The Limits and Costs of Full Electrification

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Introduction

Around the globe, many jurisdictions are adopting increasingly aggressive targets for the reduction of greenhouse gas (GHG) emissions. The European Union, the United Kingdom, Canada, Japan, and South Korea are among the growing number of nations that have enshrined net-zero emissions by 2050 into law.[1] As GHG reduction goals grow more ambitious, the strategies for achieving these reductions are coalescing around a two-stage strategy known as "electrification." The first stage involves elimination of GHG emissions in the production of electricity. The second stage involves converting almost all residential and transportation (if not industrial) energy use to electricity. In practice, the stages are not sequential. Many steps are being taken to electrify transportation, for example, even though electric systems in much of the world produce significant CO_2 emissions.

There is significant momentum behind this transformation, and many policy makers appear to view full electrification as inevitable in large sectors of the economy. As of this writing, the European Union, China, Japan, South Korea, several US states, and many other jurisdictions have declared the intention to ban gasoline and diesel cars. The residential electrification vision includes water and space heating. In 2021, the International Energy Agency recommended that policy makers worldwide ban fossil fuel furnace sales by 2025. California recently passed such a ban. Although some technological alternatives to gas and oil exist (e.g., hydrogen, biofuels), these tend to be more expensive and less than completely carbon free. In practice, the vision

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[1]See https://eciu.net/netzerotracker.

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is one of full electrification. Although the electrification process has proceeded in fits and starts, renewable electricity has grown to comprise more than 20 percent of US generation in 2021. Electric heat pumps are becoming nearly cost-competitive with more traditional fossil-fueled space- and water-heating appliances (Borenstein and Bushnell 2022), pointing to an eventual, if currently gradual, transition of residential energy use away from fossil fuels.

The most prominent aspect of electrification has been the rise of electric vehicles (EVs). The market share of all-electric vehicles in the United States has grown five-fold since 2016, to 3 percent in 2021.[2] Already, several governments and manufacturers have declared the intention to phase out production and sales of internal combustion engine cars (ICEs) altogether. The extent to which these declarations are binding or even realistic varies, but the collective will to move strongly in that direction is clear. California is a prominent example, having recently set the goal of eliminating new ICE sales by 2035. Their policy could be adopted by several other states in the United States. Of the manufacturers, Ford, GM, Volvo, Mercedes-Benz, and others have all declared a goal to sell only EVs by 2035 in "leading markets" and by 2040 worldwide.

Although the explosive growth of the EV sector now seems guaranteed, there are reasons to be skeptical of the inevitability, or at least the optimal pace, of the complete electrification of passenger transportation and residential energy uses. Research is beginning to acknowledge that, absent significant technological advancement, the complete decarbonization of electricity production may be extremely costly in terms of material inputs or quality of service. One need only observe the evolving energy crisis in Europe to confirm both the continued centrality of natural gas to the electricity system and the profound economic impacts of unreliable energy supply. Given that one of the points of decarbonizing electricity is to make it an attractive alternative to fossil fuels, rising electricity costs are an increasing concern.

In our discussion below, we divide these underappreciated costs of electrification into two categories: private and public costs. We first discuss various cost barriers that could impose sharply rising costs to increasing EV market shares. We have labeled these "private costs" in the sense that they represent real physical barriers or private consumer preferences that could in theory be overcome with increased public funding (or taxation of alternatives). In the following section, we discuss various external costs associated with an increased reliance on electricity. We have labeled these "public" costs in the sense that each represents an erosion of a public good; these costs are not overcome but instead exacerbated by the types of policies designed to overcome private barriers to adopting electrification.

Of course, one of the most significant externalities is the one that motivates the push for electrification in the first place: the costs of climate change associated with GHG emissions. Our intent is not to ignore or minimize those costs but rather to emphasize that the costs of mitigating GHGs through electrification may rise sharply at some as-yet-unknown level of market share penetration. It is quite possible that, absent technological advancement, these costs can rise above current estimates of the social cost of carbon or, more significantly, above alternative approaches to mitigating climate change. If such an outcome does arise,

[2]See https://www.iea.org/reports/electric-vehicles.

policies that rigidly adhere to 100 percent targets could prove extremely costly and ultimately counterproductive.

We focus our discussion on the domestic (US) residential energy sector, including light-duty transportation. But the costs of (and barriers to) electrification in commercial and industrial sectors are likely to share features of the residential transition. In many cases, the obstacles and costs are likely to be more pronounced where energy scale and density are important, as in heavy industries (e.g., steel production) and long-distance transportation (e.g., aviation and maritime shipping) as described in Rapson and Muehlegger (2023). Absent miraculous innovation or substantial investment, electrification will be even more challenging in the developing world, where electricity grids are less reliable and mature.

Can There Be "Too Much" Electrification?

In many regions, targets for decarbonization rely upon an assumption of near full electrification of transportation and residential energy use. Given these targets for GHG reductions, something less than full electrification would be seen as a policy failure by many in the environmental community, even though there is no consensus on the policy tools for achieving such goals.

Environmental economists tend to frame the question of the optimal level of electrification in terms of balancing the marginal benefits of a given level against the marginal social costs. Other policy makers tend to work backward from discrete requirements for GHG reductions that point to a need for removing almost all CO_2 from the transport and residential sectors, regardless of cost. Although nearly full electrification may be technically possible, it is far less clear whether it would be socially optimally or practically achievable. This will depend upon the evolution of the technologies. One of two scenarios is possible. One is that electric technologies will offer superior value to users, thereby making full adoption the optimal final state. The other is that they will be suboptimal, thereby making it desirable to have a mix of technologies.

