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The Electric Ceiling: Limits and Costs of Full Electrification

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The Electric Ceiling: Limits and Costs of Full Electrification

David Rapson ⓡ James Bushnell *

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Abstract

Electrification is a centerpiece of global decarbonization efforts. Yet there are reasons to be skeptical of the inevitability, or at least the optimal pace, of the transition. We discuss several under-appreciated costs of full, or even deep, electrification. Consumer preferences can operate in favor of and in opposition to electrification goals; and electrification is likely to encounter physical and economic obstacles when it reaches some as-yet-unknown level. While we readily acknowledge the external benefits of decarbonization, we also explore several under-appreciated external costs. The credibility and eventual success of decarbonization efforts is enhanced by foreseeing and ideally avoiding predictable but non-obvious costs of promising abatement pathways. Thus, even with all of its promise, the degree of electrification may ultimately reach a limit.

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1 Introduction

Around the globe, many jurisdictions are adopting increasingly aggressive targets for the reduction of greenhouse gas (GHG) emissions. The European Union, 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] More have declared it to be an aspiration.

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 CO2 emissions.

While the electrification process has proceeded in fits and starts, it is clear that there is significant momentum behind this transformation. Renewable electricity comprised over 20 percent of generation in the U.S. in 2021. Electric heat-pumps are growing near cost-competitive with more traditional fossil-fueled space and water-heating appliances (Borenstein and Bushnell (2022)), pointing to a looming, 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 U.S. 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 U.S. 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 2040 worldwide.

While 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 passen-

[1] https://eciu.net/netzerotracker
[2] https://www.iea.org/reports/electric-vehicles

ger transportation and residential energy uses. Research is beginning to acknowledge the idea that, absent significant technological advancement, the complete decarbonization of electricity production may be extremely costly in terms of material costs 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 under-appreciated 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 a complete reliance on electricity. We have labelled these "public" costs in the sense that each represents an erosion of a public good, and are not overcome but are 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 greenhouse gas emissions. Our intent is not to ignore or minimize those costs, but rather emphasize that the costs of mitigating greenhouse gasses 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, policies that rigidly adhere to 100 percent targets could prove extremely costly and ultimately counterproductive.

2 Can There Be "Too Much" Electrification?

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. This process is classically captured in the "adoption curve," an S-

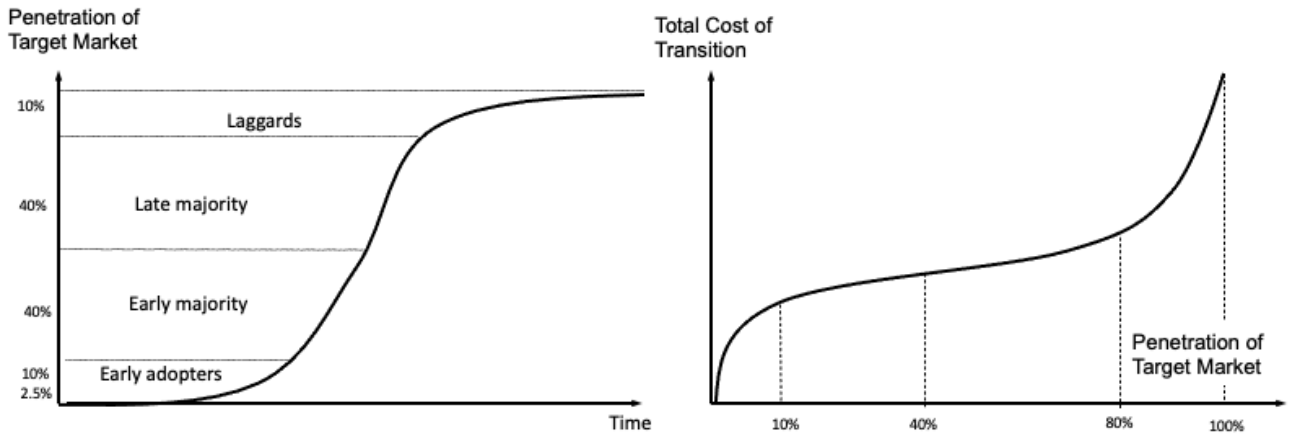

Figure 1: Adoption S-curve and marginal cost of adoption

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)). Electric vehicles are currently covered in news articles as nearing, if not surpassing, a "tipping point" between early and mass adoption. Electric space and water heating, as prominent a technology in many climate plans as that of vehicles, receive notably less attention.

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 TVs), or technologies that spawn new consumer categories altogether (e.g. smartphones). In these cases, consumers overwhelmingly chose the dominant technology at the time, and switch en-mass when a new superior option emerges. The products that electrification strategies are targeting have experienced "mixed" equlibria of multiple technology options co-existing 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 over 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.

