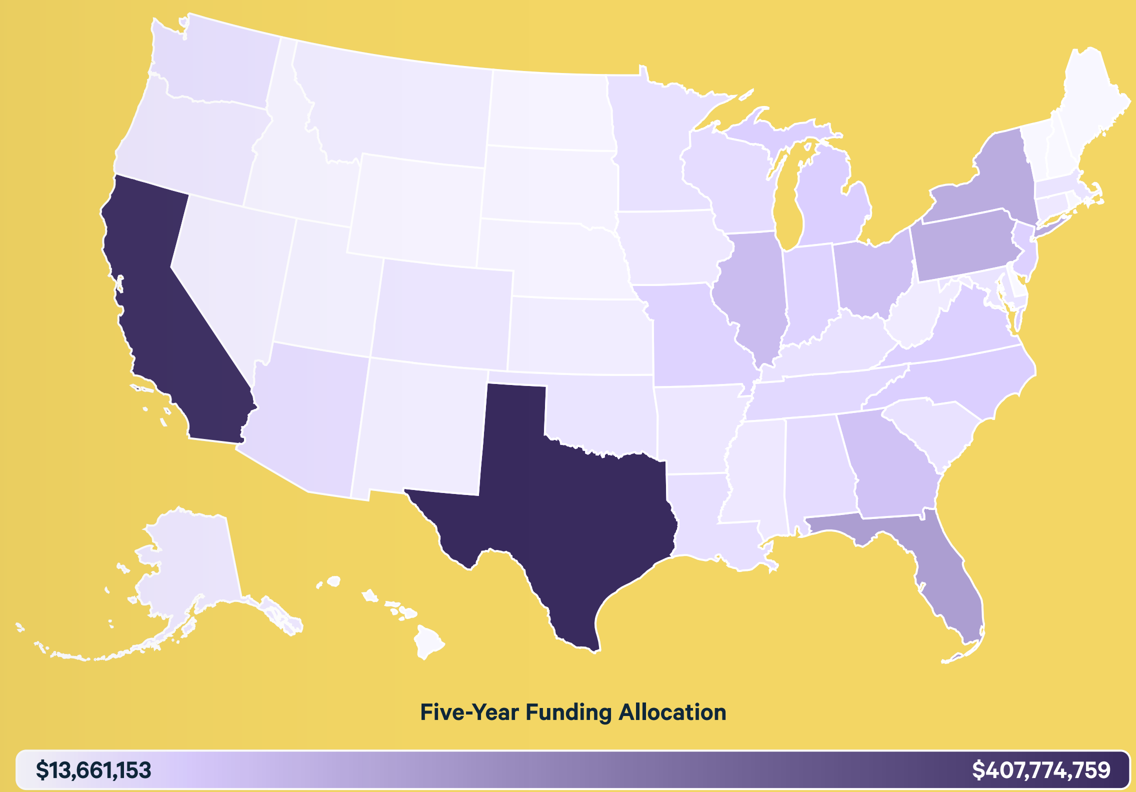
All 50 states (plus Washington, DC and Puerto Rico) submitted plans, which subsequently were approved by the Biden administration. Texas, California, Florida, and New York (in that order) received the largest allocations, with funds ranging from $175 million (New York) to almost $408 million (Texas) (Figure 1).

IMAGE MONTAGE (PREVIOUS PAGES)
Getty Images and Unsplash

FIGURE 01 (RIGHT)
Federal Highway Administration

> "Because the future of federal investments in charging stations is in flux, US states are facing a future in which they may become the sole provider of support for electric vehicle charging infrastructure."

Figure 01 State Distribution of Federal Funding through the National Electric Vehicle Infrastructure Formula Program



The plans that these four states submitted in 2022 are enlightening—particularly regarding how they approached equity considerations.

How Are States Approaching Disparities in Access to Electric Vehicle Charging Stations?

Each of these four states were explicitly relying upon NEVI funds to increase accessibility to EV charging stations in areas where private-sector investment has lagged. The states identified these underinvested places in qualitatively similar ways.

Texas notes in its plan that early investments in charging stations have been concentrated largely in urban and wealthier neighborhoods, leaving rural communities behind. To address this disparity, the state allocates approximately half of the NEVI funds to targeted investments in rural communities, with a focus on enabling long-range travel.

Florida mentions in its plan that 50 percent of the state's alternative fuel corridors are located in disadvantaged communities, noting that NEVI funds will help create a well-functioning corridor of chargers and "fill in the gaps and identify innovative solutions that support charging in rural, disadvantaged, and underserved areas."

New York, similarly, identifies coverage gaps in its existing network of charging stations and determines that the state's best approach is to target investments in rural areas and certain urban locations to serve the needs of drivers who live in multi-unit dwellings.

Finally, California's infrastructure plan states that at least 50 percent of the funding will go toward charging stations in underserved and low-income communities, helping to ensure greater accessibility for communities that have lagged in EV adoption and thus have not seen private investment in their neighborhoods.

Rural communities, then, have become a particular geographic focus of these states, despite their widely varying demographic composition and local political structures.

How Are States Incorporating Community Voices into Their Planning?

Investments in EV charging stations can have measurable effects on surrounding communities. The requirements for submitting the infrastructure plans revealed the importance of community engagement as one way to ensure these effects are positive. Bringing these communities to the table can help identify the locations and types of investments that will maximize the community benefits, above and beyond basic access to charging stations for their EVs. Yet the approaches vary widely for how these states engage with communities and incorporate community views into the infrastructure plans.

California makes a considerable effort to ensure that the voices of local communities are heard and community concerns are addressed through these investments in charging stations. The state benefits from existing structures that allow for this type of community input, as both the California Energy Commission and the California Department of Transportation, which jointly are responsible for implementing the NEVI Formula Program, have their own separate approaches to engaging with priority populations. Three distinct groups—the Disadvantaged Communities Advisory Group, the Interagency Equity Advisory Committee, and the Native American Advisory Committee—had been established previously to provide a link between community voices and decisionmakers in the state. California also has received written input from other, less formal groups about which types of charging stations would provide maximum benefits to the surrounding communities. All broad public engagement happens through a series of virtual webinars that are announced 10 days in advance.

New York also benefits from existing frameworks for community involvement that have been established through the state's 2019 Climate Leadership and Community Protection Act. The law created seven advisory panels, two of which were leveraged in the development of the state's infrastructure plan: the Climate Justice Working Group and the Just Transition Working Group. These panels receive input and have representation from a variety of community stakeholders, and the findings from these panels have been leveraged to develop targeted strategies for maximizing the community benefits of EV infrastructure investments.

Florida's approach to gathering community input on its plan was administered through eight listening sessions, 18 surveys, and a public comment period that was open for 13 days. The state received less than 200 comments, and the plan does not mention the involvement of any community groups in the state's decisionmaking process.

Similarly, Texas allowed a 15-day comment period after holding a virtual public meeting to discuss the plan. Texas conducted a multistate Tribal outreach and consultation shortly after the virtual public meeting. Information was shared with the public via online sources, including a webpage and social media. The infrastructure plan provides no further information about which, or whether, community groups provided input.

How Are States Envisioning Economic Development Around These Investments?

All four of the states with large NEVI funds identify workforce development as a benefit of investing in charging stations; however, only Florida's plan addresses local employment. Florida indicates that the state will seek to "[e]mploy a workforce that comprises residents that are geographically approximate to the location of the charging station site(s)" and requires contractors to include monthly reports on the number of its locally hired employees.

The other three states do include a focus on broader workforce-development goals. For example, Texas notes that each proposal for a NEVI contract needs to submit a "disadvantaged business enterprise plan" to be competitive. New York's infrastructure plan discusses the development of EV maintenance curricula that can be implemented in trade schools across the state. Finally, California's plan discusses the state's Zero-Emission Vehicle Market Development Strategy, which has workforce development as one of its four key pillars (along with vehicles, infrastructure, and end users).

> "Bringing these communities to the table can help identify the locations and types of investments that will maximize the community benefits, above and beyond basic access to charging stations for their electric vehicles."

> "If the price of public charging remains high, then the use of those chargers can decline and, in turn, reduce the spillover benefits to local communities."

Beia Spiller is a fellow and director of the Transportation Program and **Suzanne Russo** is a fellow at Resources for the Future.

In terms of broader economic development, California's plan introduces a competitive grant-funding opportunity to install charging stations along the state's alternative fuel corridors, which "may encourage applicants to utilize small businesses that meet the eligibility requirements as site hosts." This type of investment can provide benefits to small businesses for hosting a charging station, in the form of an increased customer base. Furthermore, the infrastructure plan describes how California will engage with rural and small businesses across the EV supply chain, thereby potentially increasing revenues for businesses beyond where the charging stations are sited.