The process of electrification has frequently been discussed in the context of disruptive technology adoption, whereby incumbent dominant technologies are supplanted, and largely eliminated, by superior new technologies. Under this framing, one role of policy—possibly the only role—would be to jump-start, or accelerate, the adoption process. This process is classically captured in the "adoption curve," an S-shaped process illustrating how new technologies diffuse slowly at first and then rapidly expand to the bulk of consumers before finally capturing slow-adopting laggards in the eventual path to market dominance (Rogers 1962). EVs are currently covered in news articles as nearing, if not surpassing, a "tipping point" between early and mass adoption. Electric space and water heating receive notably less attention, although they are as prominent as vehicles in many climate plans.

The most commonly cited success stories of technology adoption, however, involve either new technologies that are objectively superior in almost all dimensions to the incumbent technology (e.g., flat-panel televisions) or technologies that spawn new consumer categories altogether (e.g., smartphones).

In these cases, consumers overwhelmingly chose the previously dominant technology but switched en masse when a new, superior option emerges. However, the products that electrification strategies are targeting have experienced "mixed" equilibria of multiple technology options coexisting for long periods. For example, residential space heating currently features a mix of natural gas, propane, fuel oil, and electricity, each playing a significant role influenced by geography, climate, and housing vintage. Similarly, conventional hybrid vehicles have been a prominent option for more than two decades, and auto markets have supported an extremely wide range of vehicle fuel efficiency offerings.

Unlike many other heavy industries, the electricity-generation sector has also long featured a diverse set of production technologies rather than a single dominant source. This has been due to an inclination to take advantage of local resource availability—from water, to natural gas, to coal—combined with the fact that limited storage options have created a need for both high-utilization "baseload" technologies and infrequently used "peaker" sources to maintain reliable supply.

These observations point to the strong possibility that a single, dominant technology will not organically emerge—either upstream in the production of electricity or downstream in its consumer usages. Instead of creating an inevitable feedback loop of adoption, increasing levels of penetration of low-carbon technologies may eventually reach points where incremental gains in market share become increasingly costly. The dynamic will involve a tug-of-war between any momentum created from learning-by-doing (and economies of scale) and the resistance provided by resource limitations and heterogeneous consumer preferences.

If full electrification is not an inevitable consequence of evolving technology and consumer preferences, what role should policy play? From a policy perspective, the question becomes whether and how to adopt flexible policies that can reveal and adapt to the types of inflection points illustrated in figure 1. The alternative, currently favored in several parts of the world, is to make an advance commitment to "full" electrification before the costs and consequences of such strategies are fully known. Holland, Mansur, and Yates (2021) attempt to quantify the trade-offs between positive effects (such as environmental benefits and learning-by-doing) and the increased cost and lost social utility of a forced transition to EVs. Under their current estimates of the substitutability between gasoline and electric vehicles, they find that a full ban on gasoline vehicles would result in large deadweight loss—an uncompensated loss to social welfare—relative to other less rigid policies.

We observe that policy preferences tend to mirror disciplinary outlooks. The dominant policy framing tends to reflect a perspective based on engineering or natural science and to articulate policies in terms of quantitative targets, such as two degrees Celsius or "net zero by 2050." An unwavering commitment to a quantitative target implicitly signals a belief of the nearly infinite cost of falling short and therefore a willingness to incur very high marginal costs to make sure the target is attained. The environmental economics literature tends to frame these questions as balancing the marginal benefits of carbon abatement (or conversely the "social cost" of carbon) against the marginal costs of emissions abatement. Of course, the two perspectives are not incompatible in the case of extremely high social costs of carbon (SCC), in which case most conceivable abatement costs are still "worth it." However, for lower projections of the SCC, or when one expands the policy space to include options such as carbon capture, carbon removal, or geoengineering, confronting the marginal costs of abatement in specific sectors is a valuable exercise for the evaluation of both the desirability of technology mandates and their likelihood of success.

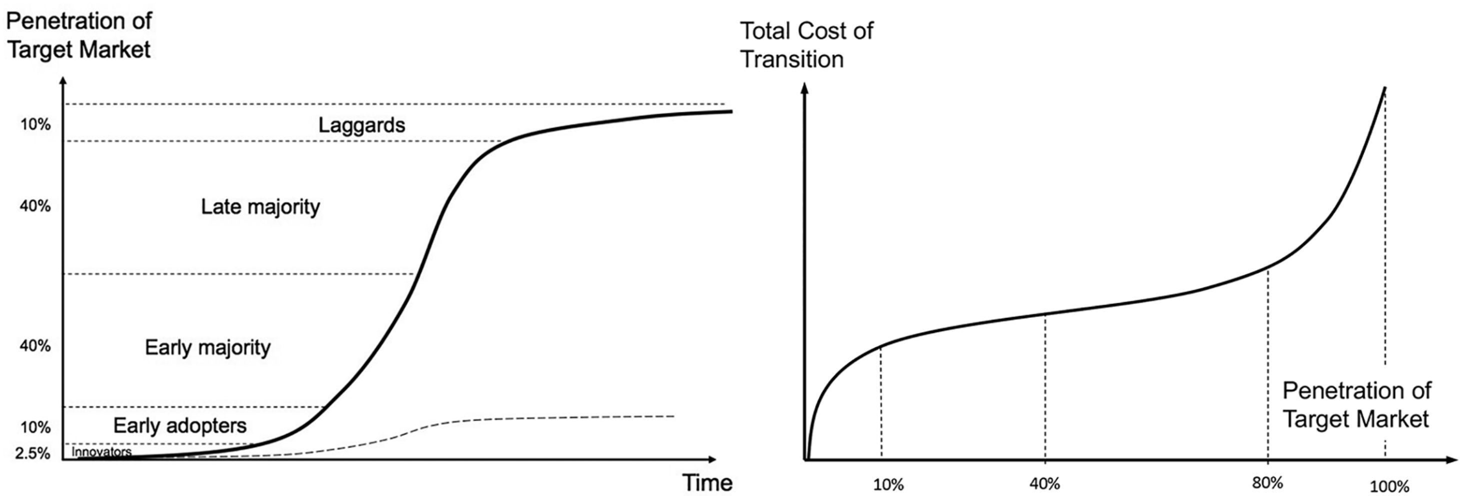

Figure 1 Adoption S-curve and marginal cost of adoption.

