

Report

Electric Vehicles for Everyone? The Impossible Dream

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Executive Summary

A dozen U.S. states, from California to New York, have joined dozens of countries, from Ireland to Spain, with plans to ban the sale of new cars with an internal combustion engine (ICE), many prohibitions taking effect within a decade. Meanwhile, the U.S. Environmental Protection Agency (EPA), in a feat of regulatory legerdemain, has proposed tailpipe emissions rules that would effectively force automakers to shift to producing mainly electric vehicles (EVs) by 2032.

This is all to ensure that so-called zero-emission EVs play a central role in radically cutting carbon dioxide (CO₂) emissions. To ensure compliance with ICE prohibitions and soften the economic impacts, policymakers are deploying lavish subsidies for manufacturers and consumers. Enthusiasts claim that EVs already have achieved economic and operational parity, if not superiority, with automobiles and trucks fueled by petroleum, so the bans and subsidies merely accelerate what they believe is an inevitable transition.

It is certainly true that EVs are practical and appealing for many drivers. Even without subsidies or mandates, millions more will be purchased by consumers, if mainly by wealthy ones. But the facts reveal a fatal flaw in the core motives for the prohibitions and mandates. As this report illustrates:

- *No one knows how much, if at all, CO₂ emissions will decline as EV use rises.* Every claim for EVs reducing emissions is a rough estimate or an outright guess based on averages, approximations, or aspirations. The variables and uncertainties in emissions from energy-intensive mining and processing of minerals used to make EV batteries are a big wild card in the emissions calculus. Those emissions substantially offset reductions from avoiding gasoline and, as the demand for

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battery minerals explodes, the net reductions will shrink, may vanish, and could even lead to a net increase in emissions. Similar emissions uncertainties are associated with producing the power for EV charging stations.

- *No one knows when or whether EVs will reach economic parity with the cars that most people drive.* An EV's higher price is dominated by the costs of the critical materials that are needed to build it and is thus dependent on guesses about the future of mining and minerals industries, which are mainly in foreign countries. The facts also show that, for the majority of drivers, there's no visibility for when, if ever, EVs will reach parity in cost and fueling convenience, regardless of subsidies.

Ultimately, if implemented, bans on conventionally powered vehicles will lead to draconian impediments to affordable and convenient driving and a massive misallocation of capital in the world's \$4 trillion automotive industry.

Introduction: Reactionary Revolutions

Few doubt, even if some lament, the centrality of the automobile in modern society. As the late MIT historian Leo Marx put it: "To speak, as people often do, of the 'impact' of . . . the automobile upon society makes little more sense, by now, than to speak of the impact of the bone structure on the human body."¹ For more than a century, policymakers have encouraged, facilitated, regulated, and taxed the production and use of automobiles.

But now, policies unprecedented in scope and consequence are planned to ban the sale of the type of vehicle that 99% of people use—that is, vehicles powered by an internal combustion engine (ICE). Instead, government policies are being launched to mandate, directly and indirectly, electric vehicles (EVs).

Rarely has a government, at least the U.S. government, banned specific products or behaviors that are so widely used or undertaken. Indeed, there have been only two comparably far-reaching bans in U.S. history: the Eighteenth Amendment to the U.S. Constitution, which prohibited the consumption of alcohol (repealed by the Twenty-First Amendment); and the 1974 law prohibiting driving faster than 55 mph. Neither achieved its goals; both were widely flouted, and the first one engendered unintended consequences, not least of which was criminal behavior.

The idea of banning the internal combustion engine (ICE)—or the de facto equivalent through Environmental Protection Agency (EPA) rules—emerges from the thesis that an "energy transition" eliminating hydrocarbon use is both necessary and inevitable. The ICE ban echoes other energy transition ideas but with an important distinction. Electricity production mandates, for example, that ban the use of coal and even natural gas "merely" raise costs, while the product that consumers use, kilowatt-hours, remains largely unchanged in its utility.² EVs, as we will explain, do not have the same utility and are neither operationally nor economically equal for most citizens. Nonetheless, hundreds of billions of dollars in taxpayer funds and corporate spending are now being directed at subsidizing and building EVs in concert with many near-term prohibitions on the sale of ICE vehicles.

Enthusiasts rightly credit Elon Musk with launching today's excitement about EVs. Until the 2012 introduction of the Tesla S—coincidentally, exactly 100 years after Studebaker closed its EV production line, then the biggest EV producer—no company had successfully introduced a

battery-only option for an on-road car. Nor, in a century, has any new car company succeeded in taking market share from the legacy competition. Last year, Tesla was the number-one luxury brand in the U.S., accounting for nearly one-fifth of sales in that coveted, profitable category. This was a laudable feat, even if that category accounts for less than 10% of overall car sales.³ Unsurprisingly, every luxury automaker has scrambled to offer an all-electric option.

We even see nonautomotive tech companies eager to join the fray in building luxury electric cars. Rumors continue that Apple will yet unveil an EV.⁴ (Indeed, the company could leapfrog the manufacturing challenge by using 10% of its cash to buy an entire company such as Hyundai.) Xiaomi, China's "Apple" and the world's number-three smartphone maker, announced a \$10 billion plan to form an EV subsidiary.⁵ Meanwhile, conventional automakers have already brought to market more than 40 different EV models.⁶

The arrival of useful EVs didn't happen because of government mandates or incentives. It was made possible by the maturation of two enabling technologies that were invented in the mid-1970s. One of them, the now-famous lithium battery chemistry, was first identified by Stanley Whittingham, while he was working at Exxon's New Jersey research labs. (Whittingham was one of three to later receive the 2019 Nobel Prize in chemistry.) The other, less well-known but pivotal (and contemporaneous), invention came from Jay Baliga, who, while working at GE's R&D center, invented the IGBT, a new class of silicon transistor capable of managing high-power electrical flows. The IGBT made possible the compact, efficient digital control of electrical power critical for all EV drivetrains. Baliga received the 2015 Global Energy Prize for "one of the most important innovations for the control and distribution of energy."⁷

Useful EVs are undeniably a significant addition to the pantheon of options for consumers. But the rhetoric and policies about the inevitability of EVs for *everyone* emerge from myths, misperceptions, and hyperbole about the underlying technologies. The International Energy Agency (IEA), for example, begins its 2023 "Global EV Outlook" by touting that EV "markets are seeing *exponential* growth as sales exceeded 10 million in 2022"⁸ (emphasis added). The finger-on-the-scale and hyperbole surrounding EVs begin right there.

Hybrids, as IEA observes in a footnote, accounted for nearly one-third of those global EV sales. Hybrids, by definition, use combustion engines that policymakers are eager to ban. And, relevant to the IEA claim that EV sales have "profound implications"⁹ for climate goals, nearly two-thirds of global sales were in China, which is, a priori, a special case—not least because its current and planned coal-dominated electric grid has profoundly negative implications in neutering climate goals.

Nonetheless, the 7 million (non-hybrid) EVs sold globally last year did constitute a huge jump from the 3,000 units sold by Tesla in 2012. And, while only 10% of all EV sales were in the United States (two-thirds of which were Teslas),¹⁰ policymakers appear confident that the "exponential" growth of EVs will make bans and mandates politically palatable because of the EV's ostensibly inevitable superiority.¹¹ Aside from the claim of clear superiority—an issue that is a key focus of this report—we note that rhetoric about growth in EV sales being remarkable or "exponential" itself isn't supported by the history of consumers embracing other new category-creating cars.

It took six years after its introduction before Tesla sold its 200,000th car. Two years after Ford introduced its electric Mustang Mach-E, sales reached only 150,000 (now the distant second most popular EV in America).¹² Compare that to 1983, when Chrysler invented the minivan, well-timed to meet a demographic shift; consumers bought more than 200,000 in one year. But the consumer adoption record belongs to the 1964 Mustang, another category-creating car and one well-timed to meet the demographic shift of that era. Ford sold 1 million Mustangs within 18 months.¹³ It took Tesla 92 months to reach that number.¹⁴



This report does not focus on whether EVs are a practical and appealing new category for many drivers. They are. The world will see tens of millions more EVs on roads even without government mandates. But in banning ICE cars and mandating the use of EVs, policymakers are explicitly betting on the truth of three crucial claims:

- EVs will lead to “profound” reductions in CO₂ emissions
- EVs are now, or will soon be, cheaper than, and operationally equal to, ICE cars
- There is a diminishing role for the automobile in modern times; in effect, there is a generational realignment in how citizens seek personal mobility.

All three are bad bets not supported by facts. Before turning to the realities of EV emissions, it is useful to consider the state of mobility as seen in U.S. driving trends. How much, where, and why people drive reveals the kinds of features actually sought in cars.

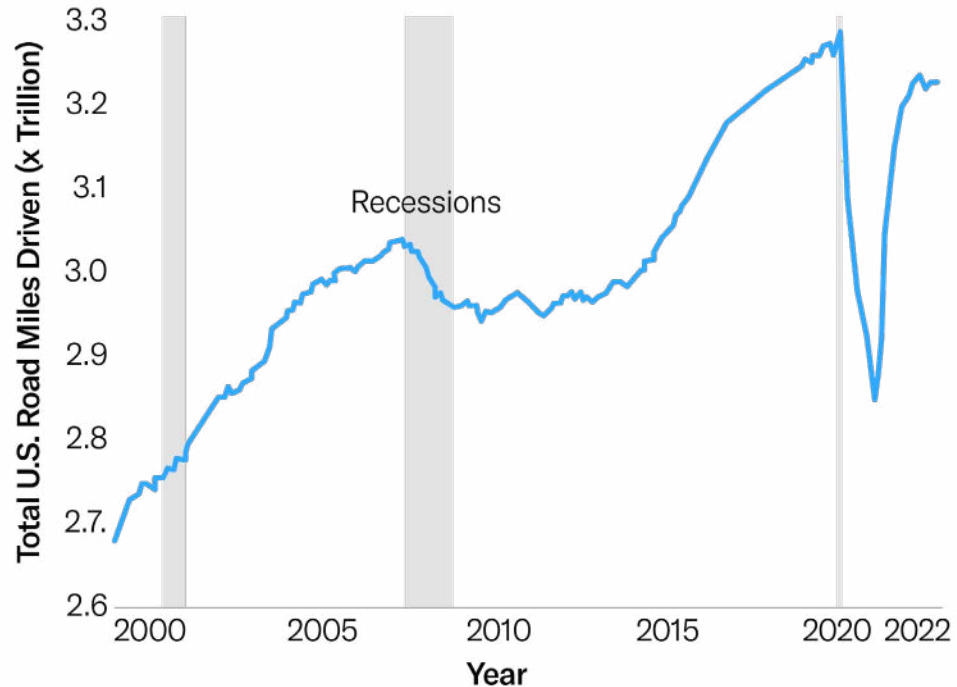
The Current State and Future of Personal Mobility

ICE prohibitionists are the same as, or at least intellectual fellow travelers with, those who claim that we’ve reached “peak car.” The argument here is that millennials (born 1981–96) and Gen Zs (born 1997–2012) don’t share the affection for cars of baby boomers (born 1946–64). The former two cohorts are ostensibly eager to embrace ride-sharing, bicycles, scooters, and mass transit. Headlines have touted that the “Western world has turned its back on car culture.”¹⁵ Goldman Sachs analysts write: “Millennials have been reluctant to buy items such as cars” and are “turning to a new set of services that provide access to products without the burdens of ownership, giving rise to what’s being called a ‘sharing economy.’”¹⁶ Pundits, especially post-Covid lockdown, intone that remote work will reduce the number of trips that people will take.¹⁷

The data show that there is nothing to the belief that people in general, or in the rising generation, are giving up driving. Millennials—the first generation of the Internet era—now constitute the largest share of the population. It is thus notable, according to a recent MIT analysis, that, compared with boomers, millennials exhibit “little difference in preferences for vehicle ownership” and that “in contrast to anecdotes, we find higher usage in terms of vehicle miles traveled.”¹⁸ The share of cars bought by the yet-to-come-of-age Gen Zs has increased fivefold in the past five years.¹⁹ The data also show that once the 2008 recession ended and millennials found work, they bought cars and took to the roads along with everyone else, restoring and even somewhat accelerating the long-run growth in total vehicle miles driven on America’s roads. Only the Great Recession, and then the draconian pandemic lockdown measures, put temporary halts on that trend (**Figure 1**).

Figure 1

Annual U.S. Vehicle Miles Driven



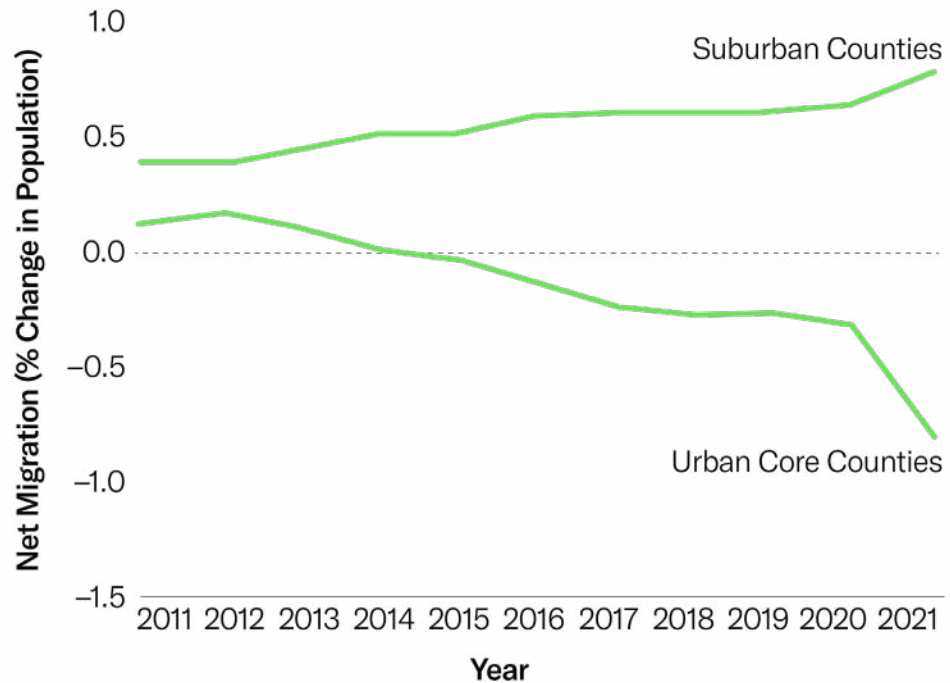
Source: FRED (Federal Reserve Economic Data, St. Louis Fed)

There is also a theory that the Internet causes a decline in car usage. Yet in 1999—at the first peak of digital enthusiasm—British sociologist John Urry presciently claimed that “travel through one medium overall increases travel through other media.”²⁰ Looking at the long history of “automobility,” Urry wrote that “most car journeys now made were never made by public transport. Car drivers undertake connections with other peoples and places that were not undertaken previously.” And that’s what the record shows: both more driving and more digital traffic.

Another pillar of the peak-car thesis is that urbanization diminishes the need for cars, especially the need for people to drive long distances. Census data, however, show that the urbanization trend ended around 2010, when net migration to nonmetro and rural areas began.²¹ While that trend was briefly accelerated by the lockdowns, the net migration to rural and ex-urban zip codes reverted to the trend “observed prior to the pandemic.”²² As one researcher noted in 2022, the de-urbanization trend could “become more commonplace” if late millennials and Gen Zs follow evidence suggesting that a rising share find “suburban and small-town life more attractive”²³ (Figure 2).

Figure 2

U.S. Nonmetro Population Trends



Source: William H. Frey, “New Census Data Shows a Huge Spike in Movement Out of Big Metro Areas During the Pandemic,” Brookings Institution, Apr. 14, 2022

Surveys reveal that not everyone who left the cities during the pandemic will move back, so the trend toward slow de-urbanization appears sticky. Other surveys also show that 60% of Americans claim that they prefer living in suburbs or rural areas and that, even if “money were no object,” only 40% would choose city life.²⁴ A survey in early 2023 found that two-thirds of Americans would “consider moving to a rural home or a subdivision” if telecommuting were an option.²⁵ Modern “zooming” has amplified Urry’s synergy of travel in the two different “media.”

One directly measurable effect of these trends is the boom in “super-commuters,” the nearly 5 million Americans now commuting some 90 minutes or longer.²⁶ Over the last decade, the super-commuting share of the workforce has increased threefold faster than the overall workforce. A 2023 survey by Upwork found that 41% of people are planning to move between two and four hours away from their current residences.²⁷ Whether telecommuting while living and driving in spread-out ex-urban areas, or super-commuting to urban areas, there is a significant increase in the population living where distances traveled are radically greater than in the city.

Consumer preferences for comfort, size, convenience, and performance have driven a remarkable transformation in the average car purchased in America. Marked from 1975—the dawn of the heavy federal hand in vehicle energy-related regulations—the average automobile today has 100 more horsepower, weighs 1,000 pounds more, and has doubled in fuel efficiency.²⁸ That last factor means that average CO₂ emissions per mile have dropped by half.



Today, for the average household, personal mobility is the number-two expense after mortgage or rent. A car is the single most expensive product that 98% of consumers ever purchase.²⁹ Banning ICE vehicles would constitute a takeover of one of the top three economic sectors of the nation, bigger than commercial banking or pharmaceuticals.³⁰

Now, in service of government climate strategies to achieve radical emissions reductions, consumers will need to adopt EVs at a scale and velocity 10 times greater and faster than the introduction of any new model of car in history. Policymakers are right about at least one thing: that won't happen naturally from market forces or consumer preferences.

EV Emissions: Elsewhere, Unclear, and Maybe Unknowable

In contrast to cars with internal combustion engines, it's impossible to measure an EV's CO₂ emissions. While, self-evidently, there are no emissions while *driving* an EV, emissions occur elsewhere—before the first mile is ever driven and when the vehicle is parked to refuel.

The CO₂ emissions directly associated with EVs begin with all the upstream industrial processes needed to acquire materials and fabricate the battery. The received wisdom that EVs will have a “huge impact” on reducing emissions is, whether the claimants know it or not, anchored in *assumptions* about the quantities and varieties of materials mined, processed, and refined to make the battery.