Are States Addressing the Affordability of Charging Services?

Public charging stations can be much more expensive than at-home EV charging (see page 8 in this magazine for more on the topic), which creates a challenge for EV owners, as EV adoption generally is marketed as a way to reduce refueling costs. The higher the price at the charger, the less affordable the EV transition will be. This cost calculation is particularly important for the distribution of benefits associated with investments in charging stations, as lower-income households tend to have less access to at-home charging. High prices for public charging mean that lower-income households would continue to face a less affordable transition to EVs.

However, none of the four states address the affordability question in their infrastructure plans. The plans from California, New York, and Texas do not include the words "affordable" or "affordability" with respect to prices at charging stations. And Florida's focus on affordability is mostly aspirational, without providing many details about implementation. Specifically, the plan notes, "Florida is committed to leading the nation in providing a statewide network of convenient, equitable, affordable, reliable, and accessible EV charging infrastructure." Florida's plan also says that "evaluation is underway to deploy sites in a manner that drives competition while fostering innovation from the contracting industry."

Conclusion: Can States Fill In Funding Gaps and Maximize Public Benefits?

Achieving widespread access to EV charging stations will require government investment through charging station subsidies and operational support, particularly until EV adoption ramps up. The NEVI funds were designed to enable states to expand access to charging stations in places where EV adoption is low or profits from charging stations may not be immediately sustainable, thereby expanding the benefits of electric transportation. By reviewing the infrastructure plans from the four states that have received the most NEVI funding to date, we've found clues about how these states approach public investments.

As their plans demonstrate, stakeholders in US states are concerned about the lack of a well-distributed EV charging network and see clear benefits from increasing accessibility to charging stations. They also are aware of benefits that can accrue in the siting, permitting, construction, and use of charging stations—yet their approaches to including community input in the planning process are highly variable. Importantly, actively engaged communities can help states identify ways to maximize the benefits of these investments.

However, few states actively pursue actions to ensure the affordability of EV charging services. This lack of action is not just an issue that affects EV drivers' wallets—affordability issues can be problematic for achieving widespread economic benefits from these investments. If the price of public charging remains high, then the use of those chargers can decline and, in turn, reduce the spillover benefits to local communities. With access to additional research, states can help make the market more competitive, regardless of their ongoing investments.

In sum, with input from communities and policies grounded in research, states can move the needle toward achieving a decarbonized transportation sector and their own goals for social and economic development. ■

Market Power in Critical Mineral Supply Chains for Electric Vehicle Batteries

Policymakers who want to increase the capacity of the United States to process critical minerals for electric vehicle batteries need to weigh the trade-offs between the cost of investment and the potential benefits of reduced Chinese market power.

TEXT Sangita Gayatri Kannan and Michael Toman
ILLUSTRATION Daniel Garcia

The World of Critical Minerals

Critical minerals are materials that are essential to the economy but with few substitutes available in the near term. As global production of battery-powered electric vehicles (EVs) increases, so does the need for the critical minerals that are used in EV batteries: cobalt, graphite, lithium, manganese, and nickel. Ensuring reliable and affordable supplies of these "battery minerals" is a priority in the transition to low-carbon vehicles.

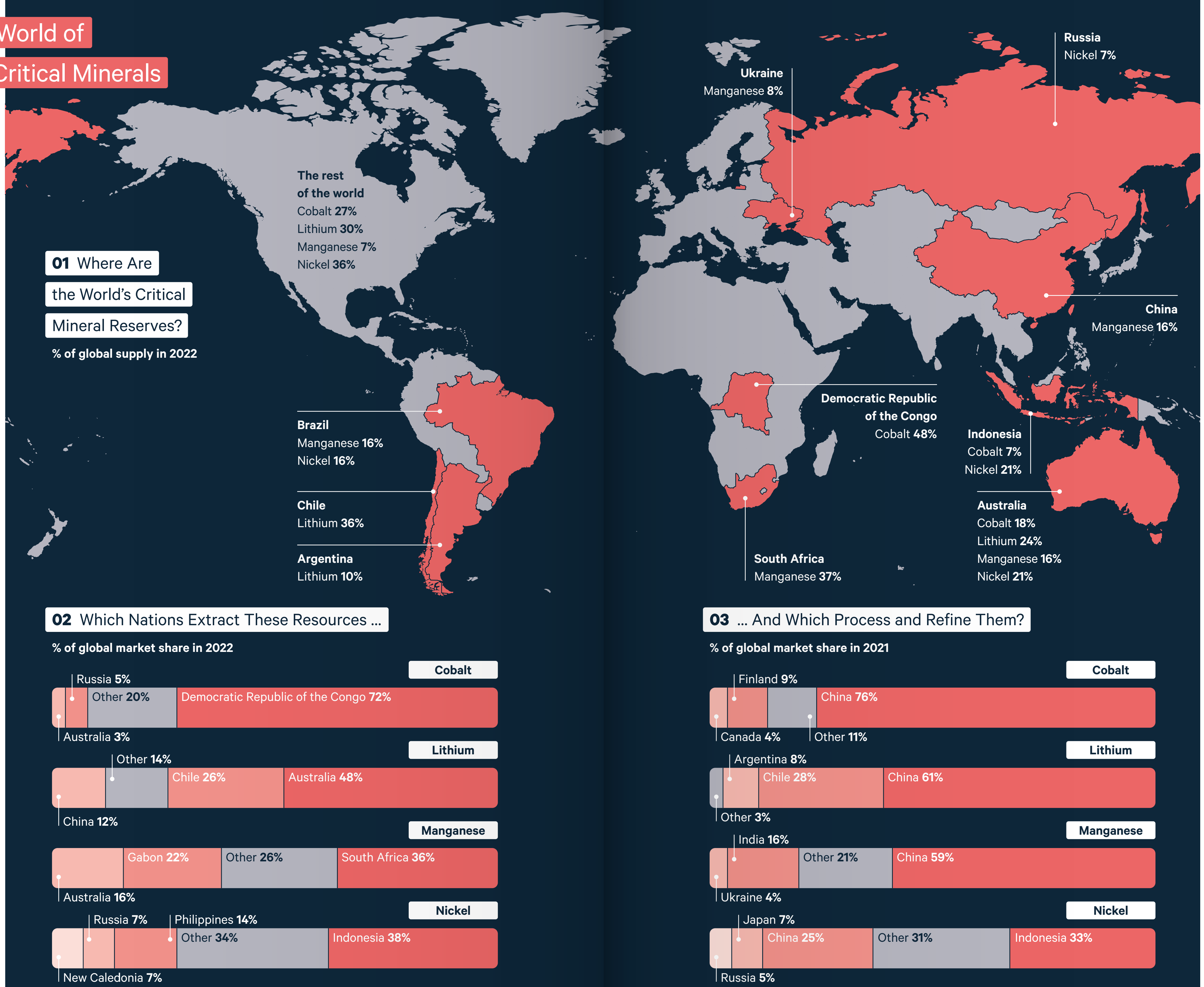
Concerns about the security of mineral supplies for batteries arise because China has a large market share in processing many of these minerals (though the extraction of most battery minerals occurs in a more geographically diverse group of countries). For example, China refined 65 percent of the global supply of lithium in 2020, and its capacity grew sevenfold from 2013 to 2020, whereas lithium processing capacity in the rest of the world expanded by only 10 percent in the same period. China also refined 74 percent of the global cobalt supply in 2021. Chinese refining capacity for cobalt grew at an annual rate of 24 percent from 1999 to 2021, whereas the rest of the world expanded capacity by less than 2 percent.

What Are the Risks?

Two types of concerns have been expressed about China's large market shares in battery mineral processing.

One is geopolitical risk; specifically, the possibility that China could be motivated by international conflicts to cut the quantities of critical minerals that it supplies to individual countries.

The other is the risk that China could exploit its market power to increase mineral prices, boost its own profits, and impose economic costs on dependent foreign buyers. China also could use its market power to flood markets and reduce prices, thereby deterring competitors from entering those markets.



INFOGRAPHIC
James Round

Evidence for Selective Supply Cuts and Exercise of Market Power by China

For China to selectively target reductions in the supply of particular minerals to specific countries would be challenging, given the way that markets for battery minerals work. Processors and buyers of minerals generally strike bilateral agreements that specify the quantities of processed minerals to be delivered and the prices to be paid. To restrict supply to particular countries, China somehow would have to effectively limit the reallocation of supply across entire markets. Accomplishing such restrictions would be a daunting prospect that could trigger retaliation.