From a policy perspective, the question becomes whether and how to adopt policies that will 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. We observe that policy preferences tend to mirror disciplinary outlooks. The dominant policy framing tends to reflect an engineering or natural-science based perspective and articulate policies in terms of quantitative targets, such as 2 degrees celsius or "net-zero by 2050." An unwavering commitment to a quantitative target implicitly signals a belief of nearly infinite cost of falling short, and therefore a willingness to incur very high marginal cost to make sure the target is attained. The environmental economics literature tends to frame these questions as balancing the marginal benefits of 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, 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 or removal, and/or geo-engineering, confronting the marginal costs of abatement in specific sectors is a valuable exercise for the evaluation of both the desirability of technology mandates and of their likelihood of success.

3 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 (and associated prices), 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. To achieve full electrification in the economy requires converting all energy services to electricity. In the residential sector, this includes home heating and cooling, cooking, water heating, etc., and firms and governments would have to do the same. We set aside these important segments for now for the main reason that electrifying the transportation fleet offers by far the largest potential emissions reduction opportunity while also being the sector in which the electric option is least substitutable, at present.

3.1 Preference Barriers to EV Adoption

Industrial organization demand models portray goods as bundles of attributes. When consumers decide whether or not 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 will help to place into context the high price of EVs today, and the necessity to provide either large ongoing cost savings or a far superior user experience to that of ICEs in order to compel EV adoption. With this in mind, we offer three aspects of the EV-ICE choice that will contribute to the EV adoption rate.

3.1.1 EV Cost Relative to Gasoline Cars

In July 2022, the average list price of an EV in the United States was $66,000, as compared to $48,000 for the average new internal combustion engine, or gasoline, car (ICE).[3] Part of this price differential arises from selection and matching. That EVs are more expensive to manufacture than ICEs makes high-income households a natural target market. Manufacturers, knowing this, offer

[3] Kelly Blue Book

EV models that tend to compete in the luxury segment. A strong, positive correlation between EV adoption and income has emerged and is well-documented (Archsmith et al. (2021), Borenstein and Davis (2016) 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, the presence or absence of which 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 less than $100 to produce, a typical EV sedan battery costs several thousand dollars, and high-capacity batteries well over ten thousand dollars. EV battery costs have declined by roughly 90 percent in the last decade, and while many are optimistic that the trend will continue, it is not guaranteed. The battery requires approximately seven times the mass of mineral inputs than appears in 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. The price of 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. The magnitude (and even sign) of these savings is idiosyncratic, depending primarily on the gasoline and electricity prices faced by drivers (see Rapson and Muehlegger (2021) for a more thorough discussion). Moreover, the extent to which ongoing cost savings are considered at the time of purchase is likely to be endogenous to the rate of EV adoption. Bushnell et al. (2022) find that, in their sample of California from 2014-2017, oil prices have several times more impact on EV demand than electricity prices. This gap may close as more EV buyers fa-

[4]https://www.iea.org/data-and-statistics/charts/minerals-used-in-electric-cars-compared-to-conventional-cars
[5]https://www.benchmarkminerals.com/lithium-prices/
[6]https://tradingeconomics.com/

miliarize themselves with the relationship between their driving behavior and their electric bill, increasing awareness of relative prices. In fact, Bushnell et al. (2022) find some evidence consistent with this. EV buyers in high electricity-price neighborhoods tend to sell their EV more quickly than those in low-price areas, which may be evidence of learning about relative costs of vehicle operation.

Government subsidies are a popular non-market channel for overcoming the EV cost disadvantage as well. 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] While EV subsidies stimulate demand, they are expensive due to the inability of subsidy design to differentiate between "additional" (marginal) and "non-additional" (inframarginal) buyers. Recently, eligibility for U.S. federal EV subsidies includes means tests and MSRP conditions on 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 subsidy-ineligible. 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 help to accelerate battery cost declines and, eventually, allow EVs to be (privately) cost-competitive with ICEs.

3.1.2 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 services. The nature of trips is diverse, and the utility derived from those trips arises from heterogeneous preferences for the match between vehicle and trip attributes. For this reason, vehicle-miles traveled (VMT) is a reasonable approximation of how substitutable drivers view 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 for the population of EVs and ICEs are not available, so researchers and policymakers alike rely on estimates of various kinds. The National

[7] Interested readers may review Chandra et al. (2010), Gallagher and Muehlegger (2011), Beresteanu and Li (2011), Clinton and Steinberg (2017) and Muehlegger and Rapson (2018) on the effects of incentives on adoption; Sallee (2011) and Gulati et al. (2017) study pass-through; and Li et al. (2017), Li (2017) and Springel (Forthcoming) estimate network effects of charging stations.