The scale of those upstream emissions emerges from the fact that a typical EV battery weighs about 1,000 pounds and replaces a fuel tank holding about 80 pounds of gasoline.³¹ That half-ton battery is made from a wide range of minerals, including copper, nickel, aluminum, graphite, cobalt, manganese, and, of course, lithium. Critically, the combined quantity of these specialty and so-called energy minerals is 10-fold greater in building an EV, compared with an ICE car.³²

As researchers at the U.S. Argonne National Labs have pointed out, the relevant emissions data on such materials “remain meager to nonexistent, forcing researchers to resort to engineering calculations or approximations.”³³ And, per IEA, data on the emissions intensity of specific minerals can “vary considerably across companies and regions.”³⁴ That is a consequential understatement. The fundamental fact to keep in mind: *every claim for EVs reducing emissions is a rough estimate or an outright guess based on averages, approximations, or aspirations.* The estimates entail myriad known unknowns about what happens upstream to obtain and process materials to fabricate the giant battery. Those factors not only vary wildly but can be big enough, alone, to wipe out from one-half to all the emissions saved by not burning gasoline.

These features of EV emissions constitute a complete inversion of the locus and, critically, the transparency and certainty compared with combustion vehicles. For a conventional car, you know the emissions if you know the fuel mileage. The quantity of gasoline burned is directly measurable and forecastable with precision. Those CO₂ emissions are the same regardless of when or where a car is refueled, or when it is driven.³⁵ And while conventional cars also have “hidden” upstream emissions—the energy used to build the vehicle and create gasoline—these constitute only 10%–20% of these vehicles' total life-cycle emissions.

The critical factor for estimating upstream EV emissions starts with knowing the energy used to access and fabricate battery materials, all of which are more energy-intensive (and more expensive) than the iron and steel that make up 85% of the weight of a conventional vehicle.³⁶ The energy used to produce a pound of copper, nickel, and aluminum, for example, is two to three times

greater than steel.³⁷ Estimates of the aggregate energy cost to fabricate an EV battery vary threefold but, for context, on average, the energy equivalent of about 300 gallons of oil is used to fabricate a quantity of batteries capable of storing the energy contained in a single gallon of gasoline.³⁸

That so much upstream energy is necessarily used is understandable if one knows that hundreds of thousands of pounds of rock and materials are mined, moved, and processed to create the intermediate and final refined minerals to fabricate a single thousand-pound battery (see **sidebar**, “Sources of ‘Hidden’ Energy to Mine and Process 500,000 Pounds per EV Battery”).

Sources of “Hidden” Energy to Mine and Process 500,000 Pounds per EV Battery

While there are dozens of variations, a typical EV battery weighs about 1,000 pounds and contains about 30 pounds of lithium, 60 pounds of cobalt, 130 pounds of nickel, 190 pounds of graphite, 90 pounds of copper,^a and about 400 pounds of steel, aluminum,^b and various plastic components.^c

The ore grades for each mineral dictate the quantities of rock that must be dug up and processed to produce minerals needed to fabricate one battery; thus:

- Lithium brines contain @ ~0.14% lithium, so that entails ~20,000 pounds of brines to yield 30 pounds of pure lithium^d
- Cobalt @ ~0.1% ore grades means ~60,000 pounds of ore dug up per battery^e
- Nickel @ ~1.3% grade, means ~10,000 pounds of ore^f
- Graphite @ ~10% leads to 2,000 pounds of ore^g
- Copper @ ~0.6% yields about 12,000 pounds of ore^h

These five elements total ~100,000 pounds of ore to fabricate one EV battery. To properly account for all the earth moved, there’s also the overburden, the materials first dug up to get to the ore; depending on ore type and location, it averages three to seven tons of overburden removed to access each ton of ore,ⁱ thus ~500,000 pounds total. The exact number varies for different batteries and mines. Note that this doesn’t include large quantities of chemicals to process and refine the ores, or the mining/refining for the other 400 pounds of battery minerals used (e.g., steel, aluminum).

^a Vladimir Basov, “The World’s Top 10 Highest-Grade Copper Mines,” *mining.com*, Feb. 19, 2017; Matt Badiali, “Tesla Can’t Make Electric Cars Without Copper,” *Banyan Hill*, Nov. 3, 2017.

^b Helena Berg and Mats Zackrisson, “Perspectives on Environmental and Cost Assessment of Lithium Metal Negative Electrodes in Electric Vehicle Traction Batteries,” *Journal of Power Sources* 415 (March 2019): 83–90.

^c Ibid.

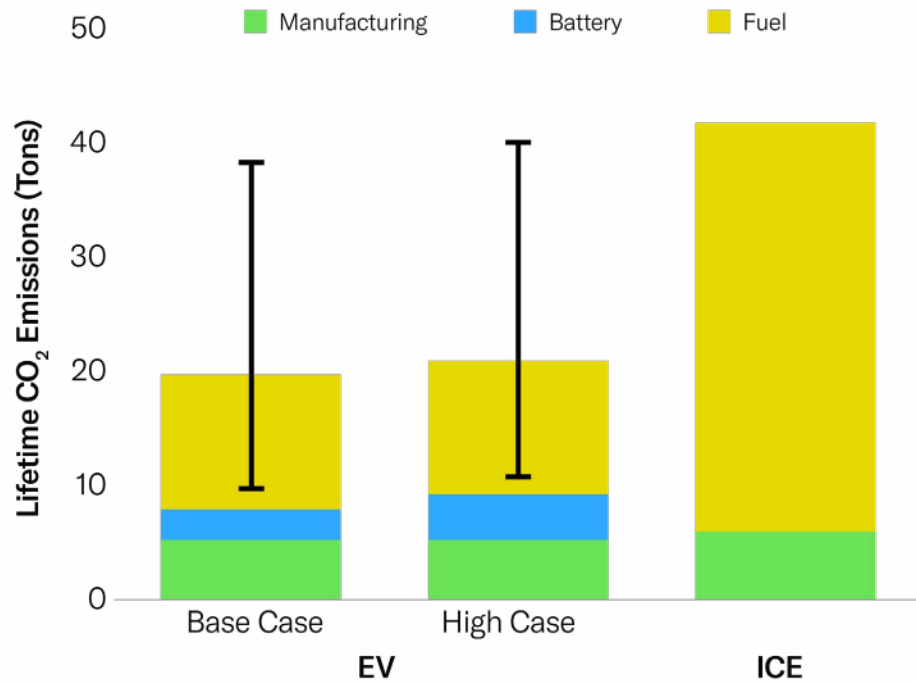
- ^d Hanna Vikström, Simon Davidsson, and Mikael Hööket, “Lithium Availability and Future Production Outlooks,” *Applied Energy* 110 (October 2013): 252–66.
- ^e John F. Slack et al., “Cobalt,” in *Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply*, United States Geological Survey (USGS), Professional Paper 1802-F, Dec. 19, 2017.
- ^f Vladimir I. Berger et al., “Ni-Co Laterite Deposits of the World—Database and Grade and Tonnage Models,” USGS Open-File Report 2011-1058 (2011).
- ^g Fred Lambert, “Breakdown of Raw Materials in Tesla’s Batteries and Possible Bottlenecks,” *electrek.co*, Nov. 1, 2016; Håvard Gautneb and Einar Tveten, “The Geology, Exploration, and Characterisation of Graphite Deposits in the Jennestad Area, Vesterålen, Northern Norway,” *Norges geologiske undersøkelse* 436 (2000): 67–74.
- ^h Guiomar Calvo et al., “Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality?” *Resources* 5, no. 4 (December 2016): 1–14.
- ⁱ Glencore McArthur River Mine, “Overburden”: the seven tons of overburden per ton of ore mined is highly variable; Slack et al., “Cobalt.”

Source: Mark P. Mills, “Mines, Minerals, and ‘Green Energy’: A Reality Check,” Manhattan Institute, July 2020

Accurately estimating the actual quantities of specific fuels used is complicated by the labyrinth of global suppliers and the lack of transparency with many of the companies. (There is far greater transparency and accuracy in tracking embodied energy for iron and steel, since at least three-fourths of production is domestic.)³⁹ Without knowing all that, no one knows the ultimate real-world emissions from making an EV. While dozens of technical papers have been devoted to analyzing uncertainties around these upstream emissions, a useful starting point is IEA’s seminal report on “energy minerals,” which includes both upstream factors and grid fueling. The agency concludes that, compared with an ICE car, there is still about a 50% reduction in life-cycle emissions for EVs⁴⁰ (**Figure 3**).

Figure 3

Estimated Life-Cycle Emissions for EVs vs. ICE Cars, per IEA



Source: IEA, “The Role of Critical Minerals in Clean Energy Transitions”

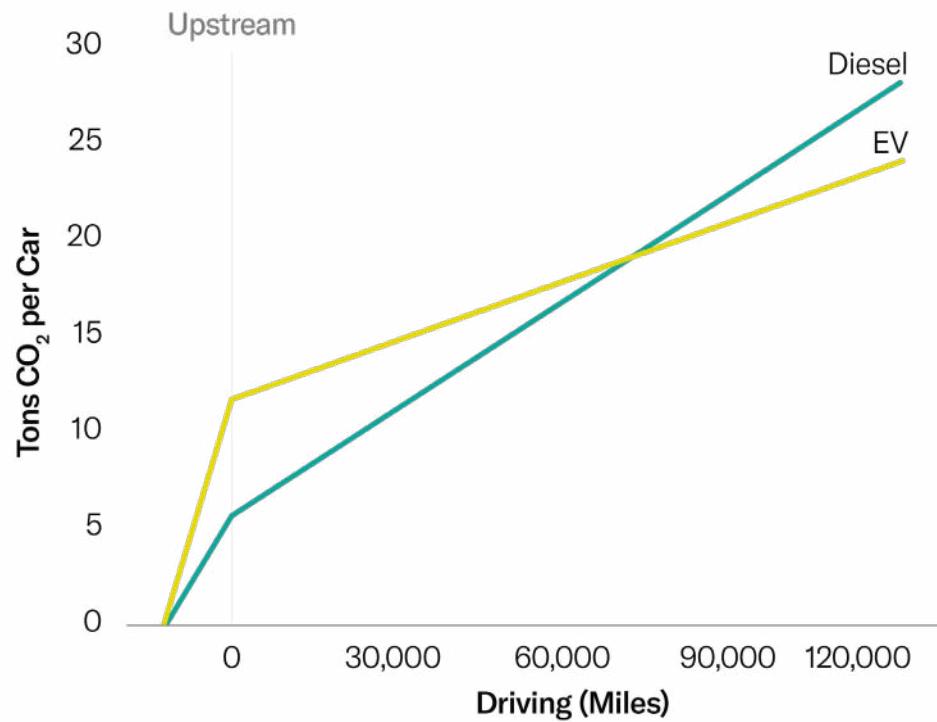
However, the IEA analysis not only uses debatable assumptions but also buries the variables and uncertainties. While IEA does illustrate variables (as black vertical “error bars” in Figure 3, or as a range of outcomes in another analysis)⁴¹ the agency actively promotes the claim—indeed, essentially a guarantee of “profound” emissions reductions—even though its own estimates show that an EV could yield *no reductions* at all, or even an increase. As a practical matter, there is no way to know where on that range any vehicle, or even most vehicles, would perform. The appearance of certainty or precision—an average 50% reduction—is illusory.

One dubious factor in the IEA estimate is the assumption about the battery size; its calculation is based on a 40 kWh (kilowatt-hour) battery pack, which is half the size of the batteries in most popular EVs.⁴² In fact, IEA itself notes elsewhere that SUVs with big batteries account for 60% of all EV options (excluding China, where it’s 40%).⁴³ Bigger batteries for more range mean that more materials are used and thus entail greater upstream emissions. The IEA calculation also ignores the greater use of aluminum for an EV body and frame (done to minimize the overall weight penalty imposed by the battery), which also adds to the upstream emissions because manufacturing that metal is so energy-intensive.

Consider, instead, estimates offered by Volvo and an EU-funded analysis of Volkswagen’s e-Golf, the latter a small sedan using a small battery.⁴⁴ The e-Golf’s upstream emissions, combined with emissions from the power plants that supply EU electricity, yield cumulative CO₂ emissions *greater* than the diesel version of that car for the first 60,000 miles of driving. After 120,000 miles, the accumulated emissions for the EV are estimated to be about 20% lower than the ICE version (Figure 4).⁴⁵

Figure 4

Life-Cycle Emissions: Volkswagen EV vs. Diesel

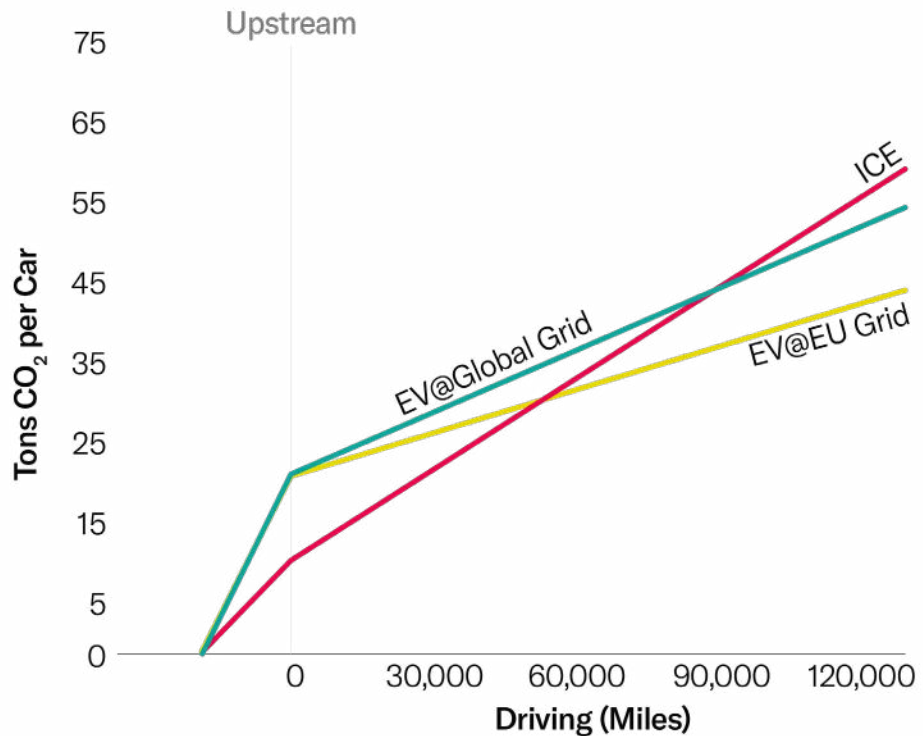


Source: Maciej Neugebauer, Adam Żebrowski, and Ogulcan Esmer, “Cumulative Emissions of CO₂ for Electric and Combustion Cars: A Case Study on Specific Models,” *Energies*, Apr. 6, 2022

Volvo’s study compares that company’s Recharge SUV using a 69 kWh midsize battery pack with its not particularly efficient gasoline-driven XC40 SUV.⁴⁶ The Volvo’s upstream emissions estimate is double that of the VW e-Golf, mainly because of a bigger battery. And similar to the VW analysis, Volvo found that its EV had *greater* total emissions than the comparison gasoline vehicle for the first 45,000 miles of driving (again, including the average emissions from electricity supplied on the EU grid). After 120,000 miles, Volvo estimates that its EV has a cumulative emissions reduction of about 30% (**Figure 5**).

Figure 5

Volvo SUV Life-Cycle Emissions: EV vs. Gasoline



Source: Elisabeth Evrard et al., “Carbon Footprint Report: Volvo C40 Recharge,” VolvoCars.com, 2021

Such estimated life-cycle emissions savings can shrink or evaporate if one assumes an EV using the more common, bigger battery sizes that consumers prefer. The “choice of methodology,” as Volvo’s study noted, “has a significant impact on the total carbon footprint.”⁴⁷ Volvo, for example, assumed a “global average electricity mix” for emissions arising from producing and refining battery materials.⁴⁸ That may sound reasonable but doesn’t reflect the actual emissions where most of those materials are processed, which, given supply-chain realities, are often on coal-dominated grids.

In another example of illusory precision, the *Wall Street Journal*—in a 2021 investigation seeking to unearth the truth about EV emissions—asserted that even accounting for grids and materials, “the data show that switching from gas to electric vehicles will make a huge impact.”⁴⁹ But that confidence was based on a study that the newspaper commissioned from a University of Toronto team.⁵⁰ For the value of the upstream emissions from fabricating a battery, that study used a number at the lowest end of the known range for such emissions, the upper end of which is 250% greater.

The *WSJ* was in good company with its confident conclusion, since IEA also asserts that emissions “along the mineral supply chain do not negate the clear climate advantages of clean energy technologies,”⁵¹ a claim parroted by governments and proponents and enshrined in mandates and bans. The fact is—as the data show, including in IEA’s reports—it’s anything but clear.