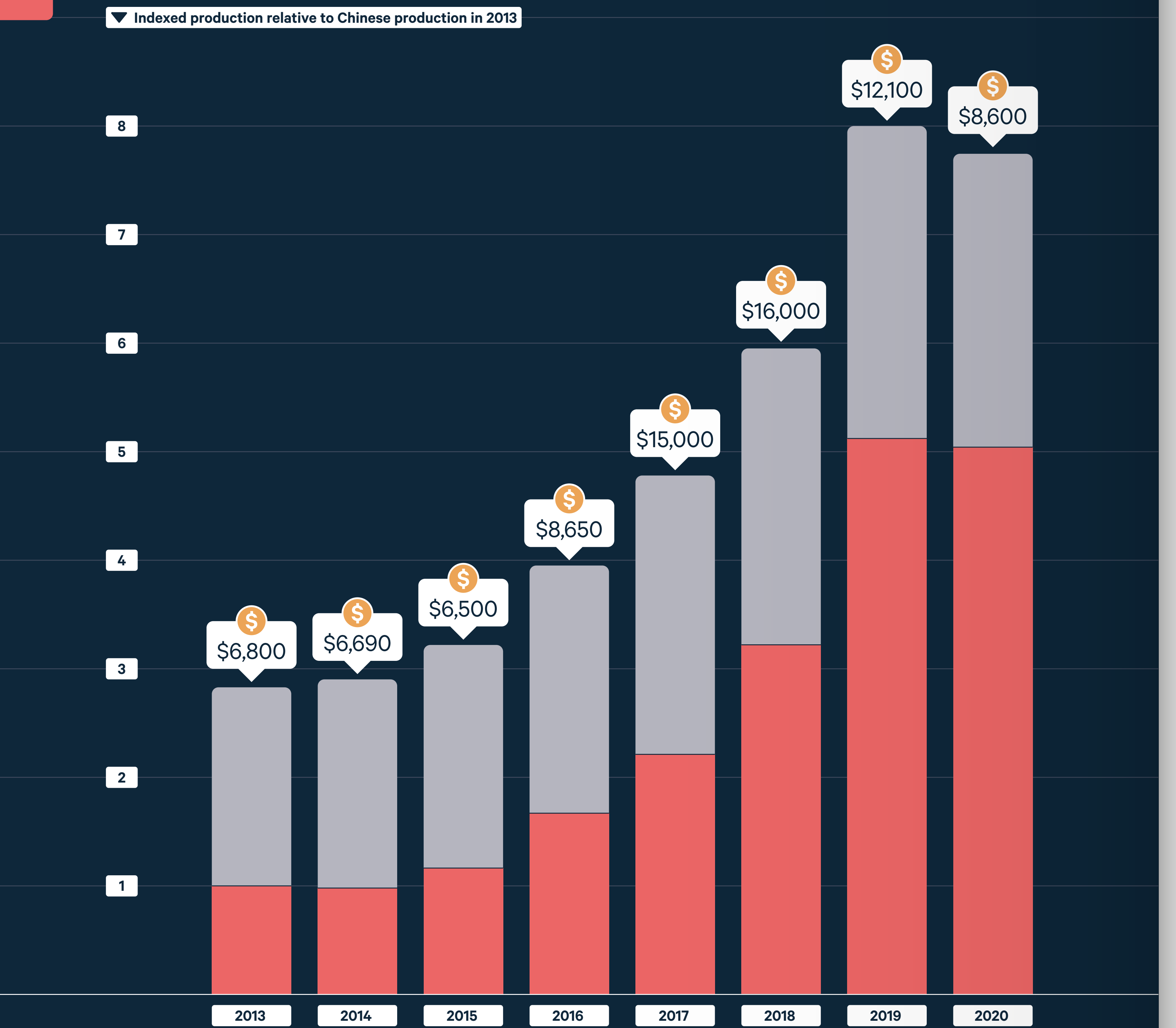
Some observers have highlighted a diplomatic dispute in 2010 between China and Japan that ostensibly led China to reduce supply to Japan of some non-battery critical minerals. The result of China's announcement of supply reductions was a jump in the price of the minerals for all buyers, which persisted well into 2011. However, an examination of relevant trade statistics shows no reduction in the supply of critical minerals to Japan during that period, nor any evidence of selective cuts in supply to any buyer between 2010 and 2019. China announced cuts in supply to the United States of the critical minerals gallium, germanium, and antimony in December 2024. Whether those announced cuts have the intended effect remains to be seen.

Some evidence suggests that China did not exercise market power when it could have. Lithium prices surged between 2015 and 2018 due to growing demand (Figure 1). This surge could have been an attractive opportunity for China to drive prices even higher by restricting lithium processing and slowing the expansion of refining capacity. However, the supply of processed lithium in China continued to increase rapidly during this period. Lithium processing also grew from 2018 to 2020, even as lithium prices declined. A similar pattern can be observed during a run-up in lithium prices

Figure 01 Production and Price of Refined Lithium in China Relative to the Rest of the World

Data: Roskill Information Services

Chinese production
Rest of world production
Price of battery-grade lithium carbonate



> **Expanding electric vehicle production is a national priority for China, which has led the country to emphasize investments that ensure the availability of sufficient inputs, including battery minerals.**

Sangita Gayatri Kannan is a former research intern at Resources for the Future and PhD student at Colorado School of Mines. **Michael Toman** is a senior fellow at Resources for the Future.

from 2021 to 2022, and during run-ups in cobalt prices from 2006 to 2008 and 2016 to 2018.

China's increase in lithium production, even as lithium prices were declining, could be interpreted as an effort to drive down prices and thereby deter competition. However, a plausible alternative explanation for these actions is that China's process for planning investment in new production capacity is biased toward overshooting expected demand—a tendency observed in their other sectors, such as steel and aluminum. For example, China's rapid increase in its capacity to process lithium outpaced the global use of processed lithium by over 150,000 tonnes in 2017. Expanding EV production is a national priority for China, which has led the country to emphasize investments that ensure the availability of sufficient inputs, including battery minerals.

The use of surplus capacity to process critical minerals for EV batteries reduces the price of these critical minerals. However, China has utilized less and less of its capacity to process lithium (from around 60 percent of capacity in 2013 to around 40 percent in 2020), and at some points, over 100,000 tonnes of lithium processing capacity have been idled but maintained.

We have not yet assessed the potential for China to apply price discrimination between domestic and foreign buyers. This kind of price discrimination would provide more benefit to China than the alternative of withholding supply from the global market, as constraining global supply would have the unwanted effect of increasing prices for domestic customers.

China previously has been found responsible for practicing international price discrimination with non-battery critical minerals, in a case successfully brought by the United States with the World Trade Organization. China's claim in the case—that it needed to restrict exports, but not domestic uses, of these minerals to mitigate the depletion of its resources—was not accepted. China also has imposed restrictions on exports of certain critical minerals, with the aim of making those minerals available to domestic customers.

Unfortunately, obtaining data on prices of Chinese minerals for customers in China to compare with the prices of Chinese minerals for customers in the rest of the world is not easy. All we can say is that price discrimination could again become an issue, although the issue will be less important if international transactions continue to grow in volume and lead to greater price transparency in other mineral sales agreements.

Policy Implications

Our analysis leads to several policy conclusions. First, we have argued that China is unlikely to be able to enforce a selective restriction on the supply of battery-related critical minerals to the United States or other mineral-importing countries. Accordingly, the physical availability of these minerals is not the key issue that should guide policymakers. Security policy for battery minerals should focus more on the risk of high prices for these materials.

Second, China has a history of price discrimination against foreign buyers of critical minerals. To safeguard their interests, importers in the United States and other countries could seek more transparency from China about the pricing of minerals. This transparency would include information about China's domestic pricing of battery minerals for comparison with the pricing of China's exports, though how buyers could obtain this information is unclear.

Finally, the ultimate remedy for the (uncertain) risk of price discrimination by China for battery minerals in global markets is increased competition from non-Chinese sources of mineral processing (along with reduced demands for critical minerals from technical innovation). With lithium, for example, processing capacity can increase in Australia for hard-rock lithium ore and in Latin America for lithium-containing brines. However, building up non-Chinese sources of processing will take time, and in the meantime, the direct costs for battery minerals from these alternative sources will be higher, unless governments significantly subsidize those sources. The uncertain risk of price discrimination needs to be weighed carefully against the risks associated with a massive and rapid build-out of new processing capacity in the United States and allied countries. ■

NO. 218 | SPRING 2025

MEET THE STUDENTS OF THE CRITICAL MINERALS RESEARCH LAB

INTERVIEWS AND TEXT Beia Spiller

A new collaboration between Resources for the Future and partner institutions creates a space for students to hone their research on critical minerals by working with each other, established experts in the field, and policymakers.