Private Cost Barriers to Electrification

The pace and extent of electrification will be dictated by three main factors: consumer preferences, physical access, and relative prices. For a given suite of product offerings, a buyer's decision to electrify will reflect the feasibility of adoption as well as a preference to select electric technologies over focusing on alternatives in the choice set. In this section, we will review elements of both constraints, focusing on consumer demand for EVs. Although full electrification would require converting all energy services to electricity—including heating, cooling, cooking, water heating, and so forth, in all homes and businesses—we set aside these important segments for now. The main reason for our focus is that electrifying the light-duty transportation fleet offers by far the largest potential emissions-reduction opportunity, and it is also a sector in which the electric option offers a significantly different consumer experience.

Preference Barriers to EV Adoption

Economic models portray goods as bundles of attributes. When consumers decide whether to electrify, they are deciding between energy-consuming durable goods that draw on different energy inputs. In this context, a product has three relevant features at the time of purchase: its up-front price, the expected ongoing cost to operate and maintain the good over its life cycle, and all the other attributes of the services that the product will provide. This framing of the choice setting provides context for the high price of EVs today and the necessity to provide either large ongoing cost savings or a far superior user experience than gasoline-powered cars, to induce EV adoption. With this in mind, we offer three aspects of the EV-ICE choice that will contribute to the EV adoption rate.

EV cost relative to gasoline cars

In July 2022, the average list price of an EV in the United States was $66,000, compared with $48,000 for the average new car with an ICE.[3] Part of this price differential arises from selection and matching. The fact that EVs are more expensive than ICEs makes high-income households a natural target market. Manufacturers, knowing this, offer EV models that tend to compete in the luxury segment. A strong, positive correlation between EV adoption and income is well documented (Borenstein and Davis 2016; Archsmith, Muehlegger, and Rapson 2021; and others).

However, in a country where the average household income hovers around the price of the average EV, a $66,000 car is unaffordable to most Americans. Widespread adoption of EVs requires a decline in the relative cost of EVs. Later, we will discuss the role of government policies; their presence or absence will also affect the relative net benefits of EVs and ICEs and consequently the rate of EV adoption.

The first-order cost disadvantage of EVs arises from the energy-storage technology. Whereas an ICE requires a polyethylene gasoline tank that costs little to produce, a typical EV sedan battery costs several thousand dollars. High-capacity batteries cost well over $10,000. EV battery costs have declined by roughly 90 percent in the past decade; although many are optimistic that the trend will continue, it is not guaranteed. The battery requires approximately seven

[3]From the Kelly Blue Book.

times the mass of mineral inputs as a comparable ICE.[4] Rare earth minerals are in high demand worldwide, and battery price declines will require that primary material supply and processing capacity growth are sufficient to meet demand. Recently, the opposite has occurred. Lithium was six times more expensive in July 2022 than it was two years earlier.[5] Prices for other EV raw material inputs such as cobalt, magnesium, and copper have also become more expensive, though less dramatically so.[6] Whether caused by transportation bottlenecks or other production capacity constraints, a sustained decline in EV costs will require a strong reversal of these trends.

Any up-front cost disadvantage of EVs may be offset, in part or in full, by cost savings in operation and maintenance. Whether there are savings, and their magnitude, depends primarily on the gasoline and electricity prices faced by drivers; see Rapson and Muehlegger (2023) for a more thorough discussion. Moreover, it is difficult to separate cause and effect when evaluating the rate of EV adoption and the extent to which ongoing cost savings are considered at the time of purchase. Bushnell, Muehlegger, and Rapson (2022) find that, in their sample of California from 2014 to 2017, oil prices have several times more impact on EV demand than electricity prices. This gap may close as more EV buyers familiarize themselves with the relationship between their driving behavior and their electric bill, increasing awareness of relative prices. In fact, Bushnell, Muehlegger, and Rapson (2022) find some evidence consistent with this. EV buyers in neighborhoods with high electricity prices tend to sell their EV more quickly than those in low-price areas, which may be evidence of learning about the relative costs of vehicle operation.

Government subsidies are a popular nonmarket channel for overcoming the EV cost disadvantage. This is the aspect of the EV market that economists have studied the most, so we will provide only the briefest reflection on EV subsidies here.[7] Although EV subsidies stimulate demand, they are expensive because of the inability of subsidy design to differentiate between "additional" (marginal) and "nonadditional" (inframarginal) buyers. In other words, subsidies may simply assist consumers who would have bought an EV even without the subsidy. Recently, eligibility for US federal EV subsidies includes means tests (so that the wealthiest car buyers are not eligible for subsidies) and limitations to discourage marking up the "sticker price" of the purchased vehicle. These will improve progressivity of the programs at the expense of failing to address the EV cost disadvantage among potential buyers who are not eligible for subsidies. Moreover, as the scale of EV adoption increases, so, too, will the burden on government budgets. The implicit hope is that production at higher scale will accelerate battery-cost declines and eventually allow EVs to be privately cost-competitive with ICEs.

Do EVs provide the same services as gasoline cars?