Upstream Emissions: Known Unknowns

A technical review of 50 different analyses reveals that the bottom lines for embodied EV emissions vary by a factor of five.⁵² It's meaningless to use an average number for such a wide range. Actual EV life-cycle emissions are dominated by the assumptions made for three key variables:

- **The size of the battery pack**

The 50-study review found that a 30 kWh battery pack was the median size analyzed and that life-cycle emissions were “rarely” calculated for large vehicles and batteries that consumers commonly choose.⁵³ In 2022, Teslas and the Mustang Mach-E accounted for nearly three-fourths of EVs bought by U.S. consumers and have 60–90 kWh batteries.⁵⁴

- **The location of the mines**

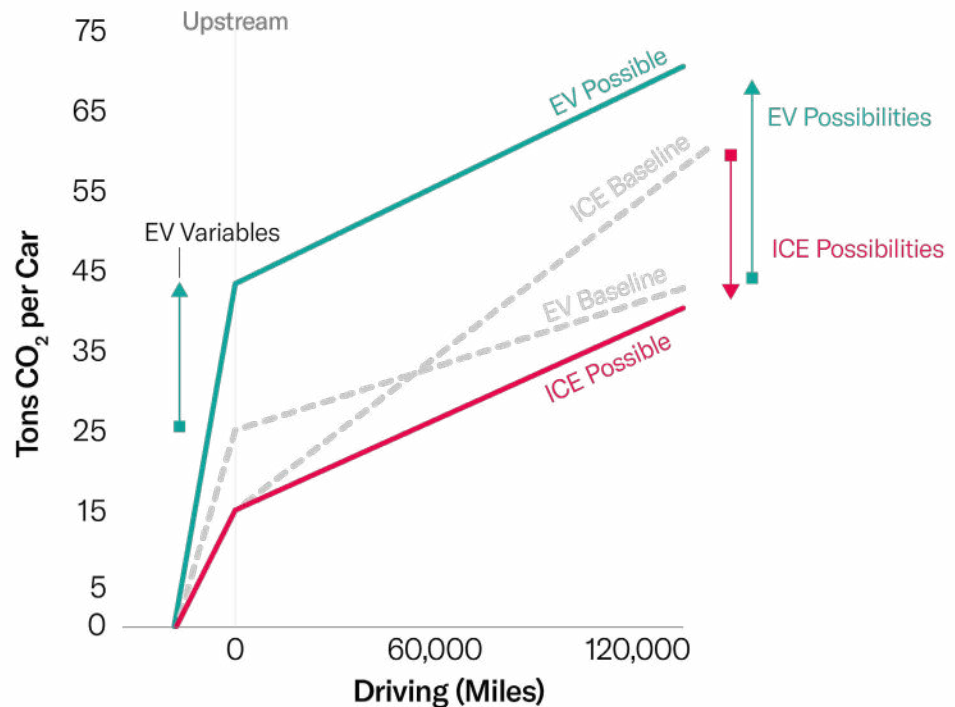
The energy used to obtain a pound of metal depends on the mineral ore grades, the size and nature of a mine, the distances that materials are transported, and the nature of the grids and fuels used at specific mines. For copper, that number can vary at least twofold and for nickel by threefold.⁵⁵ Getting accurate information is complicated by the fact that 80%–90% of relevant minerals are mined outside the U.S. and EU.

- **The location of the refineries**

The energy/emissions for specific mineral refineries vary with their age and the design of the refineries, as well as the location—and thus grids—used. Some analyses of life-cycle emissions make implausible assumptions—such as emissions from a hypothetical “average global grid”—or, for example, that the aluminum used to build U.S. EVs would come from North American production on grids that are 80% hydroelectric.⁵⁶ In reality, China refines 50%–90% of the world's suite of energy minerals.⁵⁷ The CO₂ emissions associated with refineries in China are 1.5x greater than those in the EU or United States.⁵⁸

EV proponents imagine adding clarity to the materials sourcing issues by creating rules and regulations and offering sensors and software that could, in theory, document the relevant data. Such prospects are, at best, remote, given the political, economic, and privacy challenges of such a global pursuit. Transparency in energy minerals—never mind an imposition of “clean” practices—is a far more daunting task than, say, ensuring that imported diamonds are “conflict-free.”

Keep in mind that all these uncertainties are baked in *before* making guesses about variables in where and when an EV is fueled. Nonetheless, including the range of known supply-chain possibilities yields possible scenarios wherein an EV driven on grids that will exist for the next decade leads to greater *lifetime emissions* than using an ICE car (**Figure 6**).

Figure 6
EV vs. ICE CO₂ Emissions: Scenarios with Known Unknowns


Source: Author's calculations from multiple data sources in this report; see Appendix

Then there are other variables that, though each individually is a relatively small share of the total picture, are nonetheless collectively important in the calculus of EV emissions. These include:

- **Location of the battery and EV assembly factory**

A battery plant in Norway, where dams provide about 90% of electricity, adds very little to upstream emissions from mineral processing and assembly, while a lot is added for the same plant in China, where coal supplies two-thirds of grid power. Notably, half the world's EVs in 2022 were built in China, and China is rapidly entering global markets, selling EVs across the world.⁵⁹ So far, there are no plans to repeal the Trump-era 27.5% tariff on Chinese EVs, but Chinese companies like BYD are increasingly exporting low-price (subsidized) vehicles around the world.⁶⁰

- **Battery chemistry**

There are about a dozen variations in lithium chemistry. While these entail different ratios and types of some minerals, the overall quantity of materials, and thus mining, needed per battery remains roughly the same. The exception is with lower energy-density chemistries. For example, the lithium-iron-phosphate (LPO) chemistry, popular in China and with some automakers because it doesn't use cobalt or nickel, has a 20% lower energy density. That translates into either a 20% lower driving range or building a bigger, heavier battery requiring more copper, aluminum, polymers, and lithium.

- **Materials for the rest of the vehicle**

Many analyses assume that the body and frame of the EV have the same embodied energy as a conventional car.⁶¹ But the EV's electric motor and high-power wiring necessarily use several hundred percent more copper than vehicles with iron-and-steel engines and drivetrains. In addition, automakers use more aluminum for the EV frame and body to offset the battery's weight penalty. Embodied emissions from 300 to 500 extra pounds of aluminum are roughly equal to the emissions from driving 10,000 miles in a conventional car.⁶²

- **Emissions from EV power electronics**

An EV uses about 200% more electronics for power management. Silicon device fabrication is extremely energy-intensive (about 100x more, pound-for-pound, than steel), but, as one analysis put it, energy-use “data for electronics production still needs to become better.”⁶³ The data available suggest that the uncounted CO₂ emissions embodied in each EV's power electronics roughly equal those from driving an ICE car 3,000 miles.⁶⁴

- **Battery life span**

Most analysts assume that a battery pack will last the EV's lifetime, but life spans depend on how consumers charge the battery—fast or overnight. As one study put it, using “intensive,” i.e., on-road fast charging, rather than “light” overnight charging, typically cuts a battery's life in half. Modeling the emissions from an EV fleet requires estimating what share of owners will need two batteries per car life span.⁶⁵

- **Total miles**

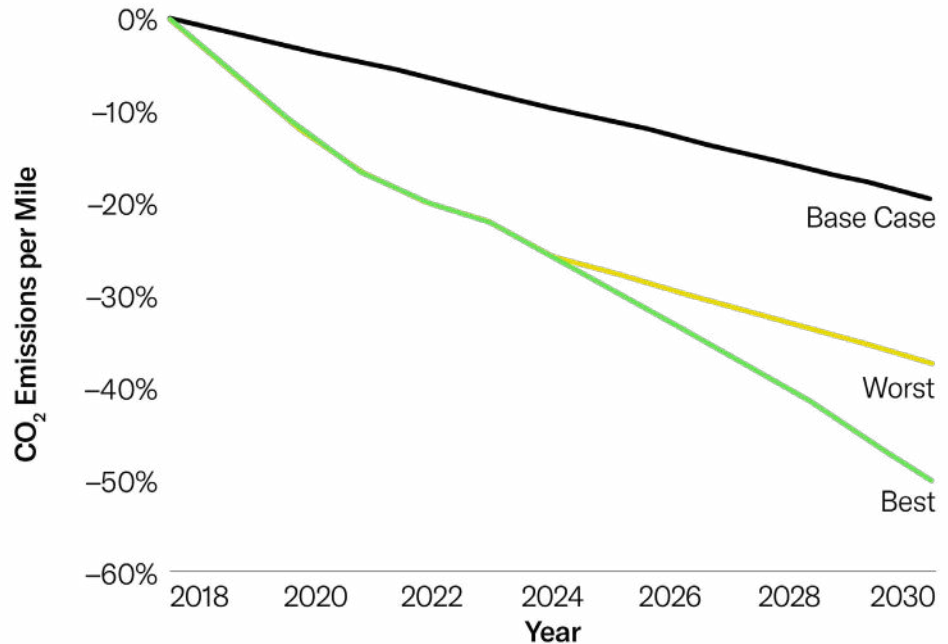
When ICE cars and EV emissions are expressed in mileage terms, i.e., grams of CO₂ per mile, that calculation necessarily assumes a number for total lifetime miles. Spreading out the upstream emissions over more lifetime miles arithmetically improves the CO₂ mileage. (An ICE-car CO₂ mileage is invariant with total miles assumed.) So far, data show that EVs are driven half as many miles per year as ICE cars. Using that lower mileage arithmetically doubles the EV's rated emissions per mile.⁶⁶

- **ICE fuel efficiency**

When EV emissions are presented as a percentage reduction over an ICE car, one assumes a fuel mileage for the latter. But realistic forecasts would incorporate future trends in combustion engine efficiency. An analysis of engine technology progress finds 30%–50% fuel efficiency gains will be on offer by 2030 and thus an equal reduction in CO₂ emissions per mile. Using the performance of a future ICE for comparison with a future EV further closes any gap in estimated emissions savings (**Figure 7**).

Figure 7

Known Potential for Internal Combustion Engine CO₂ Emissions per Mile



Source: Rohan Challa, Dipti Kamath, and Annick Anctil, “Well-to-Wheel Greenhouse Gas Emissions of Electric Versus Combustion Vehicles from 2018 to 2030 in the US,” *Journal of Environmental Management* 308 (April 2022)

Returning to the upstream materials, the dominant variable affecting EV emissions: everything about the future of EV emissions is anchored in mining, humanity’s oldest industry. Thus, by definition, estimating future EV emissions requires guesses about the future of global mining, where we find yet another array of known unknowns.

Future EV Upstream Emissions Are All About Mining, Not Recycling

Because of the astonishing magnitude of minerals needed to build an all-EV future, estimating emissions will be completely dominated by assumptions about the locations and nature of new mines and refineries. For context: the materials needed to build EVs for the world’s 70 million cars sold per year equals about 500 years of the materials now used to fabricate the 1 billion smartphone batteries now produced annually.

Hundreds of megatons of earth will need to be dug up and processed in the service of EV goals.⁶⁷ To meet “transition goals,” the materials demanded will require supplies to rise 400%–4,000%, depending on the mineral. IEA says that will require hundreds of new mines. Benchmark Mineral Intelligence puts the number at 384 new mines just to meet EV needs for the “graphite, lithium, nickel, and cobalt [that] will be required to meet EV demand by 2035.”⁶⁸ (Similar expansion will be needed for similar minerals to build solar panels and wind turbines.) EV proponents commonly invoke recycling as the solution to these monumental materials and emissions impacts, especially the holy grail of a “circular economy,” i.e., 100% recycling.

Recycling will be irrelevant for a long time, as far as mitigating upstream minerals demands. Since manufacturers claim that EV batteries will last a decade, that means that there won't be much of anything available to begin recycling until the early 2030s.⁶⁹ The best that IEA could come up with is recycled minerals meeting 1%–2% of battery demand by 2030.⁷⁰ As for the following decades, enthusiasts' unrealistic dream of perfect recycling, even were it feasible, would still leave the need for an astronomical rise in overall minerals supplied.⁷¹

The central and largely ignored issue for upstream emissions accounting is not just the known fact that minerals demand will rise but the other known fact that for future mines and refineries, emissions are increasing per pound of mineral.⁷²

Meanwhile, Upstream EV Emissions Are Rising

For all of history, the costs of a metal in both dollar and environmental terms are dictated primarily by ore grades, i.e., the share of the rock dug up that contains the metal sought. (Also related is the depth of the ore and thus the quantity of “overburden”—the rocks, dirt, trees, etc., on top of the ore—that must first be removed.) Ore grade is what accounts for the differences in the cost per pound of gold, \$15,000, and iron, \$0.05. The former ore grades are typically below 0.001% and the latter over 50%.⁷³

Iron (and aluminum) are uniquely abundant metals; not so the suite of critical “energy minerals,” for which ore grades range from 2% to 0.1%. Average nickel ore grade is under 2% and for copper below 1%, which means, arithmetically, that at least one ton of rock (excluding the overburden) must be dug up, ground up, and processed to obtain, respectively, 40 pounds and 20 pounds of metal.⁷⁴ Such geological realities determine the amount of energy used by big machines to do the digging, moving, grinding, refining, etc.

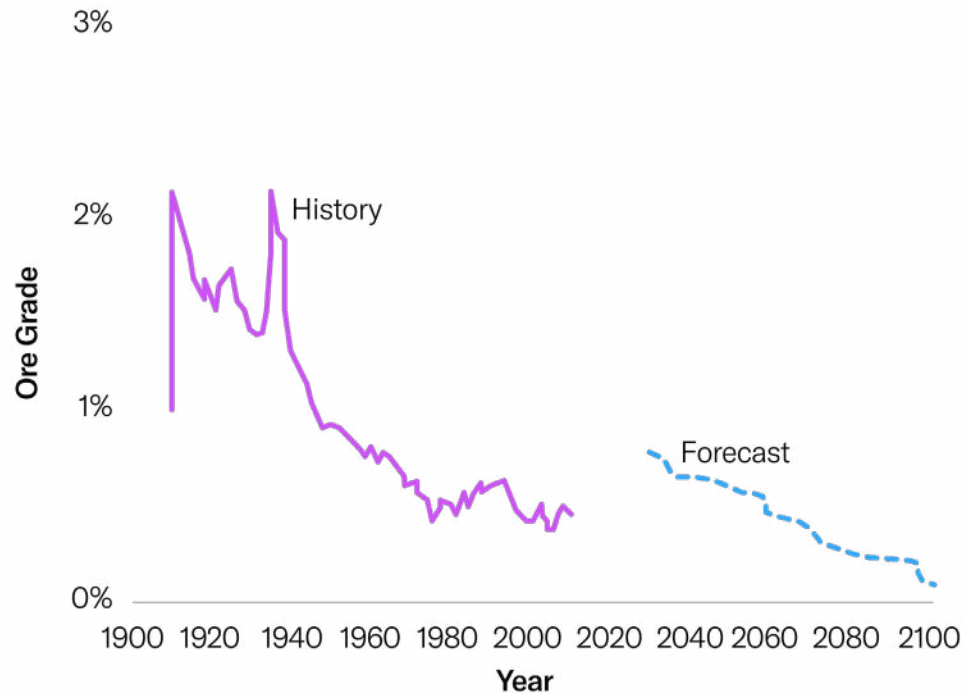
The global mining industry today already accounts for about 40% of all industrial energy use, and that's before an epic expansion that will be needed to meet green plans.⁷⁵ Petroleum itself typically accounts for half of mining-sector energy use.⁷⁶

Thus, estimating future EV energy emissions requires including the trajectory for ore grades. There is no evidence that any study is doing so.

Every metal exhibits a long-run and significant decline in ore grades. IEA acknowledges this, even if it tentatively understates the reality: “Future [minerals] production is likely to gravitate towards more energy-intensive pathways.”⁷⁷ The word “likely” dodges the fact that the data and the trends are clear. Copper is typical and is one metal for which there are no substitutes for building EVs or wind and solar hardware. As a National Renewable Energy Laboratory paper pointed out, “a decrease in copper ore grade between 0.2% and 0.4%, will require seven times more energy than present-day operations.”⁷⁸ And copper ore grades are forecast to continue the long-run decline (**Figure 8**).

Figure 8

Two Centuries of Global Copper Ore Grades



Source: S. Northey et al., “Modelling Future Copper Ore Grade Decline Based on a Detailed Assessment of Copper Resources and Mining,” *Resources, Conservation and Recycling* 83 (February 2014): 190–201

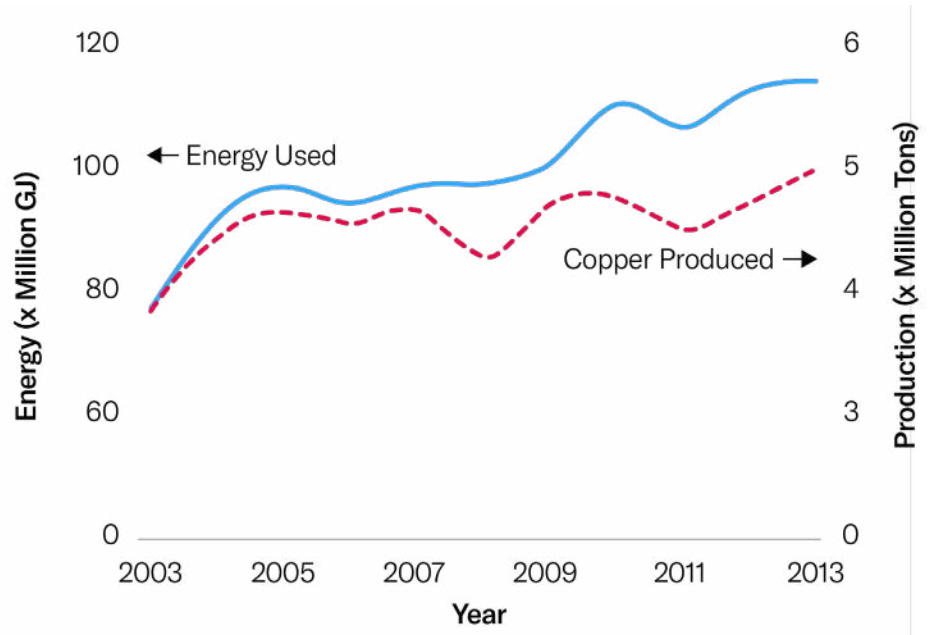
A World Bank study of EV upstream realities acknowledged the flaws in any emissions prediction. Even its own analysis, it notes, was based on “historical sources and are static” and didn’t “take into account . . . declining ore grades.” The bank called for “future research.”⁷⁹ But much of that research is available now. For example, according to IEA’s “Role of Critical Minerals” report:

- “Lithium production has been moving from brine-based recovery (mostly in Chile) to mineral concentrate production from hardrock (mostly in Australia). The emissions intensity of hardrock-based lithium carbonate production is three times higher than that of brine production.”
- “Demand is moving from lithium carbonate towards lithium hydroxide, as the latter is more suitable for batteries with higher nickel cathode chemistries. However, lithium hydroxide involves more emissions.” Notably, the nickel-based chemistry is pursued to avoid cobalt because of human rights concerns within the Congo, the dominant global cobalt source.
- “Battery-grade nickel faces a similar situation. While sulfide resources played a major role in the past, future growth is increasingly coming from laterite resources, which require more energy to produce.”⁸⁰

All the trends for declining ore grades are visible, even if they are ignored. Consider copper again and the trends in Chile, the world’s biggest supplier, where average ore grade decreased by about 25% over the decade 2003–2013.⁸¹ In those years, total copper-associated energy use—and thus emissions—grew *twice as much* as the growth in tons of copper supplied (**Figure 9**).