In **2024, Resources for the Future (RFF), with researchers at Carnegie Mellon University, Stanford University, and Colorado School of Mines, established the Critical Minerals Research Lab. For PhD students who are working on policy-relevant topics in critical minerals research around the clean energy transition, this lab provides the opportunity to connect, collaborate, and receive feedback from an international, interdisciplinary group of students. By participating in the lab, these scholars will be able to enhance the policy relevance and impact of their critical minerals research. The overarching goal of the lab is twofold: to provide students with an opportunity to present their work and receive feedback from scholars with diverse points of view and academic training, and to create a collaborative community of PhD students who are interested in similar topics.**

Some of the students already have begun coming together on relevant research, including an exploration of the EU Corporate Sustainability Due Diligence Directive and related implications for electric vehicle and battery manufacturers (with Anthony Cheng and Vaios Triantafyllou), and an analysis of the economic, legal, and social trade-offs of deep-sea mining compared to terrestrial mining (with Gabriella Berman and Elizabeth Echavarria). Once finalized, these reports will be published through RFF.

The lab also provides the opportunity for lab scholars to hear from invited experts in the field. This year's experience will culminate in a public conference in June, when the scholars will present their work to a broad audience that includes policymakers.

After a successful inaugural year, we have decided to continue this effort with more student cohorts. The second-year cohort of lab scholars will be announced soon. Here, we highlight six of the inaugural lab scholars to give a sense of who these students are, what they are excited about, and how the lab has fostered their research methods and interests.

> “Scientists are making incredible discoveries in the ocean, and the world is evaluating whether to develop an industry that could significantly… impact these crucial ecosystems.”


GABRIELLA BERMAN

Hometown
Maui, Hawai'i

Student Bio
Third-year PhD student (recently finished the JD portion of a joint JD/PhD degree) in the Environmental Science and Policy program at the University of Miami

Work and Interests
I am a marine biologist working at the intersection of marine sciences and international environmental law. I'm interested in developing marine policy that effectively balances marine conservation with global mineral needs.

Why did you choose to study deep-sea mining? What do you think is one of the most challenging issues related to public policy around mineral extraction in the deep sea?
As a deep-sea marine scientist, I saw not just a need for scientists who could leverage their scientific training to work in law and policy on this critical issue, but also a need for those with law and policy training to have a strong understanding of science. However, gaps in scientific knowledge about deep-sea ecosystems make it difficult to develop policies and regulations that adequately anticipate potential impacts from deep-sea mining—and to fully understand related trade-offs between impacts (environmental and social) and benefits (economic and social). Deep-sea mining is an increasingly important and controversial topic. Research on these knowledge gaps is essential at this time, when scientists are making incredible discoveries in the ocean and the world is evaluating whether to develop an industry that could significantly—and, in some instances, irreversibly—impact these crucial ecosystems.


HAMDIYA ORLEANS-BOHAM

Hometown
Takoradi, Ghana

Student Bio
Second-year PhD student in mining engineering at Missouri University of Science and Technology

Work and Interests
I am a dedicated researcher with expertise in critical minerals, clean energy technology, and mineral economics. I leverage interdisciplinary approaches to global challenges while passionately balancing my career and motherhood, as a proud mother of two beautiful girls.

How has participation in the Critical Minerals Research Lab helped you refine your research agenda?
Participating in the Critical Minerals Research Lab has been an incredibly enriching and transformative experience, fueling my passion for tackling the challenges of the sustainable mineral market in the clean energy transition. Collaborating with brilliant experts and engaging in dynamic, interdisciplinary discussions has sharpened my understanding of complex issues like geopolitical risks, technological breakthroughs, and environmental impacts. The lab's commitment to evidence-based research has furthered my understanding of the importance of leveraging advanced tools, such as modeling and policy evaluation, which empowers me to approach my work with greater rigor and confidence. Most importantly, the lab's focus on driving real-world solutions has energized me to align my research with meaningful, actionable strategies that address some of the most pressing sustainability challenges of our time.

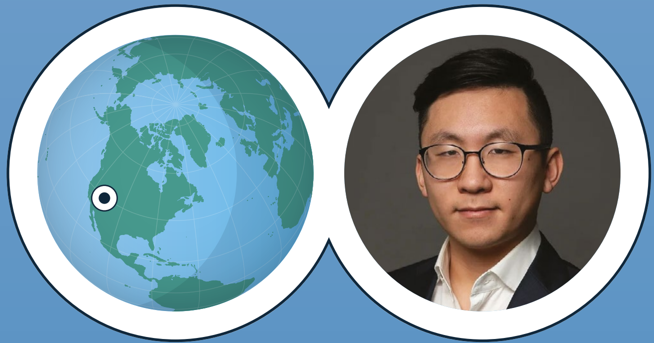

PABLO BUSCH

Hometown
Santiago, Chile

Student Bio
Third-year PhD student in energy systems at the University of California, Davis

Work and Interests
I'm an engineer and statistician from Chile, working on quantitatively modeling the demand and supply of critical minerals in the energy transition.

Which policies that address battery recycling do you think would be most beneficial in helping to achieve a cost-effective circular economy for electric vehicles?
A robust recycling market will provide many benefits, not just by reducing the amount of primary minerals we extract from the ground (and their associated mining impacts), but also by providing a sustainable long-term supply of minerals that is less geographically concentrated and prevents the negative environmental impacts that result from the inadequate disposal of batteries. Recycling policies need to tackle multiple issues simultaneously: setting collection targets for end-of-life batteries, accounting for secondhand vehicle trade with battery passports, setting incremental targets for material recovery, and implementing standards for minimum recycled content to support a secondary materials market. These policies will not only minimize end-of-life impacts, but also enable technology innovation and economies of scale for the industry. Finally, other actions will be needed across the waste hierarchy; for instance, reducing primary battery demand by applying strategies such as energy efficiency, or promoting second-life batteries by repurposing them for grid storage.



ANTHONY CHENG

Hometown
Sandy, Utah

Student Bio
Fourth-year PhD student in engineering and public policy at Carnegie Mellon University

Work and Interests
I focus on analyzing clean technologies and the policies that support them. I'm currently working in the context of the supply chains, vulnerabilities, and incentives for critical minerals, along with the broader impacts of technology adoption and decarbonization in the electric vehicle industry.

How do you think the interdisciplinary nature of the Critical Minerals Research Lab will influence your approach to studying mineral supply chains?
My work on mineral supply chains for electric vehicle batteries has required a systems-level perspective, and the interdisciplinary nature of the lab aligns well with this approach. Interacting with fellows from different fields has reaffirmed the importance of integrating technical and policy considerations, which is essential for addressing real-world issues with supply chains. Asking folks detailed questions about the lithium supply chain, so I can share in their perspectives and existing knowledge, has been helpful in narrowing my current scope of work and increasing my own understanding. I look forward to continuing to engage with my cohort of fellows beyond our tenure in the lab.

HUILIN LUO

Hometown
Inner Mongolia, China

Student Bio
Third-year PhD student in environmental engineering at Pennsylvania State University; non-degree graduate student at the Princeton School of Public and International Affairs

Work and Interests
In my research, I model the societal aspects of decarbonization, and in my life, I focus on cats and dogs.

How has your interdisciplinary background in environmental engineering and psychology, and your interactions with policymakers, helped inform your approach to researching critical minerals?
My fields may seem distinct, but they go surprisingly well with each other for critical minerals–related policy analysis. My foundation in environmental engineering allows me to bring to the lab a strong understanding of environmental systems. My research with integrated assessment modeling has deepened my appreciation of the vital role of critical minerals in the clean energy transition. Complementing these technical perspectives, my background in psychology offers valuable insights into the rationality—and sometimes irrationality—of the policymakers and advocates who shape these policies. Together, these disciplines enable me to analyze the social dimensions of critical minerals, recognizing that relevant issues related to the environment, international politics, climate, and economics ultimately center on people. As public involvement grows in decisionmaking processes, this integrated perspective will be essential for addressing the complex challenges of the field.

HÉLÈNE NGUEMGAING

Hometown
Bafoussam, Cameroon

Student Bio
Fifth-year PhD student in sustainability studies at West Virginia University

Work and Interests
My research addresses the sustainable extraction of natural resources, with a goal of developing strategies to ensure that mining drives economic and social benefits. I am particularly interested in finding ways to engage diverse stakeholders—from policymakers to local communities—and incentivize equitable and sustainable resource management.