Household Travel Survey (NHTS) provides a quinquennial representative sample of national driving behavior. The U.S. 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 type. Some car manufacturers collect VMT using telemetry technology, but most have only a partial and selected sample, and there are no public reporting/disclosure requirements. Finally, academic researchers have often either implemented their own surveys on selected subpopulations, or have used odometer readings from state-administered vehicle inspection programs. The latter are a requirement for registration and must be preformed at semi-regular intervals that depend on the age and class of the vehicle. In short, there is no clear view of VMT in the U.S.

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 vehicle-miles traveled (VMT) for light-duty vehicles in the U.S. 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 non-residential 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 eVMT that 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 to reconciling the seemingly conflicting estimates: vintage, selection, and unmeasured non-residential charging. First, both of the lowest eVMT (electric VMT) estimates arise from samples predating 2017. While 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, more commercial charging options, etc). The second channel that may reconcile these results is selection. Everyone agrees that there is immense heterogeneity in driving behav-

ior across vehicles and households. Just as it appears that Teslas are driven substantially more than other EVs, it may be that participants in the voluntary-participation studies are selected on unobservable attributes (e.g. EV enthusiasts who drive more than the average EV owner). The third potential channel is unmeasured non-residential charging. To the extent that non-residential chargers neglect to participate in government programs such as the Low-Carbon Fuel Standard (LCFS), aggregate non-residential charging load will be biased downwards. 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 are the most popular vehicle segment in the U.S. As competitive EV trucks are introduced, the prospects for meeting ambitious EV targets are improved (Archsmith et al. (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 Section 4.

3.2 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 U.S. residences don't have these amenities, and those would-be EV buyers will encounter physical barriers to access.

Many policymakers seem aware of challenges facing EV owners who live in multi-unit 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

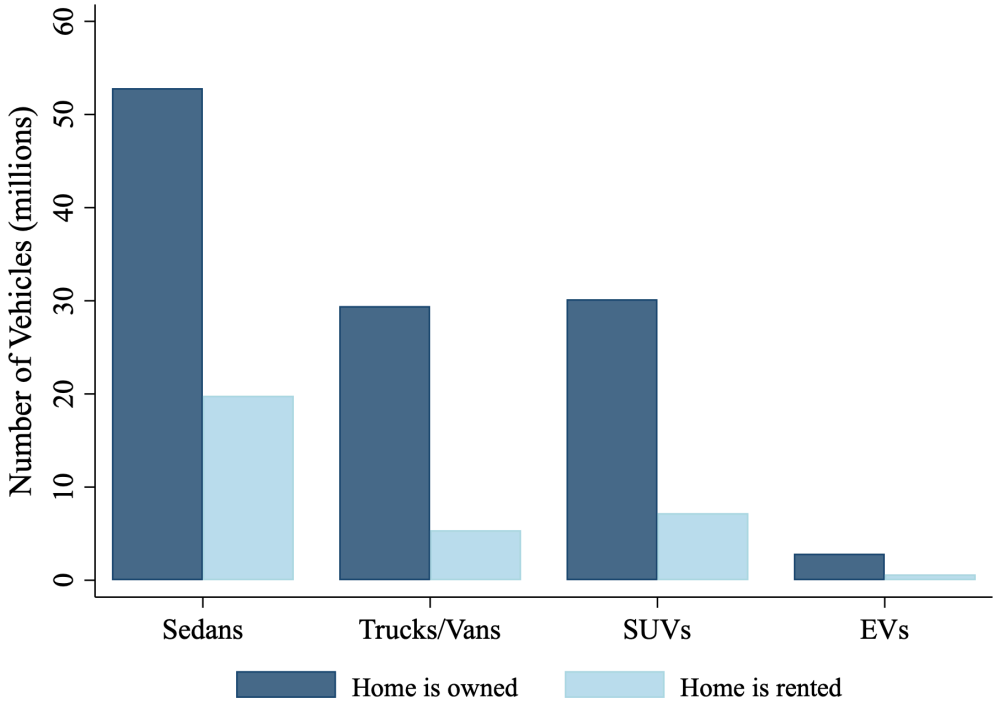

Figure 2: U.S. Vehicle Count by Type (Owners vs Renters)

higher. Cumulative costs of addressing these issues economy-wide will be substantial, and are rarely discussed.