Figure 9

Copper Trends in Chile: Production vs. Mining Energy Use



Source: Guiomar Calvo et al., “Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality?” *Resources* 5, no. 4 (November 2016)

There’s No Magic for Fixing the Battery’s Carbon Debt

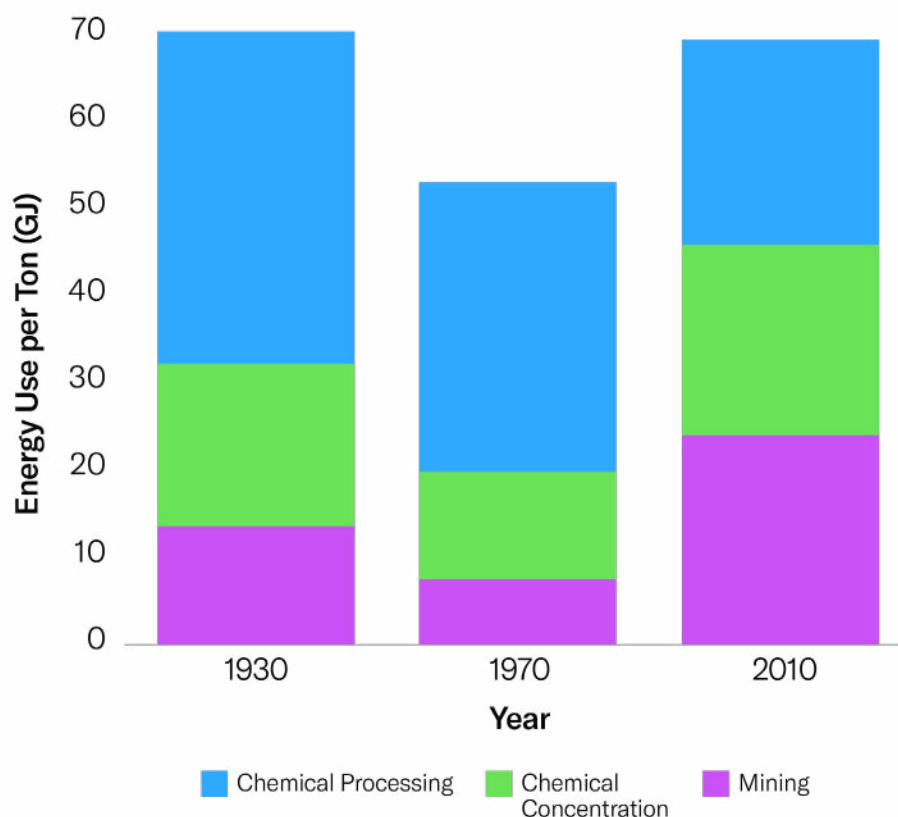
Technology offers ways to mitigate rising upstream emissions: better battery chemistry to reduce the materials used to store energy, more efficient refining processes, electrified mining trucks, and wind and solar electricity at mine sites. But none of these factors can have a significant impact *in the time frames contemplated* for the rapidly expanding EV production demanded by current transition mandates.

News stories serially claim a “breakthrough” in battery technology, but there are no commercially viable alternative battery chemistries that significantly change the magnitude of the physical materials needed. To meaningfully reduce primary mineral demands would require a nearly 10-fold leap in underlying electrochemistry efficiency. Such gains aren’t even theoretically feasible.⁸² Still, it is reasonable to imagine that some foundationally superior innovation will emerge; even so, many years would be needed to safely scale up industrial chemical systems. It was three decades from the discovery of a lithium battery to the first Tesla sedan. Batteries used in the near future will necessarily use technologies available now.

Similar realities constrain the prospects for radical efficiency gains in the various industrial mineral-refining processes. While incremental improvements are inevitable, especially in the digital era, there are no known “step function” gains visible in these well-trod fields of physical chemistry. Many processes are already operating near physics limits.⁸³ As a portent of the future, energy savings in the modern history of mining and mineral process efficiency have been wiped out by declining ore grades requiring larger volumes of ore needed to yield the same pound of metal (**Figure 10**).

Figure 10

Copper Production: Technology Trends in Energy Use per Ton



Source: Nadine Rötzer and Mario Schmidt, "Historical, Current, and Future Energy Demand from Global Copper Production and Its Impact on Climate Change," *Resources* 9, no. 4 (April 2020)

Caterpillar, Deere, and Case (and others) all have projects for electrifying mining trucks. Promising designs are on the horizon for specific applications, but batteries for most heavy equipment are not up to 24x7 performance and industrial-class demands—never mind costs.⁸⁴ And the turnover rate for mining and industrial equipment is measured in decades. Mines will use a lot of combustion-centric equipment for a very long time.

Meanwhile, pressures to rapidly increase mineral supplies will push developers to build smaller mines that are inherently faster and cheaper to build.⁸⁵ But smaller mines typically entail greater use of trucks; only big mines can justify the infrastructure costs of building dedicated (energy-efficient) rail systems. And as IEA has also pointed out, over half the electricity used in industry is not grid-connected but produced on-site, and much of it with diesel-fueled generators, especially at remote and small mines. Such on-site generation accounts for two-thirds of mining electricity in China and 95% in the rest of Asia.⁸⁶ While some mines are installing wind and solar systems, the inherently higher costs of these power sources will impose limits because energy spending accounts for about 40% of overall mining costs, setting aside the practicalities of 24x7 power needed at mine sites.⁸⁷

Over the longer run, a foundational transformation in industrial technology efficiency is coming, one that echoes that of a century ago. This time, the source will be Cloud-centric, networked machines mediated by artificial intelligence, along with new classes of autonomous smart trucks and robots.⁸⁸ But those advances won't significantly change the realities in time to meet the hypertrophied demands for industrial minerals within this decade.

The trends that are knowable for the near future show upstream emissions *rising* for EVs, even if we don't know exactly how much they will increase. Gaining clarity will be a challenge not least because, as IEA has noted, only a tiny share of players in that industry are cooperating with "emission pledges" made for the Responsible Mining Index.⁸⁹ The solution that IEA offers is "greater pressure from governments, investors, and end-use customers." We doubt that leads to clarity anytime soon.

Meanwhile, the upstream emissions uncertainties are multiplied by yet more variables: how EVs will be fueled at scale.

Kilowatt-Hours and Elsewhere Emissions: More Known Unknowns

Emissions from refueling an EV vary wildly, depending on the *where* and *when*, thanks to differences among grids, combined with hourly variations in electricity production. Accounting for those realities, and not a hypothetical average kWh, reveals that CO₂ emissions per EV fill-up can range from zero to as high as the same as just burning gasoline to drive the same number of miles.

Current estimates of EV on-road emissions are nearly universally anchored in a simple calculation based on the *average* emissions from a kWh produced on a local grid, multiplied by a vehicle's rated kWh mileage. As with upstream emissions numbers, refueling numbers also give an illusion of precision.

Because of grid variabilities, the actual (not average) emissions from producing a kWh varies dramatically, depending on the hour a battery is charged, a feature that will be complicated as more wind and solar are used. No such variability comes from ICE cars; calculating CO₂ emissions based on gallons consumed is essentially the same whenever gasoline is purchased, produced, or burned.

Similar uncertainties and disparities are associated with the mileage numbers used to calculate emissions. In the real world, an EV's kWh/mile varies quite significantly from a vehicle's claimed rating—again, unlike the minimal variability associated with ICE-car fuel mileage.

The uncertainties start with the EPA "sticker" mileage provided for consumers (and estimators). A recent study found the actual on-road EV mileage averaged 12.5% worse than the certified window-sticker rating. For ICE cars, however, the average, real-world mileage per gallon was 4% better than the EPA sticker.⁹⁰

More significantly, EV mileage is about 30% worse when it's 20°F outside, versus 80°F, because battery electrochemical reactions are unavoidably slow at lower temperatures.⁹¹ There's only a 5% drop in fuel efficiency for ICE cars over the same temperature range. On top of that, as road testers and consumers know, using an EV's heater in winter can lower kWh mileage by as much as 50%.⁹² (An ICE car scavenges free waste heat.) Such temperature factors are generally ignored, not only on EV "sticker" ratings but especially so in estimating national emissions impacts from EVs. Those factors matter, since one-third of the U.S. population lives in cold northern latitudes.⁹³ Odds are that EPA will eventually sort out accurate ways to rate EV mileage. But unlike conventional cars, the EV sticker might need to be accompanied by a map with a rating, say, for each state where it's driven, based on the share of the year experiencing low temperatures.

The realities of local grids add another set of uncertainties, something that EPA recognizes on its website with an EV emissions calculator that divides the country into 27 electricity supply regions. There, one finds that the grid assumed leads to a threefold variation in CO₂ emissions per kWh of fueling.⁹⁴

Even that EPA calculator understates the magnitude of uncertainties because actual emissions-per-kWh used do *not* depend on the average for a region but on the specific hour of the day that a battery is charged. The hourly factor is critical with fast chargers that provide a fill-up in under an hour rather than overnight, a feature essential for on-road refueling, in order to allow widespread EV adoption. Hourly emissions per kWh produced can vary by another threefold or more.

Taken all together—time of year and day, and grid specifics—the real-world CO₂ emissions per kWh actually used to charge an EV can vary about 10-fold. Emissions from a fill-up could be nearly zero during a sunny summer hour (ignoring the solar electricity’s upstream minerals emissions). Or during an hour when it’s cloudy in the winter, just the fill-up emissions, ignoring upstream factors, could be greater than that from burning gasoline to drive the same distance.⁹⁵

Such disparity exposes the lie of oft-made assertions—for example, in another recent *WSJ* article: “Regardless of where they are driven, EVs are always a climate-friendlier choice than their gasoline counterparts, according to recent studies published by the European Environment Agency and the International Energy Agency, as well as academic research.”⁹⁶ Those studies either ignore or bury in footnotes the reality of variables.

Some EV proponents know better and propose so-called smart-charging to ensure that batteries are charged only when carbon-free electricity is available by using software to track a specific vehicle location and time of charging. That information would then be used to provide incentives to fuel at the “right” time, penalties for refueling at the “wrong” time, or both, or even remotely disabling chargers when consumers are making an unacceptable choice.⁹⁷

Such machinations to influence consumer behavior and freedom are, *prima facie*, radically different from refueling conventional cars. And such realities illuminate the flaw of claiming that EVs are inevitable because of parity with, if not superiority to, conventional cars.

The Parity Trope: EVs Are Not Yet Equal with ICE Cars, and Won’t Be Anytime Soon

The EV is widely touted as a transition comparable to the shift away from the horse-and-buggy age. But changing how a car is powered has the equivalent relevance to a mobility “revolution” as changing the nature and source of a horse’s feed. And to encourage adoption of the newly invented gasoline-powered cars, governments didn’t have to ban horses.

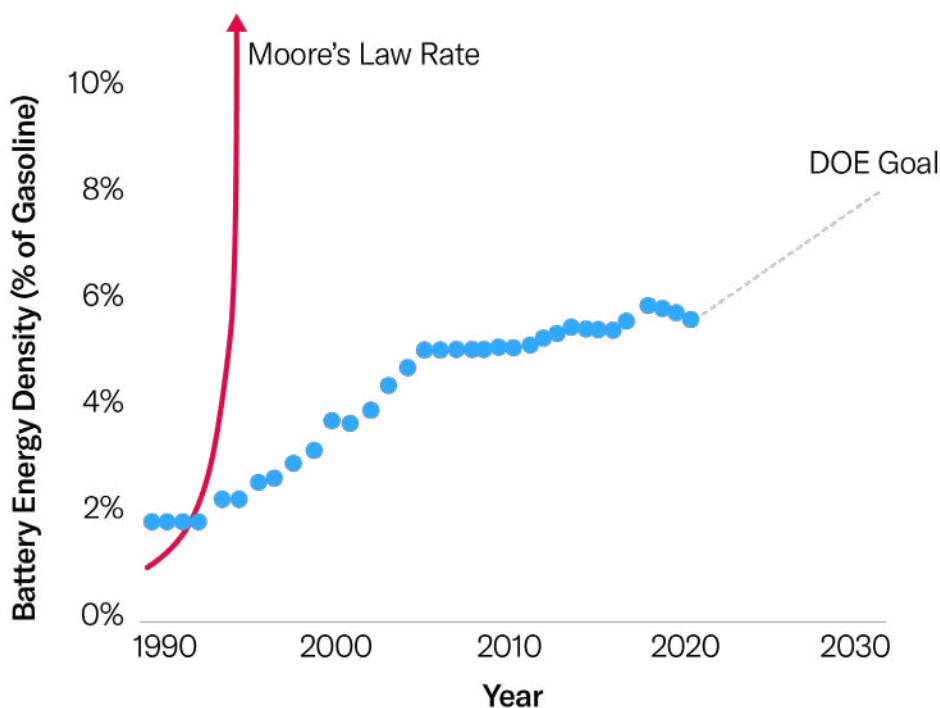
To be sure, EVs offer features that appeal to millions of drivers, mainly wealthier ones and especially the cohort of car enthusiasts who gush over “insane” acceleration.⁹⁸ Equality in all features is neither relevant nor needed for EV sales to grow, as there are many different reasons consumers choose any one of hundreds of different kinds of car models. But the premise of the inevitability of an all-EV future is not just about luxury EVs offering “insane” features, or even about reducing emissions.

The premise is that EVs are superior in every way to the old technology and thus “electric cars are going to take over the world,” as the *Wall Street Journal*’s automotive columnist, Dan Neil, enthused, or as regulators and policymakers now plan to mandate.⁹⁹ The EV is framed not only as leaving the horse era, but also doing so at the same kind of technology acceleration witnessed in computing and communications. Thus, as Neil went on: “Remember flip phones, fax machines and dial-up modems? You want an electric vehicle because they are generationally improved products: quieter, quicker, more refined, more efficient, offering superior vehicle dynamics, less maintenance, and lower per-mile operating costs.” Neil is not alone in invoking the tech analogy. For example, an International Monetary Fund report asserted: “Smartphone substitution seemed no more imminent in the early 2000s than large-scale energy substitution seems today.”¹⁰⁰

The notion that we’re witnessing a tech-like acceleration for EVs is worse than a canard—it’s nonsensical in the energy physics of moving people and cargo versus moving data. If battery chemistry—the pillar of EV inevitability—could follow the arc of computing’s progress, we would soon see a peanut-size battery power a car for its lifetime on a single charge. Only in comic books does energy tech advance at the pace of information tech, such as in Moore’s Law (**Figure 11**).

Figure 11

Progress in Lithium Battery Performance*



*The progress in lithium battery performance is shown as energy stored per pound of battery+motor as % of the weight of gasoline+engine; the comparison incorporates the 2x superior energy efficiency of electric drive systems.

Source: Alvaro Masias, James Marcicki, and William A. Paxton, “Opportunities and Challenges of Lithium Ion Batteries in Automotive Applications,” *ACS Energy Letters* 6, no. 2 (2021): 621–30; U.S. Dept. of Energy, “National Blueprint for Lithium Batteries,” June 2021; and author’s calculations

Similarly central to the inevitability and cheaper-better claims is the assertion that EVs are inherently simpler machines and that the “old” ICE technology is maxed out, with no innovation remaining. Again from Mr. Neil: “Compared to EVs’ few moving parts, the complexity of modern gas-powered vehicles terrifies me . . . [and] combustion technology is about as good as it will ever get.”¹⁰¹

The reality is otherwise. Yes, conventional cars *do* have a complex thermo-mechanical system, with the engine and automatic transmission made from hundreds of components, mated with a very simple fuel system, a tank holding a liquid with a one-moving-part pump.¹⁰² EVs, inversely, have a very simple motor made from just a few parts. However, the EV fuel tank is a complex electrochemical system made from hundreds of parts, sometimes thousands, including a cooling system, sensors, and control electronics. In addition, the EV drivetrain requires roughly double the quantity of microcontrollers and power electronics.¹⁰³

As for any claim that we’re at the end-of-innovation for combustion engines, myriad radical advances in ICE technology are already under way, as can be seen in the technical literature as well as from automotive research labs, with many commercially available (if not widely used). Engines with efficiency double that of today’s average have been demonstrated and, in some cases, deployed in nonautomotive applications.¹⁰⁴ Some new engine designs have as few moving parts as an electric motor.¹⁰⁵ Greater advances are still possible with ICE tech than are with electric motors or batteries. In terms of overall mineral resource requirements, a 1% improvement in combustion efficiency equals a 10% advance in battery-electric tech.¹⁰⁶

It is true enough that the advent of lithium battery chemistry is one of history’s rare technology pivots enabling collateral innovations in many areas, not just cars. But, *absent a prohibition of ICE cars*, the extent to which EVs capture a majority of the entire automotive market will be determined by three factors:

- Purchase price reaching parity with ICE cars
- Operating costs and convenience reaching parity
- Parity in the macro issues of supply chains and broad environmental impacts.

To understand these factors, consider:

The Future Price of EVs Is in the Hands of (Foreign) Mining & Refining Companies

So far, EVs are sold mainly in the luxury-car category, where sticker prices exceed \$60,000.¹⁰⁷ In the U.S., there are no EVs in the lowest vehicle-price category, \$16,000–\$20,000, where there are 10 models of conventional cars.¹⁰⁸ Nevertheless, the claim that EVs are getting cheaper, fast, and will soon reach parity with (or even be priced lower than) conventional cars is based on the notion that battery prices are on track to “collapse.”¹⁰⁹

Today, the battery adds at least \$10,000 to the price of an EV.¹¹⁰ Meanwhile, with higher interest rates intersecting rising prices for conventional cars, the *Washington Post* recently noted that “new cars, once part of the American Dream, [are] now out of reach for many.”¹¹¹ Consequently, purchases for “the lowest 20 percent of earners dropped to its lowest level in 11 years. Meanwhile, spending on new cars by the top 20 percent reached its highest level on record.”