Extracting minerals from existing sources of coal waste provides an opportunity for traditional coal-based communities to participate in the clean energy transition. What policies are you exploring that could help these communities take advantage of the opportunity?
For coal communities, extracting rare earth elements from acid mine drainage is a game changer, transforming a long-standing and costly pollution problem into an economic opportunity. But for this objective to succeed, policies must attract investment, ensure local benefits, and develop a regional market and processing industry for rare earth elements. First, companies need legal certainty. Clear ownership rights for extracted rare earth elements (like those defined in House Bill 4003 on the Abandoned Mine Lands and Reclamation Act in West Virginia, which clarifies who profits from rare earth elements that are extracted from mine drainage) aim to encourage the treatment of acid mine drainage by ensuring that the entities involved are able to make a profit from extraction. Second, keeping these jobs local is a key factor to success. Partnering with trade schools and colleges to train local community members and retrain former coal workers can equip people with the needed skills to participate. Finally, building domestic processing infrastructure for rare earth elements ensures that the extraction of minerals contributes to local economies. For generations, these towns have powered the United States. With the right policies, these same communities can lead a clean energy future. ■

> "For coal communities, extracting rare earth elements from acid mine drainage is a game changer, transforming a long-standing and costly pollution problem into an economic opportunity."

Beia Spiller is a fellow and director of the Transportation Program at Resources for the Future.

Promoting Sustainable Aviation Fuels: Considerations for Policymakers

NO. 218 | SPRING 2025

Sustainable aviation fuels can help the aviation industry reduce the climate impacts of air travel. Effective policies must balance diverse climate, economic, and environmental considerations.

TEXT Nafisa Lohawala **ILLUSTRATIONS** James Round

Balancing growth in the aviation industry with efforts to mitigate the risks of climate change is a complex challenge. Aviation is crucial for connecting global communities and supporting economic development, but the industry is also an important contributor to climate change. Aviation accounts for 3.5 percent of human-caused climate impacts. Emissions from air travel have doubled since the mid-1980s and potentially could triple by midcentury compared to 2005 levels, unless effective countermeasures are put in place to reduce emissions. And carbon dioxide emissions are only part of the problem. Other factors, such as contrails—clouds that are formed by aircraft during flight—also have substantial climate impacts that are potentially greater than the impacts of carbon dioxide.

The International Civil Aviation Organization, an agency of the United Nations that fosters collaboration among 193 member countries on issues related to aviation, has set an aspirational goal of achieving net-zero carbon emissions from global civil aviation by midcentury. Sustainable aviation fuels (SAFs) are expected to play a key role in this transition.

Available types of SAFs, which are derived from renewable sources or waste materials, can significantly reduce carbon dioxide emissions. These types of SAFs are compatible with today's aircraft engines and viable for use in the near term; these fuels can also reduce contrails and improve air quality, because SAFs burn cleaner than traditional jet fuels. Other types of SAFs that produce even less carbon dioxide are technically feasible and expected to become available in the future.

Despite these benefits, the production and use of SAFs remain low both in the United States and globally. While various policies have been adopted or proposed to support the deployment of SAFs, the increased emphasis on SAFs creates new questions for policymakers; for example, what principles should guide the evaluation of different policy options?

In this article, I explore four key considerations that policymakers who want to promote SAFs may want to address. I also identify existing knowledge gaps that additional research can help fill to further inform effective policy design. This article aims to support policymakers and researchers in advancing the deployment of SAFs in the aviation industry.

Sustainable Aviation Fuels Today: Production and Policies

In the United States, around 24.5 million gallons of SAFs were produced in 2023—just 0.13 percent of the total amount of jet fuels consumed by US airline companies. Recent policies aim to boost production to at least 3 billion gallons per year by 2030 and 35 billion gallons per year by midcentury.

Achieving this increase requires addressing several challenges. One major challenge is the high cost of SAF production. In 2023, SAFs consistently traded at a premium compared to conventional jet fuels and often cost about two to three times more. This substantial price difference highlights the economic challenge of adopting SAFs without supportive policies. Moreover, SAFs face fierce competition for raw materials and space in biorefineries from renewable diesel, a lower-carbon alternative to conventional diesel that is used in on-road vehicles. This competition can limit the availability of raw materials for the production of SAFs, which creates a significant barrier to scaling up production. Land use change associated with the development of agricultural raw materials for SAFs has raised additional concerns; converting land to produce biofuel can lead to deforestation (a major cause of climate change) and loss of biodiversity.

Various policies have been adopted in the United States to try to reduce the cost of SAF production. In 2021, the US Departments of Energy, Transportation, and Agriculture launched a government-wide SAF Grand Challenge to improve production efficiency, expand the availability of raw materials, develop supporting infrastructure, and assess environmental impacts.

Other policies focus on increasing the production and use of SAFs. The Inflation Reduction Act, which became law in 2022, includes tax credits for SAF producers to help offset high production costs. The Renewable Fuel Standard program, which has been run by the US Environmental Protection Agency since 2005, now provides incentives for expanding the production of SAFs. And since 2019, the Low Carbon Fuel Standard in California, which sets an annually declining limit on the emissions associated with motor fuels that are sold in the state, has categorized SAFs as "opt-in" fuels; SAF producers earn credits that they can sell to fuel suppliers, which in turn can use the credits to comply with the standard.

These domestic measures complement growing international efforts to increase the deployment of SAFs. The EU Emissions Trading System has capped emissions from flights within the European Economic Area since 2012. Airlines operating in Europe are required to monitor, report, and verify their carbon emissions and acquire a sufficient number of allowances to cover their emissions. The cap on emissions from the EU aviation sector declines annually, which induces airlines to switch to SAFs or reduce their emissions through other measures.

The European Union and some other countries, such as the United Kingdom and Japan, are also mandating that SAFs be blended with conventional jet fuels. In 2023, the European Union set ambitious requirements for blending, starting with 2 percent SAFs by 2025 and gradually increasing to 70 percent by 2050. Airlines operating flights that depart from EU airports are also obligated to obtain 90 percent of their fuel from EU airports to discourage "tankering"—the practice of refueling outside the European Union and carrying excess fuel with the aim of avoiding high EU fuel costs.

> "These fuels can also reduce contrails and improve air quality, because sustainable aviation fuels burn cleaner than traditional jet fuels."

> "A comprehensive approach to reducing emissions in aviation also requires expanding policy to address factors other than carbon dioxide, such as contrails, which studies estimate to have an even greater impact than carbon emissions."

At the global level, the Carbon Offsetting and Reduction Scheme for International Aviation is the first global, market-based measure to require airlines and other aircraft operators to limit carbon dioxide emissions from aviation. The scheme was created by the International Civil Aviation Organization, was adopted in 2016, and aims to put a cap on the net carbon dioxide emissions from international flights between participating countries. The offsetting requirement for participating airlines is calculated by multiplying the current emissions associated with an airline's operations by a sector-wide growth factor, which represents the increase in total emissions from the aviation sector since a fixed baseline (85 percent of 2019 levels). Emissions reductions from SAFs then are subtracted from this offsetting requirement, and any remaining emissions must be offset through credits from other sectors of the economy. Member countries of the International Civil Aviation Organization have agreed to adopt laws that require their airlines to monitor, report, and verify carbon dioxide emissions from international flights in accordance with the program.

Challenges and Questions for Policymakers

Climate Impacts

Policymakers face several considerations when designing policies that promote SAFs. The first consideration is that the primary objective of SAF-related policies should be to mitigate the impact of aviation on the climate, rather than just provide economic benefits to suppliers of fuels and raw materials. So, prioritizing pathways, raw materials, and practices that significantly reduce climate impacts compared to conventional jet fuels is essential, even when the potential economic benefits of other choices seem more alluring.

However, adhering to these priorities is challenging, due to a lack of consensus about the extent of the climate impacts of different types of SAFs. Hence, different policy strategies for SAFs have emerged in different regions. For instance, the European Union has excluded from its mandates SAFs that are derived from crop-based raw materials such as corn, soy, and sugarcane, while the United States allows these SAFs to qualify for tax credits (provided they meet certain thresholds for life-cycle emissions reduction). This lack of consensus may lead to inconsistency for global industry and creates uncertainty for investors.

A comprehensive approach to reducing emissions in aviation also requires expanding policy to address factors other than carbon dioxide, such as contrails, which studies estimate to have an even greater impact than carbon emissions. Quantifying the effects of contrails remains a challenge, but some studies suggest that certain blends of SAFs may reduce the formation of contrails.

Alternative Uses of Raw Materials

Policymakers also need to be cognizant that the best opportunities for some raw materials to reduce climate impacts may lie outside the aviation sector. Because sectors compete for raw materials, maximizing climate benefits would require that resources be directed to sectors where the impact may be larger, alongside exploration of other options for increasing SAF production. Consider the so-called power-to-liquid technology, which creates SAF by combining "renewable" hydrogen (produced from water through a process that is powered by renewable energy) with "renewable" carbon dioxide (captured directly from the air). Hydrogen and captured carbon dioxide have alternative uses that may offer more substantial climate benefits if used elsewhere; for instance, carbon dioxide can be sequestered, and hydrogen can power fuel cells.