The primary function of cars and trucks is to be combined with energy to provide transportation. Trips have diverse purposes, and the utility derived from those trips arises from heterogeneous

[4]See https://www.iea.org/data-and-statistics/charts/minerals-used-in-electric-cars-compared-to-conventional-cars.
[5]See https://www.benchmarkminerals.com/lithium-prices.
[6]See https://tradingeconomics.com.
[7]Interested readers may review Chandra, Gulati, and Kandlikar (2010), Beresteanu and Li (2011), Gallagher and Muehlegger (2011), Clinton and Steinberg (2019), and Muehlegger and Rapson (2022) on the effects of incentives on adoption. Sallee (2011) and Gulati, McAusland, and Sallee (2017) study pass-through, and Li (2017), Li et al. (2017), and Springel (2021) estimate network effects of charging stations.

preferences for the relationship between vehicle and trip attributes. For this reason, vehicle-miles traveled (VMT) is a reasonable approximation of how drivers view the substitution between EVs and ICEs. If EVs are driven as much as their gasoline counterparts, this reflects, to a first order, equivalent transportation services. If, on the other hand, EVs are driven less than ICEs, this is likely a reflection of less than complete substitutability.

Unfortunately, direct measurements of VMT are not available for the population of EVs and ICEs, so researchers and policy makers alike rely on estimates of various kinds. The National Household Travel Survey (NHTS) provides a quinquennial representative sample of national driving behavior.

The US Department of Transportation uses road monitors at approximately 5,000 locations nationwide, combined with aggregate fuel consumption data, to estimate VMT. However, this methodology is exposed to several potential inaccuracies and cannot distinguish between vehicle types. Some car manufacturers collect VMT using telemetry technology, but most have only a partial and selected sample, and there are no public reporting or disclosure requirements. Finally, academic researchers have often either implemented their own surveys on selected subpopulations or used odometer readings from state-administered vehicle inspection programs. The latter are a requirement for registration and must be performed at semiregular intervals that depend on the age and class of the vehicle. In short, there is no clear view of VMT in the United States.

Nonetheless, we will briefly review what we know about the relative usage of EVs and ICEs. The most recent NHTS survey was implemented in 2017 and was analyzed in Davis (2019). In that sample, the average annual VMT for light-duty vehicles in the United States is 10,200. Battery electric vehicles (BEVs) are reported to be driven 6,300 miles per year and plug-in hybrids 7,800 miles per year. Burlig et al. (2021) estimate similar driving in BEVs (6,700 miles per year) over the period 2014–2017, but they do so by scaling up estimates of home charging using aggregate data on nonresidential charging. They also find substantial heterogeneity in VMT, with Teslas being driven roughly as much as gasoline cars and all other BEVs being driven much less. Other researchers estimate that electric VMT (eVMT) exceeds that of ICEs. Tal et al. (2021) recruited a sample of 358 EV drivers to install data-tracking devices on their cars. They estimate annual VMT of 12,900 miles in this sample.

These differences highlight the need for continued research or, ideally, direct measures of VMT for a representative sample of vehicles. In the meantime, there are three main channels for reconciling the seemingly conflicting estimates: vintage, selection, and unmeasured nonresidential charging. First, both of the lowest eVMT estimates arise from samples predating 2017. Although our ongoing updates to Burlig et al. (2021) do not reveal increasing residential charging in California, many factors are changing with time that would support higher eVMT (e.g., longer driving range and more commercial charging options). The second channel that may reconcile these results is selection. Everyone agrees that there is immense heterogeneity in driving behavior across vehicles and households. Just as it appears that Teslas are driven substantially more than other EVs, it may be that participants in voluntary studies are selected on unobservable attributes (e.g., EV enthusiasts who drive more than the average EV owner). The third potential channel is unmeasured nonresidential charging. To the extent that nonresidential chargers neglect to participate in government programs such as the Low-Carbon Fuel Standard, the aggregate nonresidential charging load will be biased downward. Some combination of these factors likely explains the difference in estimates of eVMT.

To the extent that drivers prefer ICEs over EVs, EV adoption will be slow. The proliferation of EV models will help by more thoroughly saturating the product attribute space and allowing potential EV buyers to find cars that best suit their needs. The most important segment for which this gap remains large is light-duty trucks, which form the most popular vehicle segment in the United States. As competitive EV trucks are introduced, the prospects for meeting ambitious EV targets are improved (Archsmith, Muehlegger, and Rapson 2021). There may also be a substantial role for hybrid drivetrains. Allowing drivers the option to drive some of their miles on gasoline mitigates range anxiety, improves cold-weather performance, and allows for redundancy of fuel sources. We will return to the latter point in "Public Cost of Electrification."

Physical Access

Large swaths of electricity infrastructure were engineered to meet the needs of a grid without EVs as a central source of load. For at-home charging to be possible, the local distribution network requires sufficient transformer and circuit capacity to bring energy to the home, the building must be wired to accommodate that load, and there must be parking available next to chargers. Many US residences do not have these amenities, and those would-be EV buyers will encounter physical barriers to access.

Many policy makers seem aware of challenges facing EV owners who live in multiunit dwellings (MUDs). Here, we will also highlight two physical barriers that are not often discussed: residential electricity service levels in single-family homes and distribution network costs. The ease of upgrading facilities to accommodate EV load is heterogeneous. In some individual cases, upgrade costs may be in the range of a thousand dollars, but in some cases the costs will be much higher. Cumulative costs of addressing these issues economy-wide will be substantial, and these are rarely discussed.

MUDs comprise 31.4 percent of US housing today (American Housing Survey, US Census Bureau 2019). Potential EV buyers in MUDs will require charging options that are less obvious than those for people who live in single-family homes with driveways. MUD-dwellers will either need parking spaces in or near their buildings that are equipped with charging infrastructure, or they will have to rely exclusively on away-from-home charging options. Although we are not aware of any data set that reports parking spot access or the availability of suitable chargers at MUDs, surveys offer some insight into the scale of this obstacle. The 2017 NHTS reports "own" versus "rent" status, allowing us to see that 22 percent of cars reside at renter-occupied dwellings, reflecting 25 percent of nationwide VMT. Figure 2 presents the count of vehicles by type and home ownership classification. Just one in six EVs is owned by people who rent their dwelling.