The claim of plummeting battery costs is true only in hindsight, measured since the inception of lithium technology; this is a trend typical for all new technologies. But like all technologies in the world of atoms, not bits, after early years on the manufacturing learning curve, the rate of improvement slows dramatically. Over the past half-dozen years, battery cost has decreased slowly; and over the past couple of years, prices have reversed. Battery costs have risen 20% since 2021.¹¹²

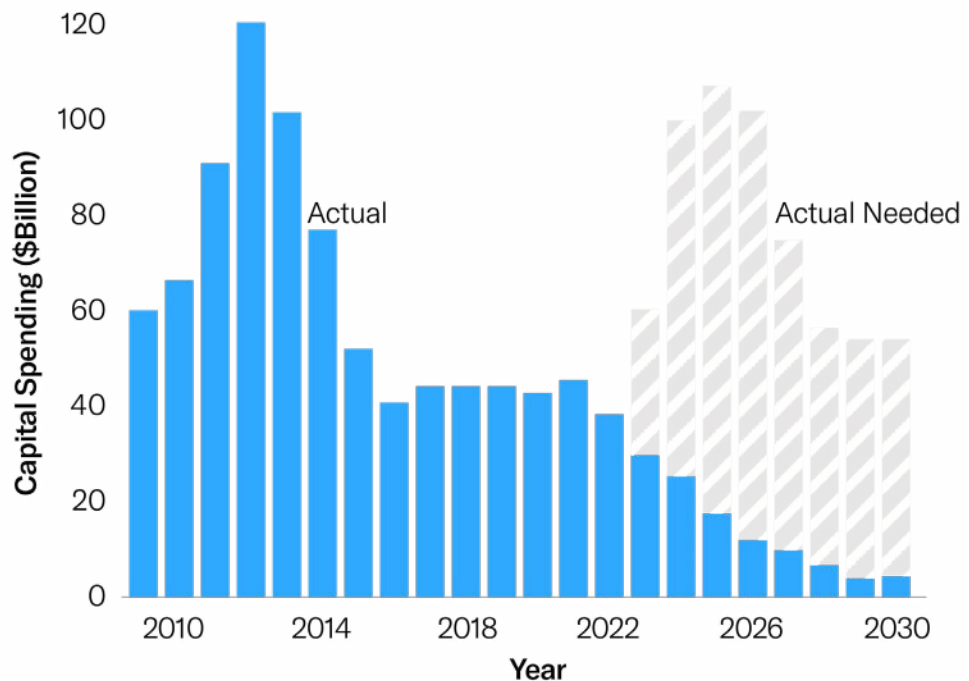
Future battery costs now depend almost entirely on a single fact: basic materials now account for 60%–80% of the cost to make batteries.¹¹³ Even if labor and capital costs decline (both are currently trending up), battery prices (and future upstream emissions) are now firmly in the hands of decisions made by global miners and refiners.

We know that a far greater supply of minerals will be needed to build an all-EV world. As a fusillade of subsidized battery factories come online in the next few years, the demand for (and the cost of extracting) these minerals will skyrocket. In the context of prohibiting ICE cars, the issue is not whether sufficient resources exist on our planet but whether there will be enough mining, soon enough. As IEA reported, it takes 10–16 years to open a new mine.¹¹⁴ Even the *New York Times* is now covering the obvious with stories headlined “The U.S. Needs Minerals for Electric Cars. Everyone Else Wants Them Too” and concluding that “the world is facing dramatic long-term shortages by any estimate.”¹¹⁵

The data show that the mining industry isn’t remotely close to scaling up the supply needed. Global spending plans to expand or add new mines are roughly 10% of what will be required by 2030 to meet green energy mineral demands¹¹⁶ (Figure 12).

Figure 12

Global Mining Industry Capital Spending



Source: Julian Kettle, “Have Miners Missed the Boat to Invest and Get Ahead of the Energy Transition?” Wood Mackenzie, July 12, 2022

We also know a lot about market concentration. The overwhelming majority of minerals supply is located outside the U.S. and EU. “None of the raw materials required for battery-cell manufacturing are currently mined in significant quantities in Europe,” a recent German government study noted. “Notwithstanding the increase in recycling and European raw material projects that have been announced, this import dependency will remain largely unchanged by 2030.”¹¹⁷ Precisely the same is true for the United States. Absent radical regulatory reforms (far more than anything enacted or proposed), that reality will remain unchanged regardless of elliptical language in subsidies to encourage reshoring in Europe or America. When it comes to resource supply, some well-known factors are relevant to price trends—factors again rife with unknowns.

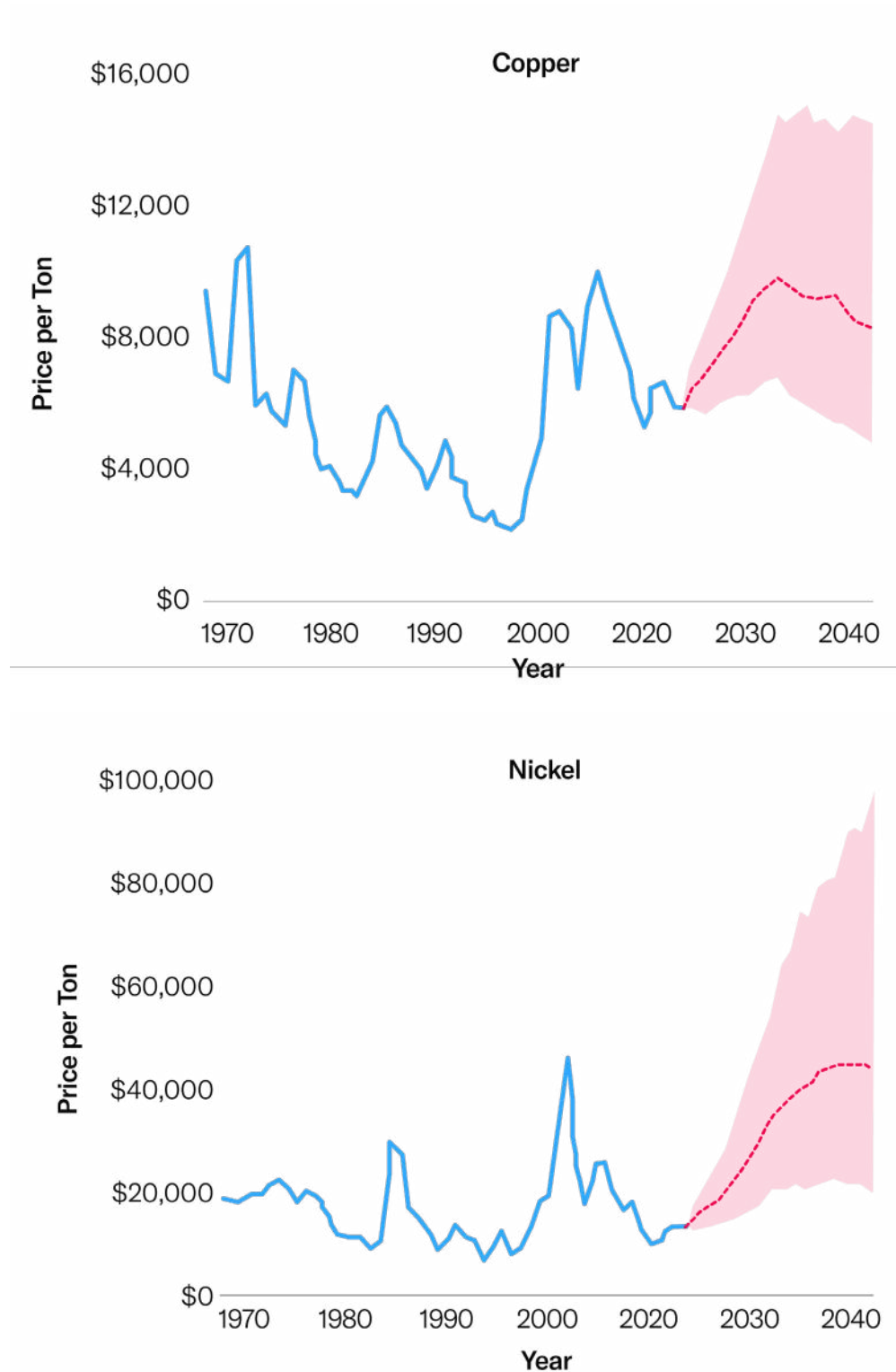
For energy minerals, China has double the market share that OPEC has with oil. China is busily expanding mining investments in Africa and South America and is on track to raise its share of the refined lithium market from 24% last year to 32% within two years.¹¹⁸ Other countries are following Indonesia’s new policy (the world’s top nickel producer), wherein exports of raw mineral ore are prohibited, requiring the construction of local refineries.¹¹⁹ Meanwhile, in South America, where two-thirds of the world’s low-cost lithium resources are known (and one-third of current production), there’s talk of a Lithium cartel.¹²⁰ The effect on prices of such market concentrations are well known. Strategies to form “buyers’ clubs” among nations, recently proposed by the U.S. government in collaboration with the EU, run up against their historical failure. Monopolies, cartels, or dominant sellers invariably have more price control.¹²¹

Even if the energy-minerals market were to be uniquely free of price manipulation, the basic economics of supply and demand points to dramatic price increases for batteries—as well as other products dependent on these minerals. For many minerals, EV demand is transitioning from a marginal share to the dominant use. Competition for these minerals’ supply, and inevitably price pressures, *will begin to have an impact on the cost of building everything from homes and buildings to appliances and computers*. Five years ago, EV markets constituted, for example, 15%, 10%, and 2% of all uses for lithium, cobalt, and nickel, respectively; last year, those shares were 60%, 30%, and 10% and rising rapidly.¹²²

Using long-run historical and financial data on minerals, IMF economists modeled the price implications from mineral demands entering a period of consistent undersupply due to all the EV and energy transition goals. The study’s unsurprising conclusion: prices for various metals would reach historical peaks “for an unprecedented, sustained period of roughly a decade” (**Figure 13**).

Figure 13

IMF Price Forecasts for Copper and Nickel



Source: Lukas Boer, Andrea Pescatori, and Martin Stuermer, “Energy Transition Metals,” International Monetary Fund working paper, Oct. 12, 2021

Among the known unknowns, the IMF economists also noted that the “integrated assessment models” for forecasting energy transition economics “do not include the . . . potential rise in [mineral] costs.” Forecasters, as well as policymakers, appear lulled by the 20th century, during which there was a long-run slow decline in the average prices of minerals (net of short-term price volatility). But that trend began to reverse just over a decade ago.¹²³ Long-term rising mineral prices would be something new not only for EV forecasters but also for economists in general and for the Federal Reserve’s inflation-fighting efforts.¹²⁴

All the underlying minerals trends are hard to square with automakers claiming that they expect to soon see lower production costs for EVs, the key to a transition from money-losing to profitable sales.

Refueling Infrastructures in an All-EV Future

So far, 90% of EVs in the U.S. have been purchased as a second or third car by wealthy households with a garage.¹²⁵ A recent JD Powers survey confirms that for luxury-car buyers, “driving performance” was the primary reason for the purchase.¹²⁶ For these owners, an exciting-to-drive EV is convenient and inexpensively refueled overnight. Consistent with this market, the data show that most EVs are used only occasionally and driven half as many miles as the average car.¹²⁷ For automakers, that’s still a tantalizingly big market because at least 50 million vehicles in the U.S. are put to occasional use by a multicar household.¹²⁸ But that’s not the all-EV world that the prohibitions on ICE vehicles intend to create.

While only one-third of American households have a garage, the fueling infrastructure challenges begin in those neighborhoods for an all-EV world.¹²⁹ If all garage owners use home chargers, it will necessitate massive upgrades to residential electric networks. Otherwise, as one study showed, “more than 95 percent of residential transformers would be overloaded,” meaning that they fail or can blow up.¹³⁰ And there’s also an inconvenient feature in the physics of heat. Even if an EV is fueled at night, when there’s less demand on the grid, the air-cooled transformers (on the local utility poles) can remain overheated after sunrise, when normal residential peak loads begin to heat them up further, thus still increasing the prospects for daytime overload failures, even using off-peak charging.

And for the rest of the non-garage-owning world, the usual mantra of “range anxiety” as an impediment to widespread EV adoption is not true, since most EVs offer gasoline-equivalent range. The key to operational parity with conventional cars is met only with convenient, ubiquitous on-road fast charging.

Shifting the primary energy for mobility from liquids to electrons sounds efficient, but it constitutes a degradation in convenience and an increase in costs for *delivering* energy. Counterintuitively, at big energy levels, *transporting* a unit of electrical energy using wires and transformers is about 20-fold more expensive than transporting the same quantity of energy as oil in pipelines and tanks.¹³¹ That gap remains wide, even adjusted for the fact that one-half to one-third as much energy is transported to EVs because of the higher efficiency of electric motors over engines. And the math for convenient electric fueling economics makes it worse.

Overnight fueling uses relatively inexpensive (~\$3,000) chargers operating at a 7 kW–19 kW power level.¹³² (For comparison, ~3 kW is the power demand for an entire average home.) To approach the convenience of filling a liquid fuel tank in a few minutes, superchargers offer fill-up times of 20–40 minutes by operating at power levels of 300 kW–1,000 kW.¹³³ Such superchargers cost about \$400,000, or more, versus a comparable gasoline pump at under \$150,000.¹³⁴

“Fast” charging is still far slower than the five to 10 minutes typical for gasoline fueling. Thus, to achieve the same convenience (avoiding waits in lines, etc.), a filling station will require about four chargers to replace each gasoline pump.¹³⁵ Quite aside from the land-use implications, this

translates into at least a doubling of the overall cost to build the average filling station (counting land, buildings, and other infrastructures as well).¹³⁶ For those who think that “Big Oil” can afford that, we note that only 1% of filling stations are owned by oil companies; nearly all are owned by small businesses.¹³⁷

In addition, installing two dozen or more superchargers at a filling station creates a grid power demand comparable to a small town or a steel mill instead of a convenience-store demand level of today’s filling stations.¹³⁸ At the same time, the higher power levels from EV chargers will radically decrease the life span of the existing power transformers on utility poles, coming at a time when costs for new transformers have inflated about fivefold.¹³⁹ Moreover, the bigger, heavier transformers needed to support high-power demands will require the replacement of many of today’s 180 million roadside utility poles.

The extra utility infrastructure costs for all that are usually paid by the power user, i.e., the station owner. All these costs will necessarily be added to the fill-up price that consumers pay. In Europe, where there’s more experience with on-road fast charging, the cost of a fast-charge fill-up is already higher than diesel for the same distances driven.¹⁴⁰ In the U.S., *Consumer Reports* notes that the cost to fill up with a Tesla supercharger is over triple the (usually assumed) cost of at-home overnight charging.¹⁴¹ Surveys already show that only a small percentage of consumers say that they would be willing to pay the premium for on-road fast charging.¹⁴² But the costs are real and will show up somewhere, even if governments engage in shell games.

Some brag that at-home fill-ups evade the road taxes paid today by other drivers. In an all-EV America, however, the \$50 billion a year collected in federal and state gasoline taxes to maintain roads will necessarily shift to EV fueling, one way or another.¹⁴³

As for a “big reset” for EV infrastructure based on the 2022 Inflation Reduction Act’s \$7.5 billion in subsidies to fund “thousands” of on-road chargers: consider the math. The all-EV future will need to replace most, if not all, of America’s roughly 1 million gasoline pumps located at the existing 145,000 filling stations. That will require over \$100 billion of superchargers, not counting the costs of electrical infrastructure upgrades. The learning curve from future high-volume production, as well as new technologies for superchargers, will shave only a little of that staggering sum.¹⁴⁴ None of these underlying economic impacts is changed by rearranging ownership models for filling stations, whether at supermarkets, shopping malls, parking garages, or automakers building their own, following the Tesla example.¹⁴⁵

The calculus of overall societal costs for an all-EV future also requires including the dramatic expansion of power generation and long-distance transmission. Replacing all the gasoline used in America with electricity would require at least 50% more electricity generation than exists or is planned, along with an even greater increase in electric power distribution.¹⁴⁶ Such power-plant and grid requirements represent multitrillion-dollar levels of spending.¹⁴⁷

An analysis from the Boston Consulting Group puts the utility grid improvement costs—never mind power generation—at \$1,700–\$5,800 per EV put on the market.¹⁴⁸ Do the math: that’s \$400 billion to over \$1 trillion for an all-EV American car fleet. While those costs would be divorced from car prices, it would constitute “sticker shock” for household electricity or tax bills.

Driving an EV for Most People: Exciting and Expensive

As the *Consumer Reports* chief for auto testing said: “Consumers tell us reliability is one of the most important factors when buying a car.”¹⁴⁹ It is received wisdom among enthusiasts that EVs have lower maintenance and are more reliable because they’re “simple” machines. Engineering reliability into any machine is the same and emerges from high quality in manufacturing and

supply chains.¹⁵⁰ Aside from the earlier-noted fact that EV and ICE complexities are comparable (albeit in different locations), only recently have there been enough EVs on the roads to provide statistically useful reliability evidence with owner surveys and road tests.¹⁵¹

In November 2022, *Consumer Reports*' annual reliability survey found that of the 11 EV models included, seven rated below average for all cars.¹⁵² Similarly, a UK survey found that during the first several years of ownership, EV owners experienced a 50% higher rate of problems, compared with conventional cars.¹⁵³ Notably, problems with software topped the list of quality-control issues for EVs, a feature that is more complex than in an ICE vehicle. Lower reliability invariably shows up somewhere in the overall economics for consumers, even if absorbed by automakers in warranties. To be sure, time will bring reliability equivalence for EVs. One recent three-year study found that overall maintenance and repair costs revealed only "a tiny difference."¹⁵⁴ Another study, from *Car and Driver*, found a slightly lower EV maintenance cost.¹⁵⁵ But so far, real-world experience doesn't seem like a slam-dunk for radically superior EV reliability.

As for insurance, the battery is the most expensive single part of an EV and, typically, costs twice as much as an ICE vehicle.¹⁵⁶ This factor alone leads to higher insurance costs.¹⁵⁷ It is exacerbated by the fact that EV batteries are largely non-repairable and thus become a write-off in the event of even small accidental damage (unlike engine damage, which is frequently repairable).¹⁵⁸

All the day-to-day operational factors put together determine the real-world costs, as all car owners know. If one includes the high cost of on-road fast charging and, say, assumes lower maintenance and equal insurance costs, the overall cost of ownership for an EV is, according to one deep analysis, some 25% higher than for a conventional car.¹⁵⁹ That cost penalty increases if one attaches an imputed value to the extra time taken for on-road charging (even with fast chargers). This is the kind of cost that economists know influences consumer decisions because people naturally value their time.