Maximizing climate benefits also requires understanding trends in decarbonization for other sectors that are competing for the same raw materials. For example, waste materials, such as used cooking oil and animal fats, can be used for both SAFs and renewable diesel. The Renewable Fuel Standard currently favors renewable diesel over SAFs by offering stronger incentives for the production of renewable

Editor's note

This article is an updated version of a previously published blog post, which first appeared online in November 2024 on our Common Resources *blog. We've made some minor edits in the text, seen here, to reflect policy updates that happened since its original publication.*

diesel. Meanwhile, policies that encourage the electrification of on-road transportation provide alternative decarbonization pathways for the transportation sector. However, the viability of electrification across the range of medium- and heavy-duty vehicles still is being determined, so renewable diesel may continue to use waste materials that otherwise could be used to produce SAFs.

Which sector would deliver the most benefits to the climate by using these raw materials remains unclear. Policymakers need to compare the potential benefits and evaluate whether current policies effectively direct raw materials to the sectors that can provide the most benefits to the climate.

Policy Design

The third consideration is how policies can encourage the demand and supply of SAFs efficiently, effectively, and equitably. Addressing these three *e's* raises several questions: How can the production of SAFs be made economically viable for firms? How can policies attract private investments and ensure long-term market stability and innovation without insulating producers from competition and risk? What strategies can drive technological innovation in the production of SAFs? How can airlines be given incentives to purchase SAFs without creating market distortions or unfair competitive advantages? How can airline customers be encouraged to reduce travel or choose lower-emission travel options?

Innovation is key for making various types of SAFs economically viable for airlines and fuel producers. Applied research and development efforts that are supported in part by the government can hasten cost reductions, especially for novel varieties of synthetic SAFs. Beyond the option of research and development, incentive-based approaches like the Carbon Offsetting and Reduction Scheme for International Aviation and the EU Emissions Trading System have built-in incentives to encourage innovations that reduce costs.

International collaboration will also be important. Airlines operate globally, and policies in one region can impact operations in other regions. Given the high cost of SAFs, a mandate to purchase SAFs in certain regions might reduce voluntary demand for SAFs in other regions, as airlines prioritize buying SAFs where required. International coordination could help address the spillover effects of any policies, harmonize policies, and mitigate undue negative impacts on global aviation operations.

Broader Impacts

Finally, policymakers need to consider the broader costs and benefits of SAFs beyond the aviation industry. For instance, how does the use of agricultural raw materials in SAFs, such as corn, affect the production and prices of food? What are the environmental impacts of producing agricultural raw materials? For example, the palm-oil industry has been criticized for destroying habitats to grow oil palm trees. In addition, how do SAFs affect air quality throughout the duration of a flight?

Other considerations for policymakers include how different SAF-related policies may create jobs and benefit local economies. These issues often can involve complex considerations. For instance, trade-offs may exist between supporting farmers and mitigating climate impacts. Policymakers will need to balance these priorities.

Conclusion

Transitioning from conventional jet fuels to SAFs is important for achieving the net-zero target for the aviation sector that has been set by the International Civil Aviation Organization. Various US and global policies represent initial efforts toward achieving this target. A robust policy framework for promoting SAFs requires consideration of the climate impacts of different raw materials and policy pathways; alternative uses of resources beyond the aviation sector; the economic, social, and environmental effects of different policy designs; and other issues beyond the energy sector. Policymakers must balance multiple factors when creating effective policies for SAFs, underscoring the need for further research to strengthen policy efforts. ■

Nafisa Lohawala is a fellow at Resources for the Future.

NO. 218 | SPRING 2025 | "The need for advanced modeling of this sector is readily apparent."

Better Forecasting Can Support the Transition to Electric Vehicles

The transition to electrify medium- and heavy-duty vehicles is complex, and predicting accurate outcomes is difficult. But better projections are possible if the models incorporate market dynamics comprehensively.

TEXT
Nafisa Lohawala, Joshua Linn, and Beia Spiller

ILLUSTRATION
Jacopo Rosati

Data from 2022 indicate that medium- and heavy-duty electric trucks constituted only 0.4 percent of registrations for all new trucks in the United States. The widespread adoption of electric vehicles could reduce greenhouse gas emissions substantially from the US transportation sector, thus improving air quality and public health while helping achieve climate goals. Incentives and regulations in the transportation sector thus aim to increase the adoption of electric vehicles. For example, in April 2024, the US Environmental Protection Agency took notable steps in the pursuit of cleaner transportation, announcing final greenhouse gas emissions standards for heavy-duty trucks. Additionally, states are rolling out their own initiatives, with California leading through its introduction of the Advanced Clean Fleets and Advanced Clean Trucks regulations for the heavier vehicle classes.

Yet, the transition to electrification for medium- and heavy-duty trucks is more complex than for passenger vehicles, requiring greater infrastructural investments and more complicated decisions that involve vehicle fleets rather than individual vehicles. Accurate models and forecasting in this sector are essential to understanding market transitions, determining the appropriate stringency of regulatory standards, and ensuring compliance with international climate pledges. In this article, we explore such complexities, emphasizing the importance of accurate modeling—and noting that failure to address these intricacies may lead to overly optimistic expectations about the costs and the efficacy of a given policy.

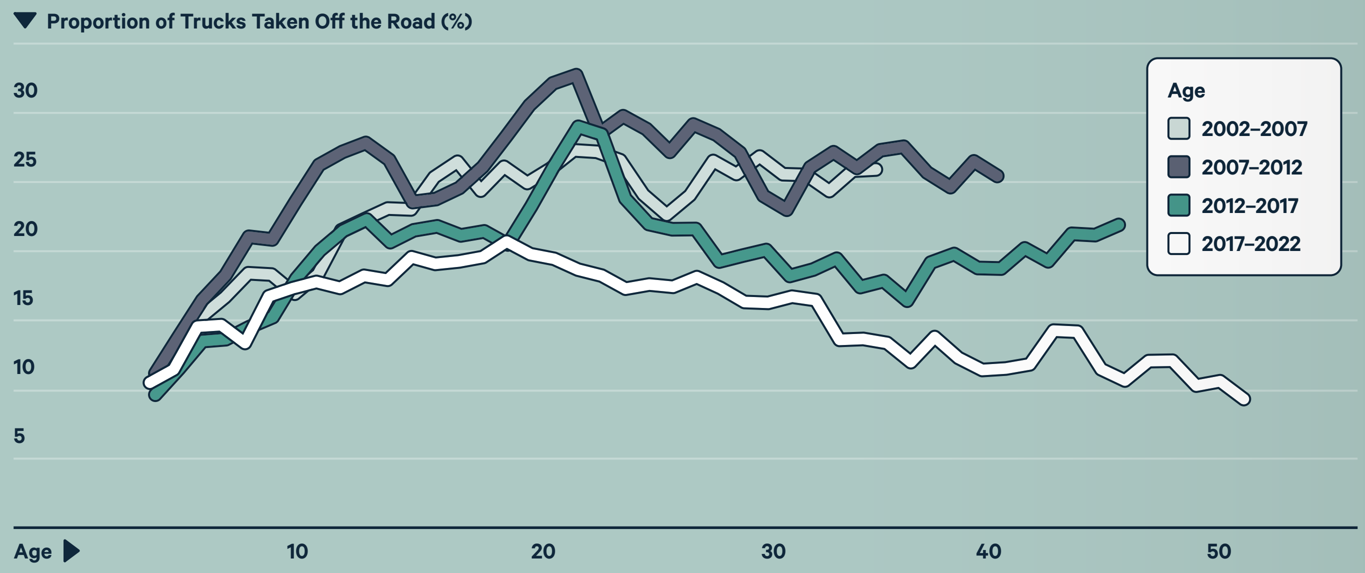
Out of Their Lane: Where Regulatory Impact Assessments Fall Short

Various hurdles hinder the widespread adoption of medium- and heavy-duty electric vehicles, including the high up-front cost of electric trucks and buses, the high cost and low availability of charging infrastructure, and complexities surrounding electricity tariffs. Regulatory impact analyses—such as those conducted by the US Environmental Protection Agency using the MOtor Vehicle Emission Simulator, or by California agencies using the

> "Accurate assessment of these market conditions is crucial for understanding how regulations and incentives influence vehicle prices."

Editor's note
This article is an edited version of a previously published blog post, which first appeared online in May 2024 on our Common Resources *blog.*

FIGURE 01 **Proportion of Aging Trucks Taken Off the Road within Five Years of Last Registration**



EMission FACtor model, or total cost of ownership–based models—often fail to fully capture some of these hurdles, particularly those that require changes in logistics, behavior, or learning by fleet managers.