A less well-discussed constraint applies broadly to prospective EV buyers who live in single-family homes. There are two options for residential charging of EVs. Level 1 charging operates from a standard 120 volt wall plug and yields on the order of 4 miles of range per hour of charge. Level 2 chargers are much faster, yielding around 25 miles of range per hour of charging, and these operate at a higher level of power. The latter typically require that the home has at least 200 amp service to accommodate demand from EV charging concurrently with other electricity services in the home.

Homes built after 1990 are typically equipped with at least a 200 amp panel, but most homes predating 1990 were initially equipped with 100 amp service or lower. Some of these

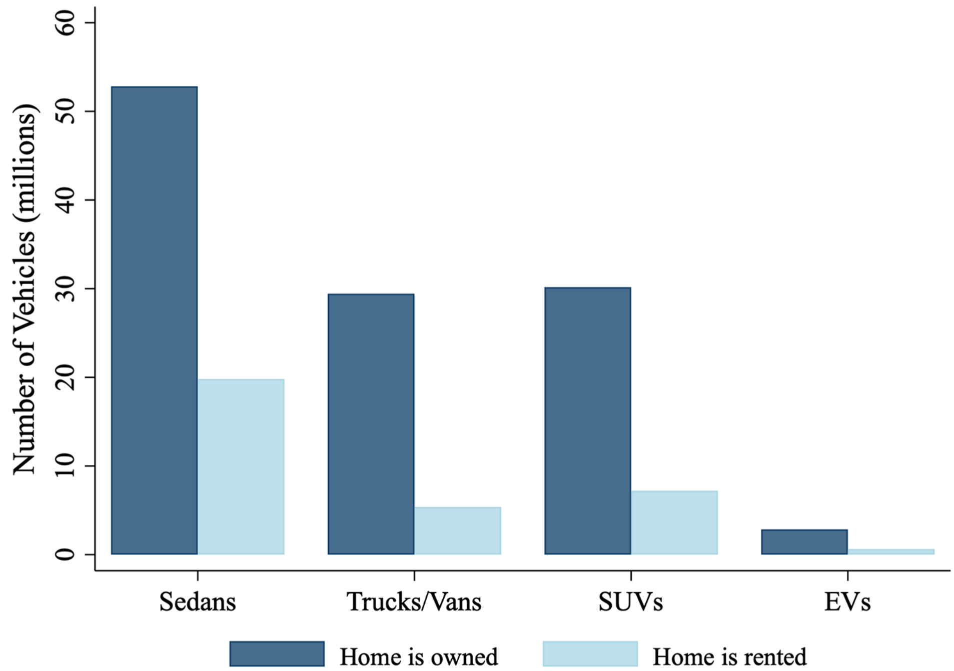

Figure 2 US vehicle count by type (owners vs. renters). A color version of this figure is available online.

older homes have upgraded their service level to accommodate electricity-intensive services such as central air conditioning (AC). However, if they have not, installing a level 2 charger in these homes typically requires upgrading the service level, at a cost of roughly $1,000–$2,500. Based on our calculations using data from the Residential Energy Consumption Survey of the Energy Information Administration (EIA), more than 20 percent of single-family homes in the United States were built before 1990 and do not have central AC. This is likely a lower bound to the number of single-family households that would have to incur the service upgrade expense to enjoy level 2 EV charging.[8]

Finally, increases in load from electrification will require substantial upgrades to the electricity distribution system. Distribution feeder and transformer capacities will need to be expanded to accommodate increased electricity demand from residential space and water heating and even more so from EVs. Elmallah, Brockway, and Callaway (2022) estimate these costs for California's largest public utilities company, Pacific Gas & Electric, using detailed data on existing distribution infrastructure capacity and forecasts of highly localized load growth. Costs depend primarily on when EVs are charged, because system size must accommodate the highest peak in demand. If demand occurs during periods of low congestion in the distribution system, system upgrade costs may be as low as around $200 per customer. However, failure to optimize demand over time and space increases those costs by an order of magnitude, to $2,000 per customer.

[8]Some households with service levels that are appropriately sized for their current electricity needs may require upgrades to accommodate an EV even if they already have, say, 200 amp service.

These costs highlight not only the advisability of accounting for these costs in social benefit–cost analyses of electrification but also the benefits of electricity rate reform that can help manage short-run local fluctuations in charging patterns in response to grid capacity constraints. Technological solutions will likely also play a role. Managed charging programs are currently being piloted to assess the benefits of centralized control as well as the willingness of drivers to relinquish full control over their charging timing.

Public Cost of Electrification

The previous section surveyed the various barriers that firms and policy makers will encounter in an attempt to achieve 100 percent electrification based on consumer preferences, resource availability, and market realities. Beyond the barriers that private costs and preferences present on the road to mass electrification, there are several public goods, or externality considerations, that rather than delaying electrification reduce the benefits of that transition. These external costs should be weighed as part of the calculus behind the proper level of public support and regulation that should be directed toward electrification goals. They also point to an additional regulatory agenda that may be necessary to accommodate even intermediate levels of electrification. This section also highlights the areas of further policy development and regulation that may become more urgent with the expansion of electrification.