Meanwhile, in a price-inflating feedback loop, a radical expansion in grid distribution hardware comes at a time of intense competition for the two key metals—copper and aluminum—needed to build transmission. Those metals constitute 20% of capital costs for electric grids—and that's before the looming minerals inflation.¹⁶⁰

Battery waste disposal should be added to the column of unknowns for future EV costs. The unique character, variety, and volume of EV batteries will present recycling and disposal challenges, which have led to rampant speculation about what those costs will be. A Volkswagen-led consortium was launched in 2022 to *study* the challenges, not to build anything.¹⁶¹ As the CEO of the nonprofit Call2Recycle said, "Recycling [EV batteries] is not going to be profitable for everybody. That's fantasy economics."¹⁶² Whatever the costs, they will ultimately be bolted on to the purchase price of a vehicle, imposed on manufacturers, or subsidized by taxpayers.¹⁶³

A Word About Parity in Supply Chains, Geopolitics, and the Environment

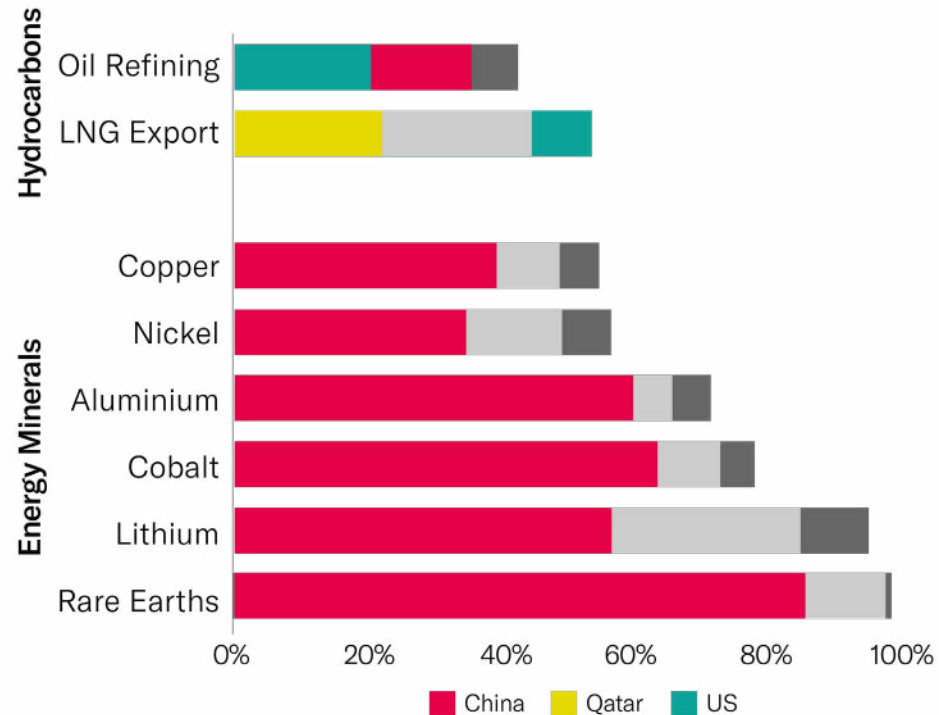
Another favored refrain from EV and green-tech advocates is that the subsidies will free us from "our geopolitical adversaries' . . . manipulation of the price of oil."¹⁶⁴ By now, most people following the energy transition narrative are familiar with the deep dependencies on minerals that are produced elsewhere, and they understand that the same geopolitical forces are in play and, indeed, have features that are arguably more worrisome—or at least that they present significant unknowns about future risks.

There is far more supplier concentration for "energy minerals" than for hydrocarbons. Chile, the largest copper producer, with a 20% market share, has a new socialist president who has promised "social justice" and environmental "reforms" in mining.¹⁶⁵ The number-two and number-three producers are Peru and the Congo. Russia, at 10% of global nickel production, is number three

in the world and is also a major global supplier of copper and aluminum, at about 4% and 6%, respectively.¹⁶⁶ And China, per IEA, has a “share of refining [that] is around 35% for nickel, 50%–70% for lithium and cobalt, and nearly 90% for rare earth elements”¹⁶⁷ (Figure 14).

Figure 14

Global Share of Top Three Countries Producing Refined Products



Source: IEA, “The Role of Critical Minerals in Clean Energy Transitions”; Harbor Aluminum, “Aluminum Production by Country.” The gray and black bars represent the other number two and three countries.

The U.S. today is dependent on imports for 100% of some 17 critical minerals, and, for 28 others, net imports account for more than half of existing domestic demand.¹⁶⁸ Assembling batteries (or solar hardware) here creates underlying dependencies equivalent to assembling conventional automobiles domestically but importing all the key parts and all the fuel.

Hence, we see media accounts and policymakers publicly handwringing over geopolitical mineral dependencies in a fashion redolent of petroleum dependency worries of the past half-century. Dependency anxieties this time around are in advance of anything equivalent to the Arab oil embargo of 1973–74, but the actions aren’t different.

Also, as global mining expands, only now appearing on the radar is a belated recognition of the lack of parity in the environmental challenges from energy minerals, compared with those associated with drilling for oil and gas. As a recent *Washington Post* investigation noticed, there is a “hidden toll” from “clean cars.” The *Post*’s investigators visited Indonesia, the world’s top nickel miner. The paper reported that “extracting [nickel], refining it and readying it for export is a gargantuan task” and is “posing steep environmental costs that have yet to be reckoned with.”¹⁶⁹ In another story, the *Post*’s headline reveals the trend: “The Underbelly of Electric Cars.”¹⁷⁰ Australia’s Institute

for Sustainable Futures noted that a global gold rush for energy minerals will take miners into “some remote wilderness areas [that] have maintained high biodiversity because they haven’t yet been disturbed.”¹⁷¹

Credit IEA researchers for acknowledging these issues, even if the implications remain largely absent from that agency’s enthusiastic promotion of EVs.¹⁷² Per IEA analysts, mining “can displace communities and threaten natural habitats.” A satellite analysis (necessary because many mines are in uncooperative regions) documented the additional land being ‘consumed’ to expand copper mining. The magnitude of copper alone needed to build forecasted ‘green’ machinery will lead to the use of hundreds of thousands of acres of previously untouched land.

Even less attention has been afforded to the asymmetries in social and humanitarian implications of a massive global shift to energy minerals. As one recent study showed, over half of all the locations where new mining will be needed are lands where indigenous people live that are often ecologically fragile.¹⁷³ Northwestern University’s Jennifer Dunn, a pioneer in analyzing life-cycle *social* impacts, has noted that “technologies that are designed to solve grand challenges such as climate change must consider both their environmental and social impacts to understand their true consequences.”¹⁷⁴

As environmental researchers in Spain observed regarding the “relocation” of environmental impacts from EVs: “Transfer of environmental burdens from the use phase to the raw materials extraction and manufacturing phases entails a delocalization of the impacts, which constitutes a new challenge at environmental, social, and legal levels.”¹⁷⁵ The researchers estimated that an EV operated in Spain would cut CO₂ emissions in half (though, we note, based on an EV with a battery half the popular size) but “will produce an increase in fine particulate matter formation (26%), human carcinogenic (20%) and non-carcinogenic toxicity (61%), terrestrial ecotoxicity (31%), freshwater ecotoxicity (39%), and marine ecotoxicity (41%) relative to petrol vehicles.”

When it comes to environmental parity, the monomaniacal pursuit of CO₂ reductions has sidelined the entire range of air, water, biodiversity, and ecosystem protections that were once core environmental goals.¹⁷⁶ It’s a bad trade, not least because EV mandates will lead to trivial, even nonexistent, reductions in CO₂ emissions.

Companies representing 40% of global car sales have joined a Science Based Targets initiative to define a “common framework” around automobile emissions, including indirect emissions.¹⁷⁷ Let’s hope that they do follow the science.

Finally, a Word About Behavior Modifications

Given the realities of mineral supplies and uncertainties about associated emissions, IEA and net zero planners have made it clear that “behavior change is critical” to achieving climate goals.¹⁷⁸ For example, “demand side measures such as limiting the growth of battery size” in electric cars can “help bridge the [mineral supply] gap.”¹⁷⁹ The most popular EVs (outside of China) have big batteries to provide the range that consumers want and that manufacturers tout, and because global trends show that buyers want large SUVs—the global SUV share is up from 15% of all new vehicles two decades ago to one-third now, and over one-half in the United States. But according to IEA, “this trend could be curbed by enacting policies that discourage vehicles with extremely large batteries, for example by linking incentives to battery sizes or, in the longer term, taxing EVs with large batteries.”¹⁸⁰ Put differently, that goal is to make it more costly to buy the (larger) EVs that most consumers prefer.

Then, to discourage the use of energy-intensive battery materials and components produced overseas, policymakers promote (and Europe has implemented) the idea of a “border adjustment” carbon tax to induce “cleaner” production and indirectly subsidize domestic sources.¹⁸¹ While

the effect of such policies might lead to slightly more domestic mining and minerals refining, it will certainly raise the cost of batteries and EVs. Certifying who escapes such a tax would require a regulatory apparatus that would dwarf today's Orwellian automobile fuel-efficiency standards.

That's not the only behavior change that EV transitionists believe needs to happen. Given the challenges with meeting charging demands, that, too, would be addressed with "behavioral intervention."¹⁸² Smart-charging will necessarily morph into a regime wherein when and where you can refuel an EV will be controlled, even dictated, by regulators.

Consumers are also to be persuaded, or forced, to drive less in general and travel more by bus, bicycle, rail, ride-share, or on foot, and to own fewer cars in the first place. As stated in the IEA net zero goal: the number of global households *without* a car needs to *rise* from 45% today to 70% by 2050, reversing a century-long trend of rising ownership.¹⁸³ One researcher simply stated: "There is therefore a need for a wide range of policies that include measures to reduce vehicle ownership and usage."¹⁸⁴ As usual, California regulators are ahead of the proverbial curve in admitting that the state's emissions goals will require citizens of that state—on top of being forced into EVs—to drive 25% fewer miles than they did *30 years ago*.¹⁸⁵ (emphasis added).

The car culture is viewed in many environmental circles as inherently toxic and unnatural. As a recent *New Yorker* article put it: "The grip of the car as a metaphor for liberty is as firm as that of guns, if perhaps with similarly destructive results."¹⁸⁶ The transitionists see car ownership as a "cultural attachment" and profess to believe that "fewer cars on the roads would not mean a sacrifice in the quality of life, convenience."¹⁸⁷ There would be significant "progress" in keeping people out of cars by banning inexpensive ICE vehicles and mandating expensive EVs.

In the face of all this, it would be reasonable to reach the conclusion that, put simply, they're coming for your cars.

Conclusion: There's No Such Thing as a Carbon-Free Lunch

For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled.

—Richard P. Feynman, 1974¹⁸⁸

Imagining a hypothetical all-EV world requires acknowledging the unavoidable fact of a rats' nest of assumptions, guesses, and ambiguities regarding emissions. Much of the necessary data may never be collectible in any normal regulatory fashion, given the technical uncertainties and the variety and opacity of geographic factors, as well as the proprietary nature of many of the processes. Those uncertainties could lead to havoc if U.S. and European regulators enshrine "green disclosures" in legally binding ways, and it all will be subject to manipulation, if not fraud.¹⁸⁹

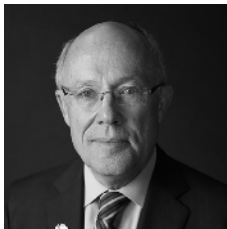
If ICE prohibitions do take effect, it will happen before EVs are available at a price that most people can afford or have features that most people need or want. One predictable consequence will be far fewer new cars available, leading to a massive increase in the demand for, and the cost of, used ICE cars.

If the policy goal is to reduce automotive petroleum use, there are far easier and more certain ways to achieve that. Combustion engines have already been built and are commercially viable that can cut fuel use by 50%.¹⁹⁰ In fact, an earlier IEA analysis finds that gains in automobile fuel efficiency will displace at least 300% more petroleum than adding 300 million EVs to the world's roads by 2040.¹⁹¹

It would be easier, cheaper, faster—and transparently verifiable—to incentivize consumers to purchase more efficient internal combustion engines or hybrids. Subsidies redirected away from wealthy EV owners would buy far greater, and documentable, emissions reductions per dollar if offered to, for example, lower-income gasoline “superusers”—the 10% of drivers consuming one-third of all gasoline¹⁹²—with a credit tied to trailing odometer mileage. Such a policy would, additionally, be progressive, rather than regressive, in tax terms.

The future will see tens of millions more EVs on the roads, even without government programs that favor or mandate them. But the entire edifice of subsidies, prohibitions, and regulations to move most, if not *all*, citizens from ICE cars into EVs is based on a profoundly weak—or, in some cases, false—foundation of claims about emissions reductions and economic parity.

Meanwhile, if implemented, ICE bans will lead to a massive misallocation of capital in the world's \$4 trillion personal mobility industry.¹⁹³ It will also lead to draconian constraints on freedoms and unprecedented impediments to affordable and convenient driving. And it will have little to no impact on global CO₂ emissions. In fact, the bans and EV mandates are more likely to cause a net increase in emissions.



About the Author

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Appendix: Details Underlying Figure 6

Anatomy of CO₂ “Guesstimates” and Known Unknowns: Estimated Lifetime EV Emissions Range from 50% Less to 50% More than ICE

To illustrate the uncertainties in estimating EV lifetime CO₂ emissions, we use Volvo’s analysis as a baseline because it is thorough and incorporates many, though not all, variables.¹⁹⁴ Per Volvo: “Choice of methodology has significant impact on the total carbon footprint. . . . [C]are should be taken when comparing results from this report with those from other vehicle manufacturers.” The company showed that, compared with an internal combustion engine’s knowable emissions, the estimated EV emissions range from an idealized 50% lower to a realistic 8% lower.¹⁹⁵

While theoretical scenarios allow for estimating lower EV emissions, the outcome is not a fact or a measurement. On the other hand, as illustrated below, if the Volvo analysis is adjusted to include some, but not all, *known* variabilities (discussed in this report), EV lifetime CO₂ emissions can be *15% higher* than the baseline ICE car, or if the comparison is with a 30% more fuel-efficient engine, estimated EV lifetime emissions can be more than *50% higher*.

Below, we summarize six key known unknowns for four upstream materials features that Volvo estimates cause **18 tons** of a total of 25 tons of CO₂ emitted to *build* the EV, and we add two downstream sets of variables for the baseline of the additional **16 tons** emitted from vehicle charging. (The outcome is illustrated in Figure 6 of this report.)

1. Battery size and refueling anxiety: 18 tons CO₂ → 22 tons

EV buyers prefer large batteries, not to address “range anxiety” per se but because that minimizes the frequency of on-road fueling that, even with fast chargers, takes 4x–10x longer than with gasoline. Volvo assumes a 71–78 kWh battery. But 90–100 kWh is common, and, as IEA notes, the trend is up. Bigger batteries mean more materials. Assuming a 25% larger battery than Volvo changes the 18 tons of CO₂ from materials and refining to 22 tons.

2. Emissions from energy used producing battery materials: 22 tons → 25 tons

Volvo shows nonaluminum minerals contributing two-thirds of upstream CO₂ based on energy supplied by the “average global grid.” But most “energy materials” are refined in China with a grid that has 50% higher CO₂ per kWh. Assuming half the materials are China-sourced adds three tons to revised factor no. 1 above, thus raising the total to 25 tons.¹⁹⁶

3. Energy/emissions from near-future mining: 25 tons → 34 tons

The unprecedented expansion of mining to meet massive EV minerals demands means that each new ton produced will come from mines with declining ore grades (a long-run geological reality), which increases energy use. Energy per ton of copper mined has doubled in the past decade. Assuming only a 50% increase in CO₂ per ton for (nonaluminum) materials adds another nine tons to the adjustment in no. 2 above, raising the upstream total to 34 tons.¹⁹⁷



4. Aluminum sourcing: 34 tons → 36 tons

The Volvo baseline shows six tons of CO₂ emissions from aluminum production. Specific manufacturers may source aluminum from low-emissions countries, but China is over 55% of the world's supply.¹⁹⁸ Producing a ton in China emits 20 tons of CO₂.¹⁹⁹ The average EV has 0.5 tons of aluminum and rising.²⁰⁰ Assuming that half the aluminum comes from China adds two tons to the baseline, raising the total battery embodied CO₂ to **36 tons**.

5. Balance of materials: 36 tons → 43 tons

The Volvo baseline includes 7 tons of CO₂ from fabricating the balance of hardware (battery module assembly, electronics, other materials, etc.). We ignore for this illustration the known variabilities for those factors but note, for example, that the 200 extra pounds of non-battery copper used for EV wiring and motors entails wide emissions variabilities. Thus, many EVs manufactured now and in the near future will arrive at a dealer, before the first mile driven, with upstream CO₂ emissions totaling at least **43 tons**.

After the emissions from supplying upstream materials (44 tons) to build the EV, one then adds the variables in downstream emissions, from fueling the EVs battery.

6. Drive on U.S. grids, not the EU grid: downstream 16 tons CO₂ → 22 tons

Emissions due to battery charging vary, depending on the electricity used (also the time of day, as discussed elsewhere). Average emissions from all U.S. grids, as well as for many regional grids, are about 40% greater than the EU average.²⁰¹ With the contemplated expansion of wind and solar, we assume instead a 35% increase. Thus the **16 tons** emitted over 120,000 miles of EU charging (per Volvo analysis) becomes **22 tons** in many U.S. states.

7. Drive vigorously, or use the heater or air conditioner: 22 tons → 24 tons

Using air conditioning, heat, or vigorous driving increases EV energy use from 10% to 50%. Assume that many users will experience at least a 10% increase in electricity used per mile over the rated efficiency, and the 22 tons in no. 5 above increases to 24 tons of CO₂.

The Bottom Line: 43 Tons of Estimated Emissions Rises to 67 Tons

The realistic potential of 43 tons of upstream emissions combined with operating realities of 24 tons of downstream emissions (over a vehicle lifetime) yields a total of 67 tons of EV CO₂. This is 15% more than the 59-ton baseline for a comparable gasoline-fueled SUV. Or, assume instead that a consumer purchases an ICE car with 30% better fuel efficiency; that vehicle's lifetime CO₂ emissions drop to 40 tons, which is **~27 tons, or 50% less than many possible EV scenarios**.