For example, the EMission FACtor model relies on sales forecasts from the US Energy Information Administration's *Annual Energy Outlook* to assess the impact of regulatory measures, but the model doesn't account for how these regulations influence decisions for fleet purchases. Consider California's Advanced Clean Trucks regulation, which mandates that manufacturers sell a certain percentage of zero-emissions vehicles. If significant barriers constrain electric vehicle adoption, the model will likely yield overly optimistic projections for new electric vehicle sales.

While the total cost of ownership–based models effectively capture visible hurdles, such as the up-front price of vehicles and chargers, they do not include less obvious hurdles such as fleet owners' preferences for specific vehicle features, nor transition costs such as those that arise from having to navigate complex electricity tariffs. By not incorporating the preferences of fleet owners or transition costs in their models, regulatory agencies risk underestimating the costs or overestimating the efficacy of a regulation.

Furthermore, total cost of ownership–based models do not adjust new and used vehicle prices and sales forecasts in response to stringent regulations. Because regulations target only new trucks, these policies may contribute to increased up-front costs to purchase these vehicles (and potentially affect the price of vehicles in the used market); thus, these models would fail to consider the very real possibility that fleets might continue using older vehicles for extended periods. In fact, historical data reveal a consistent increase in truck lifespans and a decline in their scrappage rates.

A New Road for Analysis

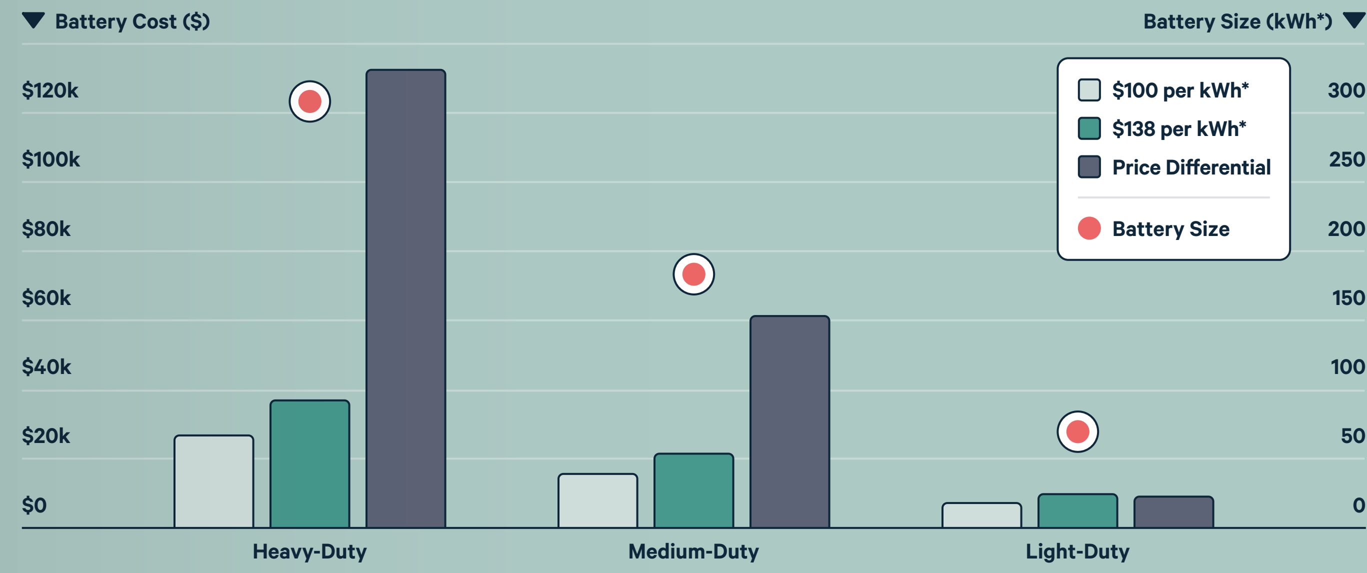
To explore this issue more directly, we analyzed vehicle registration records from five different years: 2002, 2007, 2012, 2017, and 2022. Figure 1 shows the five-year scrappage rates for certain classes of medium- and heavy-duty vehicles, broken down by vehicle age for these years. Each line represents a different five-year interval. For each age group, the values show the percentage of trucks that were taken off the road within that five-year interval. For example, the yellow curve indicates that 10 percent of 50-year-old trucks registered in 2017 were taken off the road before 2022. Moreover, the end points of the curves on the x-axis indicate the age of the oldest vehicles that were registered in each year.

Figure 1 shows that the likelihood of a truck being taken off the road has decreased notably over time. As a result, the oldest vehicles registered in the United States were 36 years old in 2002, which progressively aged to 41 years in 2007, 46 years in 2012, and as old as 51 years in 2017.

This trend may be attributed, in part, to regulations that allow older trucks to remain in operation without adhering to newer emissions standards, potentially reducing the financial incentive to invest in newer, more environmentally friendly models. By omitting information about scrappage decisions by fleet owners in their models, agencies risk overestimating the benefits of regulations.

Moreover, additional market dynamics, such as market power held by one or a few truck manufacturers, can maintain high prices, further hindering the adoption of new technologies by vehicle fleets. These dynamics are especially true at the beginning of a market transition, when a recognizable brand dominates the market until higher-quality products become available and gain market share.

FIGURE 02 **Price Differential and Battery Cost Across Vehicle Type**



This challenge of persistent high prices necessitates a more sophisticated approach to modeling outcomes that is grounded in game theory, which can adequately incorporate market structure into analyses. A 2023 analysis from Resources for the Future underscores this issue by scrutinizing data on truck characteristics from 2021 to 2023. The report shows that, for large vehicles, the price gap between conventional and electric trucks markedly exceeds the intrinsic cost of the battery (Figure 2). In the case of the largest vehicles (the heavy-duty category), the price differential is about three times the cost of the battery. This discrepancy can be partly attributed to low economies of scale and limited competition within the market, factors that exacerbate the challenge of transitioning fleets to more sustainable options.

Rather than estimating price markups based on game-theoretic foundations and actual data, agency analyses often simply assume the size of the markup. Accurate assessment of these market conditions is crucial for understanding how regulations and incentives influence vehicle prices. For example, the Inflation Reduction Act's purchase subsidies for electric vehicles and charging stations may not be fully passed through to the buyer. This is because, in markets with low competition, incentives that are designed to encourage electric vehicle adoption may inadvertently enable manufacturers to increase pre-incentive prices. This dynamic may, in the end, delay the transition to electric vehicles. Failing to accurately capture the market structure can lead to overestimated cost reductions for fleets.

The need for advanced modeling of this sector is readily apparent. The complexity of the transition to electric fleets, and the myriad policies implemented to support this transition, call for the development and use of a comprehensive econometric, data-based analysis of demand and supply in the medium- and heavy-duty vehicle sector that captures preferences for vehicle characteristics, market dynamics that affect price, and real-world costs of electrification. Without this type of modeling, predictions about the costs and efficacy of existing policies may be overly optimistic. ■

*kWh = kilowatt-hour

Nafisa Lohawala is a fellow, **Joshua Linn** is a senior fellow, and **Beia Spiller** is a fellow and director of the Transportation Program at Resources for the Future.

At Resources for the Future, People Are Our Greatest Asset

Resources magazine recently spoke with three individuals who, in addition to their professional work at Resources for the Future (RFF), also choose to support RFF philanthropically: Elizabeth Albert, benefits and payroll administrator; Emma DeAngeli, senior research analyst; and Kristin Hayes, senior director for research and policy engagement. Below are excerpts from the conversation, which covered the influence of family, the search for truth, what excites them about their work, and more.

Resources magazine: What initially attracted you to RFF?

Emma: I found previous environmental conservation work that I was doing to be meaningful but thought it was missing a strong foundation: What do the economics say? What impacts will this policy have? I appreciated that RFF was trying to tackle those types of questions objectively. Environmental policy is something I'm passionate about, and working on environmental policy in a way that's focused on facts and data aligns with my personal interests. It's important to have that strong research foundation to essentially put forward the truth.

Kristin: I had been working for advocacy organizations up to that point, and I really wanted to work someplace nonpartisan. I was drawn to this "nerd ethos" at RFF, and the desire at RFF to infuse new information into environmental conversations was appealing to me.

What do you enjoy most about your work at RFF?

Kristin: I feel fortunate that I have a role in the organization that lets me interact with pretty much everyone, so I have a bird's-eye view of things. That means I get to see the maximum amount of creativity from all the departments. The breadth of information I get to work on and the diversity of people I get to connect with is great. It's been a joy.

Elizabeth: The people, culture, and RFF community we've created are key for me. Within a few weeks of joining, I developed an immediate love for RFF's culture, the community, and the immense value of the work. We focus on hiring staff who will work well together, which has a huge overall impact on the organization. Ultimately, this intentionality creates a community of sincere, kind, good people who care about one another, and who share their personal talents and scholarly expertise. I've also come to know our researchers individually and their passion to effect change, inform, and educate, which is ever present and evident in their work ethic and philosophies. I consider myself fortunate to have become part of this amazing community.