Relative Inefficiency of the Electricity Sector

A significant yet largely undiscussed implication of large-scale electrification is the shift of massive amounts of energy production and consumption from the relatively competitive and productive US petroleum and natural gas sectors to an electricity sector where government ownership and direct economic regulation play a substantial role. Although roughly 75 percent of electricity generation has been partially deregulated, the transmission and distribution sectors, which account for just under half of industry costs, continue to operate as regulated natural monopolies. It is true that pipeline transportation and distribution are partially regulated in the gas and petroleum sectors as well, but these activities comprise smaller shares of total costs in those sectors than in electricity and face more competition from alternatives such as rail, trucking, and tankers.[9] Estimates of productive efficiency are sparse in the electricity sector. However, research has illustrated the gains resulting from existing regulatory restructuring (Davis and Wolfram 2012; Cicala 2022), suggesting that inefficiencies remain in the regulated portions of the industry.

One of the most prominent inefficiencies of the electricity sector is the setting of retail prices, which diverge from estimates of marginal cost much more significantly than retail gasoline or natural gas prices. In other words, electricity prices do not closely track the costs of production, which include fixed costs (infrastructure) and marginal costs (the cost of producing one more unit). This divergence is persistent over the long term but can be extreme over

[9]Davis and Hausman (2022) note that pipeline capital and depreciation cost are roughly 25 percent of the delivered cost of natural gas. The EIA cites distribution as comprising roughly 12 percent of the price of gasoline (https://www.eia.gov/energyexplained/gasoline/factors-affecting-gasoline-prices.php) and transmission and distribution as comprising 44 percent of the delivered cost of electricity (https://www.eia.gov/energyexplained/electricity/prices-and-factors-affecting-prices.php).

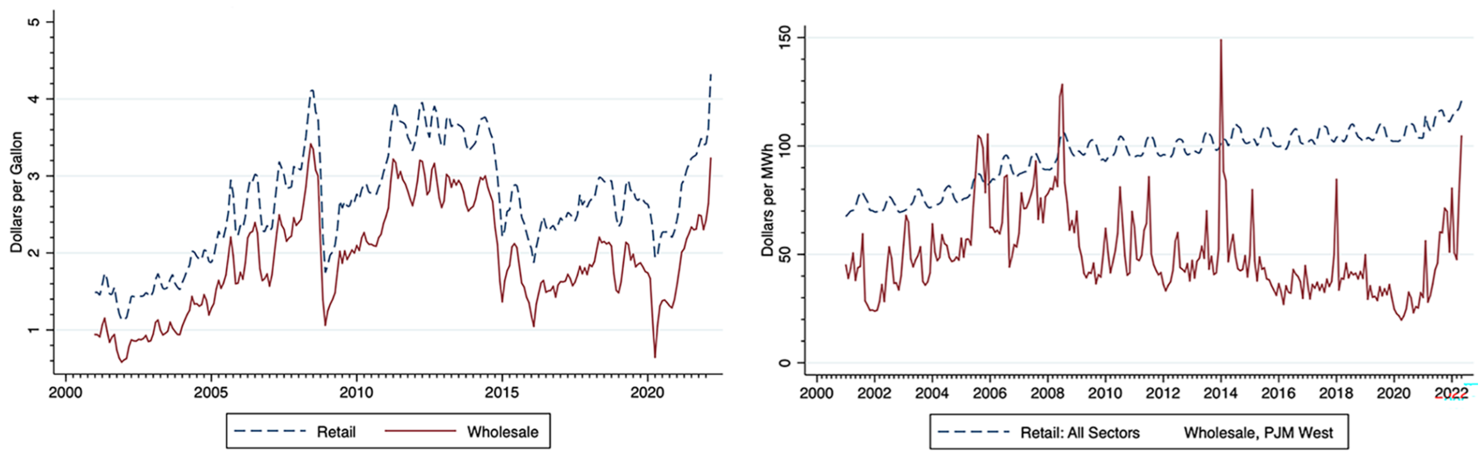

Figure 3 Wholesale and retail prices. MWh = megawatt-hour. A color version of this figure is available online.

short-run periods. The right-hand panel of figure 3 compares monthly average wholesale electricity prices at a Pennsylvania trading index with US average retail prices; the left-hand panel does the same for gasoline. This illustrates the relatively tight relationship between wholesale gasoline prices, which in turn closely track world oil prices, and retail prices, in a pattern that is consistent across the United States. By contrast, retail electricity prices are notoriously rigid, changing monthly by modest amounts, but in many places they remain constant for many months or even years. Even figure 3 understates the inefficient rigidity of electricity prices given the high degree of hourly price variation in wholesale electricity markets. Borenstein and Bushnell (2022) estimate the hourly delivered marginal cost of electricity and compare it to the marginal price reflected by the most common electricity rate for most electricity retailer providers in the United States.

Given the discussion in the subsection “Remaining CO_2 Emissions in the Electric Sector,” it is important to consider not only the divergence between private marginal cost of production and retail prices but also the relationship between social marginal cost (SMC) and retail prices. Borenstein and Bushnell (2022) estimate, at least partially, the relationship between SMC and prices for electricity, natural gas, and gasoline in the United States between 2014 and 2017. The SMC estimate is partial in the sense that the environmental externality costs are limited to the air-pollution costs of the direct energy production for each source. There is large regional variation in the separation between price and SMC, particularly for electricity and gasoline. However, electricity prices again stand out as uniquely inefficient by this metric. Although gasoline is overpriced (including taxes) in most areas, average gasoline prices for roughly 85 percent of the population averaged within 20 percent of SMC. By contrast, electricity prices were within 20 percent of SMC for less than 50 percent of the population, and nearly 30 percent of the population faced prices more than 30 percent above SMC. Again, these figures understate the severity of mispricing of electricity, because the multiyear averages mask monthly and even hourly variation in SMC.