Endnotes

- ¹ Leo Marx, “Technology: The Emergence of a Hazardous Concept,” *Social Research* 64, no. 3 (Fall 1997): 981.
- ² Such bans also degrade grid reliability, wherein the solution also (radically) raises costs.
- ³ Lewin Day, “Tesla Takes Top Spot in US Luxury Car Sales, Dethroning BMW,” *The Drive*, Jan. 11, 2023; Statista, “Luxury Cars in the United States, 2021.”
- ⁴ “Apple Car: It’s No Secret, Apple’s Actively Working on Car Tech,” *MacRumors*, May 24, 2023.
- ⁵ Arjun Kharpal, “Chinese Smartphone Giant Xiaomi to Launch Electric Car Business with \$10 Billion Investment,” *CNBC*, Mar. 30, 2021.
- ⁶ “BEV Models Currently Available in the US,” *evadoption.com*, Mar. 3, 2023.
- ⁷ Kathi McBlief, “Baliga Receives Global Energy Prize,” *NC State University College of Engineering News*, Oct. 6, 2015.
- ⁸ IEA, “Global EV Outlook 2023: Catching Up with Climate Ambitions,” April 2023.
- ⁹ *Ibid.*
- ¹⁰ Sam Heller, “Tesla’s US Dominance in EVs Slips,” *Investopedia*, Nov. 30, 2022.
- ¹¹ Mark Kane, “US: All-Electric Car Sales Surged in January 2023—7% Market Share,” *InsideEVs*, Mar. 18, 2023.
- ¹² Peter Johnson, “150,000th Mustang Mach Rolls Off the Line as Ford Strives to Make 2M EVs Annually by 2026,” *electrek.co*, Nov. 30, 2022.
- ¹³ “Ford Mustang,” *Wikipedia*.
- ¹⁴ Mark Kane, “Tesla Sales Surpass 1 Million Electric Cars Globally,” *InsideEVs*, May 9, 2020.
- ¹⁵ Leo Mirani, “The Western World Has Turned Its Back on Car Culture,” *Quartz*, Feb. 2, 2015.
- ¹⁶ “Millennials Coming of Age,” *Goldman Sachs*, 2023.
- ¹⁷ Danah Boyd, *It’s Complicated: The Social Lives of Networked Teens* (New Haven, CT: Yale University Press, 2014).
- ¹⁸ Christopher R. Knittel and Elizabeth Murphy, “General Trends in Vehicle Ownership and Use: Are Millennials Any Different?” MIT Center for Energy and Environmental Policy Research, working paper, Feb. 8, 2018.
- ¹⁹ Marty Miller, “Gen X Makes Up the Largest Segment of New Vehicle Buyers,” *Experian*, July 1, 2021.



Electric Vehicles for Everyone? The Impossible Dream

- ²⁰ John Urry, “Automobility, Car Culture and Weightless Travel: A Discussion Paper,” Dept. of Sociology, Lancaster University (UK), January 1999.
- ²¹ John Cromartie and Dennis Vilorio, “Rural Population Trends,” USDA Economic Research Service, Feb. 15, 2019.
- ²² Miguel González-Leonardo, Francisco Rowe, and Alberto Fresolone-Caparrós, “Rural Revival? The Rise in Internal Migration to Rural Areas During the COVID-19 Pandemic. Who Moved and Where?” *Journal of Rural Studies* 96 (December 2022): 332–42.
- ²³ William H. Frey, “New Census Data Shows a Huge Spike in Movement Out of Big Metro Areas During the Pandemic,” Brookings Institution, Apr. 14, 2022.
- ²⁴ Sam M. Huisache, “2023 Data: 75% of Americans Have Regrets About Moving,” *Home Bay*, Mar. 2, 2023.
- ²⁵ Danny Gavin, “Migration Trend: What to Make of It, Why It’s Happening and Where It’s Headed,” AEM (Association of Equipment Manufacturers), Feb. 16, 2023.
- ²⁶ Chris Salviati and Rob Warnock, “Explosion of Super Commuters Offers Lessons for Sustainable Growth,” *Apartment List*, Aug. 16, 2021.
- ²⁷ Adam Ozimek, “The New Geography of Remote Work,” Upwork, Mar. 3, 2023.
- ²⁸ U.S. Environmental Protection Agency (EPA), “2022 EPA Automotive Trends Report,” December 2022.
- ²⁹ A recreational boat is the only other comparably expensive product, though only a tiny share of consumers purchase boats more expensive than cars; see “U.S. Boat Sales Reached 13-Year High in 2020, Recreational Boating Boom to Continue Through 2021,” NMMA (National Marine Manufacturers Association), Jan. 6, 2021.
- ³⁰ “The 10 Biggest Industries by Revenue in the US,” IBISWorld.
- ³¹ Small EVs can have smaller batteries, an issue addressed later in this report; nevertheless, nearly two-thirds of EVs purchased use large batteries in the 1,000-pound range.
- ³² IEA, “The Role of Critical Minerals in Clean Energy Transitions,” May 2021.
- ³³ Qiang Dai et al., “Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications,” *Batteries* 5, no. 2 (2019).
- ³⁴ IEA, “The Role of Critical Minerals in Clean Energy Transitions.”
- ³⁵ For the chemical cognoscenti, altitude and ambient temperature do induce small variations in fuel efficiency and therefore emissions.
- ³⁶ Mekonnen Asmare Fentahun and Mahmut Ahsen Savas, “Materials Used in Automotive Manufacture and Material Selection Using Ashby Charts,” *International Journal of Materials Engineering* 8, no. 3 (2018): 40–54.
- ³⁷ IEA, “The Role of Critical Minerals in Clean Energy Transitions.”



Electric Vehicles for Everyone? The Impossible Dream

- ³⁸ Jens F. Peters et al., “The Environmental Impact of Li-Ion Batteries and Role of Key Parameters—A Review,” *Renewable and Sustainable Energy Reviews* 67 (January 2017): 491–506.
- ³⁹ “Steel Imports Up 43% in 2021,” American Iron and Steel Institute, Feb. 24, 2022.
- ⁴⁰ IEA, “The Role of Critical Minerals in Clean Energy Transitions.”
- ⁴¹ IEA, “Well-to-Wheels Greenhouse Gas Emissions for Cars by Powertrains,” Feb. 25, 2021.
- ⁴² Ibid.: 40 kWh battery pack, 194.
- ⁴³ IEA, “Global EV Outlook,” April 2023.
- ⁴⁴ VW published its own analysis, “From the Well to the Wheel,” Volkswagen Group, Apr. 24, 2019, with similar outcomes. VW discontinued the e-Golf in late 2020 and removed that analysis from its website in early 2023; the press release, as of this writing, was still at the VW newsroom. VW now markets its ID.4 EV, which has far larger battery options, 62 kWh or 82 kWh.
- ⁴⁵ Maciej Neugebauer, Adam Żebrowski, and Ogulcan Esmer, “Cumulative Emissions of CO₂ for Electric and Combustion Cars: A Case Study on Specific Models,” *Energies*, Apr. 6, 2022.
- ⁴⁶ Elisabeth Evrard et al., “Carbon Footprint Report: Volvo C40 Recharge,” VolvoCars.com, 2021: analysis based on a 69 kWh battery EV and a 24-mpg XC40 conventional SUV.
- ⁴⁷ Ibid., 6.
- ⁴⁸ Ibid., 27.
- ⁴⁹ Russell Gold, Jessica Kuronen, and Elbert Wang, “Are Electric Cars Really Better for the Environment?” *Wall Street Journal*, Mar. 22, 2021.
- ⁵⁰ “Supplementary Information / the *Wall Street Journal*,” University of Toronto Faculty of Applied Science and Engineering, Mar. 17, 2021; the U of T study commissioned by the *WSJ* stated an assumption of ~77 kg/kWh for embodied CO₂ for battery fabrication, compared with the meta-study by Christian Aichberger and Gerfried Jungmeier, “Environmental Life Cycle Impacts of Automotive Batteries Based on a Literature Review,” *Energies* 13, no. 23 (December 2020): 6345, which reviewed 50 similar analyses, finding an embodied emissions range of 70–175 kg/KWh.
- ⁵¹ IEA, “The Role of Critical Minerals in Clean Energy Transitions,” 15.
- ⁵² Aichberger and Jungmeier, “Environmental Life Cycle Impacts of Automotive Batteries.”
- ⁵³ Ibid.
- ⁵⁴ Dan Mihalascu, “EVs Made Up 5.6 Percent of US Car Market in 2022 Driven by Tesla,” *InsideEVs*, Feb. 20, 2023.
- ⁵⁵ IEA, “The Role of Critical Minerals in Clean Energy Transitions.”
- ⁵⁶ Dai et al., “Life Cycle Analysis of Lithium-Ion Batteries.”
- ⁵⁷ Localizing Clean Energy Value Chains Will Come at a Cost,” *BloombergNEF*, Nov. 7, 2022.



Electric Vehicles for Everyone? The Impossible Dream

- ⁵⁸ Jarod C. Kelly, Qiang Dai, and Michael Wang, “Globally Regional Life Cycle Analysis of Automotive Lithium-Ion Nickel Manganese Cobalt Batteries,” *Mitigation and Adaptation Strategies for Global Change* 25 (March 2020): 371–96.
- ⁵⁹ Linda Lew and Nicholas Takahashi, “China’s EV Revolution Shows Grim Future for Japan Car Titans,” Bloomberg, Mar. 20, 2023.
- ⁶⁰ Nora Naughton and Tim Levin, “Cheap Chinese Electric Cars About to Upend the US Vehicle Market,” *Business Insider*, May 21, 2023.
- ⁶¹ Georg Bieker, “A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars,” International Council on Clean Transportation Europe (ICCT), July 2021.
- ⁶² Producing 400 lb. aluminum emits ~6,000 lb. CO₂, per the Aluminum Institute; burning 1 gal. gasoline emits 20 lb. CO₂, per EPA, thus 20 lb. per 30 mi. at 30 mpg.
- ⁶³ Erik Emilsson and Lisbeth Dahllöf, “Lithium-Ion Battery Production Status 2019 on Energy Use, CO₂ Emissions, Use of Metals, Products Environmental Footprint, and Recycling,” IVL Swedish Environmental Research Institute, November 2019.
- ⁶⁴ A rough approximation calculated based on data from Gauthier Roussilhe et al., “From Silicon Shield to Carbon Lock-in? The Environmental Footprint of Electronic Components Manufacturing in Taiwan (2015–2020),” arxiv.org, Sept. 26, 2022.
- ⁶⁵ “Effects of Battery Manufacturing on Electric Vehicle Life-Cycle Greenhouse Gas Emissions,” ICCT, July 2021. Innovators are working on increasing the tolerance to fast charging for future batteries; those built today are degraded by repeated fast charging.
- ⁶⁶ Fiona Burlig et al., “Low Energy: Estimating Electric Vehicle Electricity Use,” NBER (National Bureau of Economic Research), February 2021; Lucas W. Davis, “How Much Are Electric Vehicles Driven?” *Applied Economics Letters* 26, no. 18 (2019): 1497–1502; Sebastian Blanco, “Average EV Owner Drives Half as Many Miles as Other Drivers—Study,” *Car and Driver*, Feb. 14, 2021; Lucas Davis, “Three Facts About EVs and Multi-Vehicle Households,” Energy Institute at HAAS, Sept. 20, 2021.
- ⁶⁷ Simon P. Michaux, “Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels,” Geological Survey of Finland, Aug. 20, 2021.
- ⁶⁸ Alan G. Jones, “Mining for Net Zero: The Impossible Task,” *The Leading Edge*, April 2023.
- ⁶⁹ Nick Ferris, “Why Recycling Is No Golden Ticket to Endless Critical Minerals,” *Energy Monitor*, Mar. 24, 2023.
- ⁷⁰ IEA, “Global Supply Chains of EV Batteries,” July 2022, 60.
- ⁷¹ Moana Simas, Fabian Aponte, and Kirsten Wiebe, “The Future is Circular: Circular Economy and Critical Minerals for the Green Transition,” SINTEF (for World Wildlife Fund [WWF]), Nov. 15, 2022.



Electric Vehicles for Everyone? The Impossible Dream

- 72 For conventional cars, the current and future upstream emissions from oil production and gasoline refineries have very little variability and a high degree of transparency. That's because that industry is well established, happens in places and with processes that are well understood and tracked, and most of the supply for domestic cars takes place in the U.S.
- 73 Guiomar Calvo et al., "Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality?" *Resources* 5, no. 4 (November 2016). The majority of gold mines have an ore grade one-half to one-tenth that average.
- 74 IEA, "The Role of Critical Minerals in Clean Energy Transitions."
- 75 Joel Guilbaud, "Hybrid Renewable Power Systems for the Mining Industry: System Costs, Reliability Costs, and Portfolio Cost Risks" doctoral thesis, University College of London (June 2016).
- 76 Marc Allen, "Mining Energy Consumption 2021," Engeco.
- 77 IEA, "The Role of Critical Minerals in Clean Energy Transitions."
- 78 Tsilile Igogo et al., "Integrating Clean Energy in Mining Operations: Opportunities, Challenges, and Enabling Approaches," NREL (National Renewable Energy Laboratory), July 2020.
- 79 World Bank, "Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition," 2020.
- 80 IEA, "The Role of Critical Minerals in Clean Energy Transitions."
- 81 Calvo et al., "Decreasing Ore Grades."
- 82 Mark P. Mills, "The 'New Energy' Economy: An Exercise in Magical Thinking," Manhattan Institute, March 2019.
- 83 Julian M. Allwood et al., "Material Efficiency: Providing Material Services with Less Material Production," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* (Mar. 13, 2013).
- 84 Statement of Andrew Boyle Before the U.S. Senate, Committee on Environment and Public Works, Subcommittee on Clean Air, Climate, and Nuclear Safety, Hearing on "Cleaner Vehicles: Good for Consumers and Public Health," Apr. 18, 2023.
- 85 Rhiannon Hoyle, "Iron-Ore Miners Strive to Avoid Past Mistakes as Prices Boom," *Wall Street Journal*, May 28, 2021.
- 86 IEA, "Aluminum," September 2022.
- 87 Nicolas Maennling et al., "The Renewable Power of the Mine," Columbia Center on Sustainable Investment, Dec. 10, 2018.
- 88 Mark P. Mills, "Real Robots in Our Near Future: The Rise of Capable Industrial Automatons," *Dakota Digital Review*, Mar. 9, 2023.
- 89 IEA, "The Role of Critical Minerals in Clean Energy Transitions."



Electric Vehicles for Everyone? The Impossible Dream

- ⁹⁰ Caleb Miller, “EVs Fall Short of EPA Estimates by a Much Larger Margin than Gas Cars in Our Real-World Highway Testing,” *Car and Driver*, Apr. 21, 2023.
- ⁹¹ Rohan Challa, Dipti Kamath, and Annick Anctil, “Well-to-Wheel Greenhouse Gas Emissions of Electric Versus Combustion Vehicles from 2018 to 2030 in the US,” *Journal of Environmental Management* 308 (April 2022).
- ⁹² Jeff S. Bartlett and Gabe Shenhar, “How Temperature Affects Electric Vehicle Range,” *Consumer Reports*, Mar. 1, 2023; Ellen Edmonds, “Icy Temperatures Cut Electric Vehicle Range Nearly in Half: AAA Research Finds HVAC Use in Frigid Temperatures Causes Substantial Drop in Electric Vehicle Range,” AAA, Feb. 7, 2019.
- ⁹³ David Montgomery, “American latitude,” Feb. 23, 2018.
- ⁹⁴ EPA, “Power Profiler.”
- ⁹⁵ @20 lbs. CO₂ produced per gal. burned, 300 mi. & 10 gal. = 200 lbs. CO₂, vs. @2.3 lbs. CO₂ per coal kWh for 300 mi. & 100 kWh fueled = 230 lbs. CO₂.
- ⁹⁶ William Boston, “Driving an EV Is Getting Greener, Especially in the U.S.,” *Wall Street Journal*, May 10, 2023.
- ⁹⁷ Alex Brown, “Electric Cars Will Challenge State Power Grids,” Pew Trusts, *Stateline* (blog), Jan. 9, 2020.
- ⁹⁸ Brian Silvestro, “Best Electric Trucks You Can Buy in 2023,” *Road and Track*, May 12, 2023.
- ⁹⁹ Dan Neil, “Should You Buy an EV Now?” *Wall Street Journal*, Oct. 21, 2022.
- ¹⁰⁰ Reda Cherif et al., “Riding the Energy Transition: Oil Beyond 2040,” IMF working paper, May 2017, 17.
- ¹⁰¹ Neil, “Should You Buy an EV Now?”
- ¹⁰² Nicole Wakelin, “How Many Parts Are in a Car?” *Know How* (blog), NAPA Online, July 2, 2021.
- ¹⁰³ Luke Gear, “EV Power Electronics: Driving Semiconductor Demand in a Chip Shortage,” *IDTechX*, Sept. 23, 2021.
- ¹⁰⁴ “There’s Still Life in the Old Combustion Engine: Meet the Argon Power Cycle,” TechXplore, Eindhoven University of Technology (Netherlands), Mar. 12, 2021.
- ¹⁰⁵ “Aquarius Engines Inks Five-Year R&D Contract with the U.S. Army,” PR Newswire, Aug. 9, 2022.
- ¹⁰⁶ Arithmetically (as earlier noted and cited), EVs require ~10x greater use of mineral resources and associated mining, so a 10% gain in efficiency (reducing materials per unit of energy) is equal to a 1% gain in combustion efficiency.
- ¹⁰⁷ We exclude China, with half the world’s EVs, because that country’s enormous number of low-income citizens are apparently willing to buy tiny, low-performance vehicles that few American consumers voluntarily buy and because of the distortion in Chinese-government subsidized energy-minerals industries.