Why do you support RFF philanthropically, in addition to the work you do day to day?

Emma: I went straight from my undergraduate program to graduate school to RFF, so this is my first job. When I joined, my parents told me, "It's good to give to your organization; it's just something that you should do." I definitely agree with my parents—I think it's the right thing to do—and it's a reflection of RFF's value to me, in the economics sense. I'm valuing the place where I work—an organization whose mission I believe in—and the research that my colleagues and I do.

Why should others support RFF?

Kristin: For people who don't have the experience of being here with our colleagues day to day, I personally can attest that it's such a wonderful community. I think people who search for truth as best they can and follow where the data leads them are even more important now than in recent years. We have an honest desire here to wrestle with hard questions and think about impacts across a range of factors. Combine smart people with important questions, and that's RFF.

Emma: We're doing valuable research at RFF that could help a lot of people. I hope that other people also want to find the truth in terms of science, economics, and good environmental policy, so that we can responsibly and effectively tackle the climate crisis together.

Elizabeth: An organization like RFF, which executes crucial research that guides decisionmaking at a global level, should be supported by others who also believe in RFF's mission. I'm proud that RFF and its expertise exist to sustain the earth—not only today or for the next few generations, but for hundreds of years to come! I want to be part of ensuring RFF's longevity, while being a small part of helping our world to thrive. Why wouldn't you want to be part of this, too? ■

Supporter Spotlight

In the RFF Supporter Spotlight, our partners and colleagues share their insights about climate, energy, and environmental issues and how they've made a difference by working with Resources for the Future—all in their own words.

> "I hope that other people also want to find the truth in terms of science, economics, and good environmental policy, so that we can responsibly and effectively tackle the climate crisis together."
>
> Emma DeAngeli

PHOTOS (ABOVE, CLOCKWISE)
Emma DeAngeli, Kristin Hayes, Elizabeth Albert

Four Ways You Can Support RFF

1 Give through our website

Visit www.rff.org/donate to make a one-time donation, or to set up a monthly recurring donation.

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Send your check to Resources for the Future | 1616 P Street NW, Suite 600 | Washington, DC 20036

3 Give through a donor-advised fund

Donate through a DAF account at a community foundation or financial institution to support RFF while receiving favorable tax benefits.

4 Give through a will, trust, or gift plan

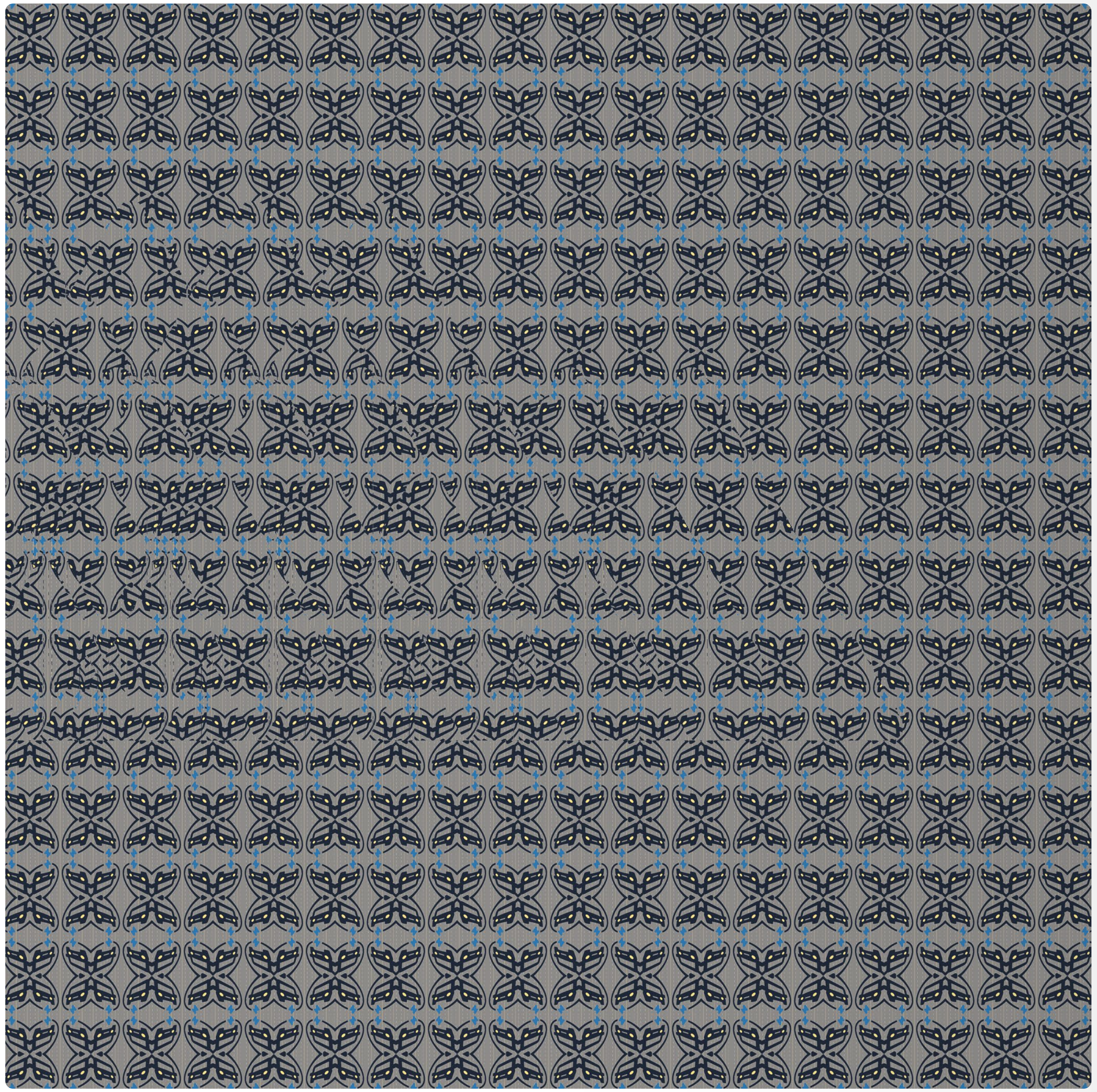
Include RFF in your estate plans to provide meaningful, long-lasting support.

Discover other ways to give at rff.org/waystogive or contact Ryan Sabot at rsabot@rff.org

A Focus on the Transportation Sector

What's next for transportation feels like a mystery that lies beyond the curve of the road we're on. At Resources for the Future, we're holding on to optimism for when the horizon comes into focus. What's revealed in the "magic eye" autostereogram below is perhaps one big reason for staying optimistic.

Instructions: *Hold the center of the printed image right up to your nose. It should be blurry. Relax your focus, as if you're looking through the image into the distance. Slowly move the page away from your face until the hidden image appears. What do you see?*



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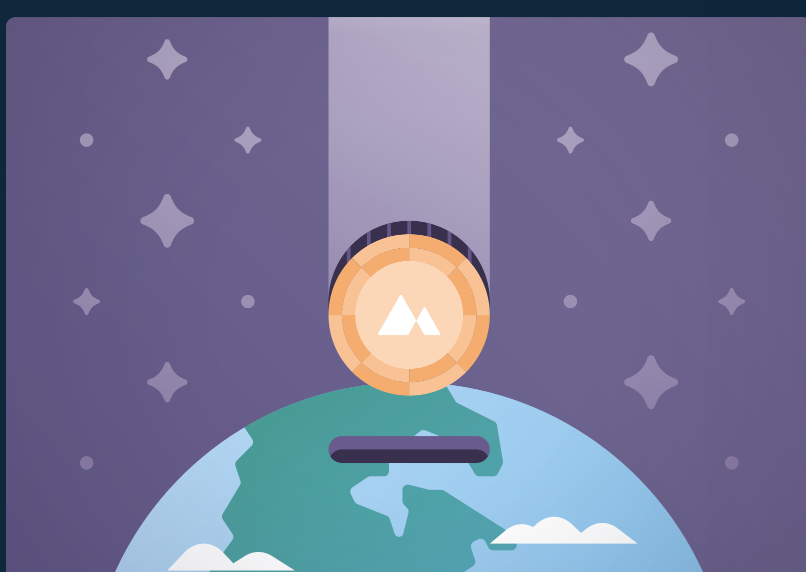

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The generous investments of visionary supporters are what drive RFF forward—to explore new questions, take calculated risks, and bring together people and ideas in new ways. If you believe that today's environmental challenges deserve independent analysis and innovative solutions, become an RFF supporter today.

Read more about options to support RFF on page 47 of this issue.