Remaining CO_2 Emissions in the Electric Sector

A central tenet of the electrification strategy is that consumer goods powered by electricity will be cleaner than the alternatives and eventually will be carbon free. However, to the extent that the electric system continues to produce CO_2 emissions in the generation of power, EVs and other electric appliances will not be truly “zero-emissions” products. Several papers have illustrated that EVs have been less polluting on balance than comparable ICE vehicles, but with significant regional disparities and nowhere near zero emissions (Graff Zivin, Kotchen, and Mansur 2014; Archsmith, Kendall, and Rapson 2015; Holland et al. 2016). Although a zero-carbon grid remains a distant prospect, there are many positive trends to consider. First, CO_2 emissions in the US power sector have declined by 36 percent since 2005. Most of this reduction is due to coal production being supplanted by natural gas, but utility-scale renewable generation has grown from 2 percent to nearly 12 percent of total US electricity. Although these trends have reduced average CO_2 emissions rates in the electric sector, marginal emissions rates have risen in some parts of the country (Holland et al. 2020). Currently, 21 US states and the District of Columbia have varying degrees of commitment to achieving 100 percent clean energy between 2030 and 2050. However, those 22 jurisdictions account for only 29 percent of CO_2 emissions in the US electric sector.

The prospect for a low-carbon grid will almost certainly continue to be dependent upon policies forcing or accelerating a transition. Holland, Mansur, and Yates (2022) indicate that, even with relatively strong low–carbon policy benefits, the sources of electricity that may power EVs in the longer term will not be carbon free, and the marginal emissions will be highly dependent upon charging patterns. Though they argue that 100 percent renewable power in Hawaii is "remarkably affordable," Imelda and Roberts (2018) also find that without changes to pricing and demand response, costs sharply rise as renewable penetration rises above 80 percent.

It will also be a challenge for essential investments in electricity grid infrastructure to keep up with growth in renewable generation capacity. Transmission wires are a case in point. Larson et al. (2021) estimate that a threefold increase in the rate of US transmission investment is required to meet the goal of a net-zero-carbon economy by 2050. Davis, Hausman, and Rose (2023) identify three reasons for pessimism. First, no centralized authority exists for approving new transmission projects. Proposed investments are exposed to a patchwork of federal, state, and local authorities, making it difficult to achieve consensus. Second, even when stakeholders agree, determining who will pay can be contentious. Finally, negotiating right-of-way permissions can be expensive and often encounters local siting challenges ("not in my backyard"). These and other challenges will need to be overcome to eliminate CO_2 from the electricity sector in the developed world.

Internationally, the picture is even less optimistic. China and India, the countries with the largest and fourth-largest auto markets in the world, feature heavily coal-intensive electric grids. As they expand renewable production, they also continue to add coal-fired generation capacity. Although China is rapidly adopting EVs, it is not at all clear that this is a net win for the climate, given the near-term coal usage of the Chinese power system (Qiao et al. 2017; Zhang et al. 2017).

Noncarbon Environmental Externalities

Another consideration of the potential public cost of electrification is the degree to which electrification changes the amount and incidence of noncarbon externalities. For example, a large-scale shift of residential heating to heat-pump technology will expand the use of chemical refrigerants. Leakage of refrigerants, themselves potent GHGs, remains a concern in residential applications and may claw back some of the climate benefits of reduced fossil fuel combustion (Pistochini et al. 2022).[10]

Many studies find benefits from reductions in local pollution from electrification, but there are reasons to suspect that those advantages may decline. Emissions of local air pollutants are notoriously concentrated in older vehicles, and newer ICE vehicles that comply with air-quality regulations are increasingly minor contributors to local pollution (Jacobsen et al. 2023).

Further, recent analyses have highlighted concerns over air pollutants from brake and tire wear, both of which are more pronounced in EVs (OECD 2020; Wang et al. 2023). In addition to the air-quality impacts from metal, rubber, and microplastics, recent research has pointed to tire-chemical runoff as lethal to several species of salmon (French et al. 2022).

Finally, copper, nickel, lithium, and countless other minerals are critical inputs to an electric economy. The mining and processing of these resources often cause adverse environmental

[10]Not all heat-pump conversions imply a net increase in the deployment of refrigerant, as many will replace existing central air conditioners. However, almost all heat-pump water heaters will expand refrigerant usage.

impacts, such as the disruption of fragile ecosystems and groundwater depletion or contamination. See Lee et al. (2020) for a discussion of these effects and the difficulty of quantifying their costs in a systematic way.

Other External Impacts

Although analysis of the net benefits of EVs often considers the local air-pollution benefits (e.g., Holland et al. 2016), less attention has been given to the significant nonpollution externalities associated with passenger-vehicle use. Typically, the list of major vehicle externalities focuses on traffic congestion, accidents, GHG emissions, and local pollutants (see, e.g., Proost and Dender 2011). The costs of lost time due to traffic have been estimated to be orders of magnitude larger per mile than the costs of air pollutants (Parry, Walls, and Harrington 2007), with the costs of accidents somewhere in between. The GHG emissions have typically been the smallest of the major automobile-related externalities, but most studies have used what may be today considered modest SCC.[11]

Consideration of the economic costs of accidents highlights another potentially major externality-generating aspect of EVs: their weight. Across all vehicle classes, EVs are typically heavier, often much heavier, than their ICE counterparts. In addition, EV offerings have migrated upscale, with a higher average suggested retail price that has coincided with a focus on the luxury sedan, truck, and SUV categories. These factors have combined to produce a wave of vehicles ranging from the 4,500-lb Tesla S, to the 6,000-lb Ford Lightning, up to the enormous 9,000 lb-Rivian R1T and GMC Hummer. These reflect weights ranging from 1,000 to 3,000 lb greater than their ICE counterparts.