Electric Vehicles for Everyone? The Impossible Dream

- ¹⁰⁸ Austin Irwin, “10 Cheapest New Cars for 2022,” *Car and Driver*, Feb. 26, 2022.
- ¹⁰⁹ See, e.g., Philippe de Montigny, “Major Drop in Lithium Prices Could Mean Cheaper Electric Vehicles,” *CBC News*, Apr. 17, 2023.
- ¹¹⁰ Overall, the EVs total bill-of-materials for parts, components, minerals, etc. is double that for building a conventionally powered car. In second and third place contributing to higher costs (after the battery) are the body and frame, the result of the greater use of aluminum (to offset battery-weight penalty) and a doubling in power electronics; see “Who Makes the Car of the Future,” Bank of America Institute, *Global Automotive Supplier Review*, June 8, 2022.
- ¹¹¹ Rachel Siegel and Jeanne Whalen, “New Cars, Once Part of the American Dream, Now Out of Reach for Many,” *Washington Post*, May 7, 2023.
- ¹¹² “Lithium-Ion Battery Pack Prices Rise for First Time to an Average of \$151/kWh,” *BloombergNEF* (blog), Dec. 6, 2022; IEA, “World Energy Investment,” June 2022.
- ¹¹³ Fabian Duffner et al., “Large-Scale Automotive Battery Cell Manufacturing: Analyzing Strategic and Operational Effects on Manufacturing Costs,” *International Journal of Production Economics* 232 (February 2021).
- ¹¹⁴ IEA, “The Role of Critical Minerals in Clear Energy Transitions,” 12.
- ¹¹⁵ Ana Swanson, “The U.S. Needs Minerals for Electric Cars. Everyone Else Wants Them Too,” *New York Times*, May 21, 2023.
- ¹¹⁶ IEA, “World Energy Investment 2022”; Julian Kettle, “Have Miners Missed the Boat to Invest and Get Ahead of the Energy Transition?” *Wood Mackenzie*, July 12, 2022.
- ¹¹⁷ “Resilient Supply Chains in the Battery Industry,” German Federal Ministry for Economic Affairs and Climate Action, March 2023.
- ¹¹⁸ “China Could Control a Third of the World’s Lithium by 2025,” *Bloomberg News*, Mar. 12, 2023.
- ¹¹⁹ Erwida Maulia, “Indonesia Bets on Critical Mineral Export Bans as Deadline Nears,” *NIKKEI Asia*, May 23, 2023.
- ¹²⁰ Kevin Hughes, “South American Countries Planning to Create LITHIUM CARTEL,” *Natural News*, Mar. 12, 2023.
- ¹²¹ Andrew Duehren, “U.S. and EU Advance Buyers’ Club for EV Battery Minerals,” *Wall Street Journal*, Feb. 15, 2023.
- ¹²² IEA, “Global EV Outlook 2023: Catching Up with Climate Ambitions,” April 2023.
- ¹²³ U.S. Geological Survey (USGS), “Metal Prices in the United States Through 2010,” 2012.
- ¹²⁴ Daniel E. Sullivan, John L. Sznopce, and Lorie A. Wagner, “20th Century U.S. Mineral Prices Decline in Constant Dollars,” *USGS*, June 21, 2021.
- ¹²⁵ Davis, “Three Facts About EVs.”



Electric Vehicles for Everyone? The Impossible Dream

- ¹²⁶ JD Powers, “Owner Satisfaction Gets a Jolt from New Models as Electric Vehicle Market Grows,” Feb. 28, 2023; Sullivan, Sznoppek, and Wagner, “20th Century U.S. Mineral Prices Decline.”
- ¹²⁷ Blanco, “Average EV Owner Drives Half as Many Miles”; Davis, “Three Facts About EVs.”
- ¹²⁸ There are ~100 million vehicles owned by two- and three-car households, per American Association of State Highway and Transportation Officials (AASHTO), “Commuting in America: The National Report on Commuting Patterns and Trends 2021.”
- ¹²⁹ About 70% of Americans live in a single-family home, per Charlotte O’Malley, “80 Percent of Americans Prefer Single-Family Homeownership,” *Builder*, Aug. 13, 2013; and 50% of U.S. households have a personal garage, per “How Many Americans Have Access to Electricity Where They Park?” *CleanTechnica*, Jan. 5, 2022.
- ¹³⁰ “Electrification Impact Study,” City of Palo Alto, Utilities Advisory Commission Staff Report, Nov. 4, 2020.
- ¹³¹ Daniel DeSantis et al., “Cost of Long-Distance Energy Transmission by Different Carriers,” *iScience* (Environmental Science) 24, no. 12 (Dec. 17, 2021). Century-long electrification has been driven not because electricity is a cheaper form of energy but because of what electricity enables that is impossible with combustion engines (e.g., powering computers, air conditioners, and lasers).
- ¹³² U.S. Dept. of Transportation, “Charger Types and Speeds.”
- ¹³³ “The U.S. Convenience Store Industry,” National Association of Convenience Stores (NACS): “[I]t takes customers, on average, 3 minutes and 33 seconds from the time they leave their cars until the time they get back in their cars with a purchase.”
- ¹³⁴ Robert N. Charette, “The EV Transition Explained,” *IEEE Spectrum*, 2023: the cost of a fast charger (with four ports) ranges from \$470,000 to \$725,000. Michael Nicholas, “Estimating Electric Vehicle Charging Infrastructure Costs Across Major U.S. Metropolitan Areas,” ICCT, August 2019: the cost of a 350 kW fast charger (four ports) is over \$500,000 and costs \$25,000 to install. Sam Pournazeri, “How Much Does Electric Vehicle Charging Infrastructure Actually Cost?” ICF, Jan. 25, 2022: fast charger installation costs can be as high as \$137,000; “How Many EV Charging Stations Will \$10 Billion Buy for America?” *EVAdoption*, Aug. 18, 2021: cost of 350 kW fast charger \$400,000. Comparison: the average cost of a gasoline pump (with four dispensers) including installation is less than \$150,00, per Joe Wagner and Shawn Bowers, “Evaluating Equipment Replacement Costs for Gas Station Losses,” *JS Shield*, 2022.
- ¹³⁵ Tesla, the market leader in supercharger deployment, doesn’t publish costs, but media reports put them at “as little as \$42,000 per connector,” per Mario Merano, “Tesla Superchargers Are Dwarfing Competitors in Size and Cost Efficiencies,” *Teslarati*, Sept. 22, 2022. That translates into ~\$300,000, i.e., \$160,000 for four ports (the comparisons cited herein) plus another \$140,000 in installation. Tesla’s supercharger at the time of the media report is 250 kW, while costs reported in other sources are for more expensive, faster chargers, at the 350 kW level and up. Tesla recently announced a 600 kW supercharger; no costs reported.
- ¹³⁶ Brent McOlson, “How Much Does It Cost to Build a Gas Station,” *Costhack.com*, Apr. 10, 2023: \$2.5 million for eight pumps; land, lights, signs, buildings, etc.: \$180,000.



Electric Vehicles for Everyone? The Impossible Dream

- ¹³⁷ Garrett Golding and Lutz Kilian, “Don’t Look to Oil Companies to Lower High Retail Gasoline Prices,” Federal Reserve Bank of Dallas, May 10, 2022.
- ¹³⁸ National Grid et al., “Electric Highways: Accelerating and Optimizing Fast-Charging Deployment for Carbon-Free Transportation,” November 2022.
- ¹³⁹ Charette, “The EV Transition Explained.” Demand for more transformers and upgrades to existing ones (since current infrastructure cannot support the power levels) come at a time of shortages and price inflation for the basic utility-pole transformer. See, e.g., Robert Bryce, “Untransformed,” Mar. 31, 2023.
- ¹⁴⁰ Hellenic Association of Energy Economics, “An Energy Economic Perspective of EV Charging in Greece,” Mar. 21, 2023.
- ¹⁴¹ Jon Linkov, Jeff S. Bartlett, and Alex Knizek, “How Well Do Tesla Superchargers Work for Non-Tesla EVs?” *Consumer Reports*, Mar. 17, 2023.
- ¹⁴² Bill LeBlanc, “EV Charging and Pricing: What Are Consumers Willing to Pay?” *E Source*, Feb. 14, 2022.
- ¹⁴³ “Motor Fuel Taxes,” Urban Institute, State and Local Backgrounders.
- ¹⁴⁴ An emerging class of high-power electronics has the promise for significant supercharger cost reductions, perhaps 30% or more (based on semiconductors silicon carbide and gallium nitride instead of silicon), but that will still leave a very high all-EV cost penalty for fueling stations, approaching \$1 trillion.
- ¹⁴⁵ Dan Neil, “2023 Genesis Electrified GV70: How Many More Miles to the Next Charger?” *Wall Street Journal*, May 4, 2023.
- ¹⁴⁶ Assuming EVs need half as much energy delivered to market as contained in the 3 billion bbls/yr of gasoline now consumed, that arithmetically means about 2 trillion kWh are needed, i.e., 50% of today’s US electricity production of about 4 trillion kWh/yr.
- ¹⁴⁷ Charette, “The EV Transition Explained.”
- ¹⁴⁸ Bart Ziegler, “Can the Power Grid Handle a Wave of New Electric Vehicles?” *Wall Street Journal*, Feb. 5, 2023.
- ¹⁴⁹ “Hybrids, Sedans Have Fewest Problems in Consumer Reports’ 2022 Annual Auto Reliability Survey: Electric Vehicles and Full-Size Pickup Trucks Are Least Reliable,” *Consumer Reports*, Nov. 15, 2022.
- ¹⁵⁰ John Goreham, “Study: 3-Year Maintenance & Repair Cost Difference Between ICE and EV Just \$235,” *Torque News*, Nov. 16, 2021.
- ¹⁵¹ Roberto Baldwin, Sasha Richie, and Dave VanderWerp, “EV vs. Gas: Which Cars Are Cheaper to Own?” *Car and Driver*, Oct. 28, 2022.
- ¹⁵² “Hybrids, Sedans Have Fewest Problems,” *Consumer Reports*.
- ¹⁵³ Neil Lancefield, “New Electric Cars Less Reliable than Petrol or Diesel Models—Survey,” *Belfast Telegraph* (UK), May 30, 2023.



Electric Vehicles for Everyone? The Impossible Dream

- ¹⁵⁴ Goreham, “Study: 3-Year Maintenance & Repair Cost Difference.”
- ¹⁵⁵ Baldwin, Richie, and VanderWerp, “EV vs. Gas.”
- ¹⁵⁶ Danny Russo, “How Much Does It Cost to Replace an Engine?” *Consumer Affairs*, Apr. 29, 2022.
- ¹⁵⁷ Chantel Wakefield, “Does It Cost More for Electric Car Insurance?” *Kelly Blue Book*, May 10, 2023; Federico Alcala, “10 Hidden Costs of Owning Electric Vehicles,” *Top Speed*, Apr. 19, 2023.
- ¹⁵⁸ Nick Carey, Paul Lienert, and Sarah Mcfarlane, “Scratched EV Battery? Your Insurer May Have to Junk the Whole Car,” Reuters, Mar. 20, 2023.
- ¹⁵⁹ Andrew Burnham et al., “Enabling Fast Charging—Infrastructure and Economic Considerations,” *Journal of Power Sources* 367 (November 2017): 237–49.
- ¹⁶⁰ IEA, “The Role of Critical Minerals in Clean Energy Transitions,” 11.
- ¹⁶¹ “Volkswagen-Led Research Team to Develop Closed-Loop Battery Recycling,” Automotive Manufacturing Solutions (AMS), June 14, 2022.
- ¹⁶² Gregory Barber and Aarian Marshall, “Cars Are Going Electric. What Happens to the Used Batteries?” *Wired*, Nov. 2, 2021.
- ¹⁶³ Costs in battery recycling are exacerbated by safety challenges because of high voltages and exposures to hazardous chemicals. None of these factors are issues for recycling conventional cars, where 85% of the weight is in iron and steel (see Fentahun and Savas, “Materials Used in Automotive Manufacture”), both of which are easy to recycle.
- ¹⁶⁴ Neil, “Should You Buy an EV Now?”
- ¹⁶⁵ “Chile’s New President Boric Signs Escazu Environmental Treaty,” *Al Jazeera*, Mar. 18, 2022.
- ¹⁶⁶ Zahra Awan, “Aluminium Price Surges to New Record High, Driven by Ukrainian–Russian Conflict,” *Aluminum International Today*, Feb. 25, 2022; “Aluminum,” Mining.com, Markets, May 30, 2023.
- ¹⁶⁷ IEA, “The Role of Critical Minerals in Clean Energy Transitions,” 11.
- ¹⁶⁸ USGS, “Mineral Commodity Summaries 2020.”
- ¹⁶⁹ Rebecca Tan, Dera Menra Sijabat, and Joshua Irwandi, “To Meet EV Demand, Industry Turns to Technology Long Deemed Hazardous,” *Washington Post*, May 10, 2023.
- ¹⁷⁰ Aaron Steckelberg, Hannah Dormido, and Ruby Mellen, “The Underbelly of Electric Cars: Where All Those EV Batteries Come From,” *Washington Post*, May 21, 2023.
- ¹⁷¹ Ashley Stumvoll, “Are There Potential Downsides of Going to 100 Percent Renewable Energy?” *Pacific Standard*, June 20, 2019.
- ¹⁷² IEA, “The Role of Critical Minerals in Clean Energy Transitions.”



Electric Vehicles for Everyone? The Impossible Dream

- ¹⁷³ Deanna Kemp, John Owen, and Kado Muir, “54% of Projects Extracting Clean Energy Minerals Overlap with Indigenous Lands, Research Reveals,” *Phys.org*, Dec. 2, 2022.
- ¹⁷⁴ Amanda Morris, “Understanding Cobalt’s Human Cost,” *Northwestern Now*, Dec. 17, 2021; Gabriel Bamana et al., “Addressing the Social Life Cycle Inventory Analysis Data Gap: Insights from a Case Study of Cobalt Mining in the Democratic Republic of the Congo,” *One Earth* 4, no. 12 (December 2021): 1704–14.
- ¹⁷⁵ Gonzalo Puig-Samper Naranjo et al., “Comparative Life Cycle Assessment of Conventional, Electric and Hybrid Passenger Vehicles in Spain,” *Journal of Cleaner Production*, April 2021.
- ¹⁷⁶ Aichberger and Jungmeier, “Environmental Life Cycle Impacts of Automotive Batteries,” 6345.
- ¹⁷⁷ “Ambitious Corporate Climate Action,” *Science Based Targets*.
- ¹⁷⁸ Reuven Sussman, “IEA: Behavior Change Is Critical for Reaching Net-Zero Energy,” ACEEE, June 3, 2021.
- ¹⁷⁹ IEA, “Global Supply Chains of EV Batteries,” July 2022.
- ¹⁸⁰ Ibid.
- ¹⁸¹ European Commission, “Carbon Border Adjustment Mechanism,” May 2023.
- ¹⁸² Tyler Irving, “U of T Researchers Model the Health Benefits of Electric Cars, Find ‘Large Improvement in Air Quality,’” June 8, 2020: “If we want to address the climate crisis, we’re going to need behavioural modifications as well.” See also Mario Herberz, Ulf J. Hahnel, and Tobias Brosch, “Counteracting Electric Vehicle Range Concern with a Scalable Behavioural Change,” *Nature Energy* 7 (2022): 503–10.
- ¹⁸³ IEA, “Net Zero by 2050: A Roadmap for the Global Energy Sector,” May 2021, 89.
- ¹⁸⁴ Alexandre Milovanoff, I. Daniel Posen, and Heather L. MacLean, “Electrification of Light-Duty Vehicle Fleet Alone Will Not Meet Mitigation Targets,” *Nature Climate Change* 10 (2020): 1102–7.
- ¹⁸⁵ Charette, “The EV Transition Explained.”
- ¹⁸⁶ Adam Gopnik, “How to Quit Cars,” *The New Yorker*, May 15, 2023.
- ¹⁸⁷ Thea Riofrancos et al., “Achieving Zero Emissions with More Mobility and Less Mining” Climate and Community Project, University of California–Davis, Jan. 24, 2023.
- ¹⁸⁸ Richard P. Feynman, “Cargo Cult Science,” 1974 Commencement Address at Caltech. Feynman won the 1965 Nobel Prize in physics.
- ¹⁸⁹ Fabiana Negrin Ochoa, “Europe’s ‘Green’ Disclosure Rules Give Fund Investors Clarity—and Confusion,” *Wall Street Journal*, June 25, 2021; Cheryl Winokur Munk, “The New Math of Socially Responsible Investing,” *Wall Street Journal*, June 27, 2021; Paul Kiernan, “SEC Weighs Making Companies Liable for Climate Disclosures,” *Wall Street Journal*, June 28, 2021.
- ¹⁹⁰ Chris Perkins, “Nissan Says It’s Working on an Engine with 50-Percent Thermal Efficiency,” *Road and Track*, Feb. 26, 2021.



Electric Vehicles for Everyone? The Impossible Dream

- ¹⁹¹ IEA, “World Energy Outlook,” November 2018, 140: 9 million barrels per day (mmb/d) of oil avoided from fuel efficiency gains by 2040.
- ¹⁹² “Gasoline Superusers,” Coltura.org, July 2021.
- ¹⁹³ “Global Car & Automobile Sales,” *IbisWorld*, Oct. 31, 2022.
- ¹⁹⁴ Evrard et al., “Carbon Footprint Report: Volvo C40 Recharge.”
- ¹⁹⁵ Volvo, “XC40 Recharge Specifications,” June 1, 2020. The 50% lower emissions assumes 100% of recharge electricity comes from wind. We note that the Volvo analysis ignores upstream emissions from wind materials and construction and the additional generation capacity to ensure wind availability.
- ¹⁹⁶ Volvo’s baseline 18 tons of emissions from all materials becomes 22 tons; nonaluminum minerals are 15 tons; increase 50% of the latter by $1.5x = 3.8$ tons.
- ¹⁹⁷ The nonaluminum 12 tons of emissions became 18 tons in no. 2, and is increased by 50% here, adding ~9 tons.
- ¹⁹⁸ “Aluminum Production by Country,” Harbor Aluminum.
- ¹⁹⁹ Archy de Berker, “Understanding Your Aluminum Emissions,” *Carbon Chain*, 2023.
- ²⁰⁰ Lurah Lowery, “Ducker Study Sheds Light on Newest Shift to Aluminum Vehicle Components,” *RDN (Repairer Driven News)*, Apr. 28, 2023.
- ²⁰¹ Average emissions from power production for the U.S. grid ~380 g/kWh; for the EU grid, the average emissions ~260g/kWh; for China, ~650 g/kWh; and the global avg., ~450 g/kWh.