In addition to the direct cost impacts on road infrastructure, vehicle weight is one of the important considerations in the severity of accidents. Anderson and Auffhammer (2013) found that an additional 1,000 lb of car weight increased baseline fatality probability by nearly 50 percent. A key consideration is the relative size of vehicles involved in a crash (Jacobsen 2013), with the greatest danger being from a heavy car hitting a smaller one. However, these earlier findings applied to a fleet where vehicle weight was correlated with body size and other attributes that enhanced passenger safety rather than correlated with a battery. It is worth noting that most of the work in this area predates the advent of EVs, so other safety aspects of EVs may mitigate or exacerbate the impact of their weight in considering net accident risks. Absent other incentives regarding vehicle weight, however, there is concern that fatalities could increase as a result of electrification (Shaffer, Auffhammer, and Samaras 2021).

Public Costs Discussion

We conclude this brief survey of the public costs of electrification by noting the importance of policy context and regulatory incentives. In some cases (e.g., traffic congestion), electrification does not make these problems worse, per se, except through the channel of increased fleet size and usage (e.g., passenger miles). One of the attractive features of transportation electrification is the per mile cost of driving, which is mostly lower, even in areas with high electricity prices (Borenstein and Bushnell 2022). To the extent that lower marginal costs

[11] For example, whereas Parry, Walls, and Harrington (2007) discuss a range of SCC, they use a value in the range of about $20, which translates to 6 cents/gallon, in their summary table.

spur driving to increase—the "rebound" effect—the external costs of accidents, tire wear, and traffic will increase, potentially offsetting climate gains.[12] Of course, EVs are not pure substitutes for ICE vehicles. Some attribute differences, notably range, may increase the convenience costs of driving and thereby reduce the amount of driving. Research on eVMT is preliminary and the results are mixed, so it is too early to conclude whether widespread electrification would increase or reduce VMT.[13] However, increased driving is certainly a distinct possibility in the long run because of lower operating costs, as well as during the transition, as a result of government subsidies that are likely expanding the overall size of the vehicle fleet.

Policy influences are of course crucial in this regard. Although countries such as Norway have incentivized EVs largely by increasing the costs of owning and using ICE vehicles, the United States has applied a combination of tax credits and other public subsidies for EVs. This latter approach not only will leave existing nonclimate externalities unaddressed by electrification but also may very well exacerbate them by increasing the amount and usage of high-weight passenger vehicles. Economists have long argued for alternative mechanisms for addressing these externalities, such as congestion pricing and registration charges based on VMT or vehicle weight (Shaffer, Auffhammer, and Samaras 2021). Such policies, along with a renewed regulatory focus on vehicle weight, as well as the chemical composition of tires, will likely become more urgent as fleets electrify, whether or not we reach 100 percent electrification.

Conclusions

Of the 97.3 quadrillion Btu of primary energy inputs to the US economy in 2021, less than 40 percent (36.7 quadrillion Btu) went to electricity generation.[14] Remarkably, 65 percent of this was lost to technical inefficiencies in the electric system, leaving only 12.9 quadrillion Btu sold for end use. Full electrification therefore requires changing the source of the 82 percent of energy end uses in the US economy. Although even the most aggressive plans do not foresee electrifying all industries, a vision of completely electrifying residential energy use and transportation is commonly repeated.

Calls for 100 percent zero-carbon electricity generation and 100 percent electrification, even of "just" household and transportation energy sources, represent an "all or nothing" mindset that is typically resisted by economists, who are more accustomed to aligning marginal costs with marginal benefits. Although large uncertainties remain regarding both the costs and benefits of such policies, the cost of 100 percent electrification using today's technologies would almost certainly exceed even the more extreme forecasts of the SCC.

Commitments to full electrification therefore represent a bet that technological advancement in the production and distribution of zero-carbon electricity will dramatically reduce the costs of those activities. For electrification to be the appropriate policy for all applications,

[12]See Gillingham, Rapson, and Wagner (2016) for a review of this literature.
[13]Davis (2019) finds that respondents to the 2017 NHTS survey drive EVs less than ICE vehicles. Using surveys of EV owners, Hardman et al. (2018) find much higher eVMT in California. Burlig et al. (2021) find surprisingly low increases in residential electricity use by EV owners, but with substantial heterogeneity by vehicle type.
[14]See https://www.eia.gov/energyexplained/us-energy-facts.

this cost reduction would have to exceed the cost reductions of other low-carbon approaches, as well as exceeding the cost of adaptation technologies such as direct air capture and solar radiation management.

A more likely optimal scenario would involve a mixed solution, where a large percentage of electricity generation is zero carbon and a large percentage of household and transportation energy use is powered by electricity—but each of those shares is somewhere short of 100. Under this scenario, some fraction of household energy use and electricity production would remain powered by fossil fuels or as-yet-unidentified alternatives.

Policies that target 100 percent electrification through rigid mandates and bans create at least two significant risks. The first is that they drive up electricity costs so rapidly that the policies undermine the very electrification goal they pursue. The shorter the transition period that is imposed, the greater this risk. The second risk is the foreclosure of opportunities for more efficient, lower-cost pathways to decarbonization. Such pathways may either exist today for some energy uses or emerge as broadly applicable as technology advances.

Therefore, it is important that policies pursuing zero-carbon electrification retain some flexibility in the form of cost containment, alternative compliance mechanisms, or frequent reevaluation. It is unclear to us whether the political process will foster this degree of flexibility once leaders commit their constituents to an electric future. Despite their current lack of favor, the flexibility inherent in market-based, technology-neutral climate policies will likely become even more important as electrification progresses.

In addition, we have surveyed several significant public costs—from particulate emissions from tires to the inefficient pricing of power—that would remain or even expand in an electrified future. The doubling of the size of the electric sector will also involve the efficiency costs of shifting a large portion of economic activity from relatively unregulated industries to a much more heavily regulated one. The process of electrification therefore accelerates the need to reform electricity regulation and move toward more efficient pricing of services offered by electric utility companies.

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