MUDs comprise 31.4 percent of U.S. housing today (American Housing Survey, 2019). These potential EV buyers 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 must rely exclusively on away-from-home charging options. While we aren't aware of any dataset that reports parking spot access or the availability of level 2 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 in order 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 pre-dating 1990 were initially equipped with 100 amp service or lower. Some of these older homes have upgraded their service level to accommodate electricity-intense services like central air conditioning. However, if they have not, installing a level 2 charger in these homes will typically require upgrading the service level at a cost of roughly $1,000-$2,500. Based on our calculations using data from the EIA's Residential Energy Consumption Survey, over 20 percent of single-family homes in the U.S. 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 additional service upgrade expense in order 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. Brockway et al. (2022) estimate these costs for California's largest public utilities company, Pacific Gas & Electric, using granular data on existing distribution infrastructure capacity and forecasts of highly localized load growth. Costs depend primarily on when EVs are charged, since system size must accommodate instances of 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; but failure to optimize demand over time and space increases those costs by an order of magnitude, to $2,000 per customer. This highlights not only the necessity to account for these costs in social cost-benefit analyses of electrification, but also to the benefits of electricity rate reform that can help to manage short-run local fluctuations in charging patterns in response to grid capacity constraints.

[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.

4 Public Cost of Electrification

The previous section surveyed the various barriers firms and policy-makers will encounter in an attempt to achieve 100 percent electrification based upon consumer preferences, resource availability, and market realities. Beyond the barriers private costs and preferences present on the road to mass electrification, there are several public goods, or externality considerations which, 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.

4.1 Remaining CO2 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 will eventually be carbon free. To the extent that the electric system continues to produce CO2 emissions in the generation of power, electric vehicles and other electric appliances will not be truly "zero emissions" products. Several papers have illustrated that electric vehicles have been on-balance less polluting than comparable ICE vehicles, but with significant regional disparities, and nowhere near zero-emissions (Archsmith et al. (2015);Graff Zivin et al. (2014); Holland et al. (2016)). While a zero-carbon grid remains a distant prospect, there are many positive trends to consider. First, CO2 emissions in the U.S. 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. Further, twenty-one U.S. 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 CO2 emissions in the U.S. electric sector.

The prospect for a low-carbon grid will almost certainly continue to be dependent upon policies forcing or accelerating a transition. Holland et al. (2022) indicates 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. While arguing that 100 percent renewable power in Hawaii is "remarkably affordable," Imelda et al. (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 U.S. transmission investment is required to meet the goal of a net-zero carbon economy by 2050. Davis et al. (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 encounter local siting challenges ("not in my back yard"). These and other challenges will need to be overcome in order to eliminate CO2 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 and, while expanding renewable production, also continue to add coal-fired generation capacity. While China is rapidly adopting electric vehicles, it is not at all clear that this is a net win for the climate given the near-term state of the Chinese power system (Zhang et al., 2017; Qiao et al., 2017).

4.2 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 U.S. petroleum and natural gas sectors to an electricity sector where government ownership and direct economic regulation play a substantial role. While roughly 75 percent of electricity generation has been partially deregulated, the transmission and distribution sectors, which account for over 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

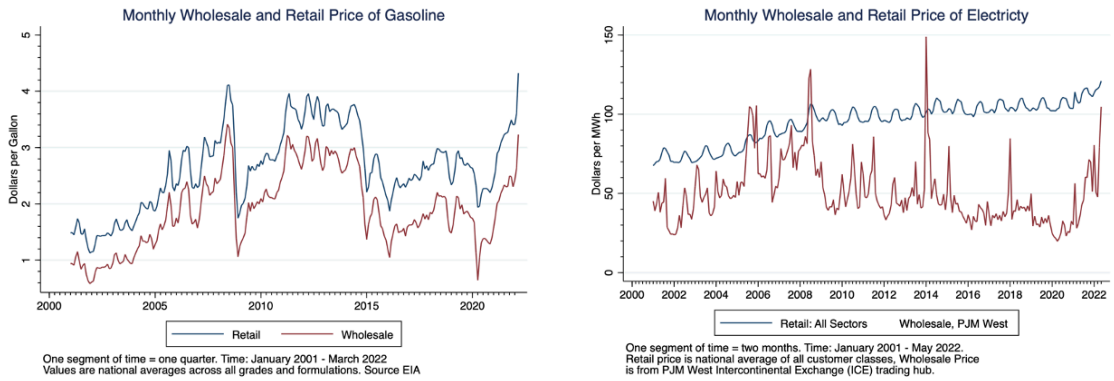

Figure 3: Wholesale and Retail Prices

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. Estimates of productive efficiency are sparse in the electricity sector. However, research has illustrated the gains brought from the regulatory restructuring that has occurred (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 prices or natural gas. This divergence is persistent over the long term but can be extreme over short-run periods. The left-hand panel of Figure 3 compares monthly average wholesale electricity prices with retail prices in Pennsylvania and the right-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 that is consistent across the United States. By contrast, retail electricity prices remain notoriously rigid, changing monthly by modest amounts, but in many places remaining 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 U.S.

Given the discussion of section 4.1, it is important to consider not just the divergence between private marginal cost and retail prices but also the relationship between social marginal cost (SMC)

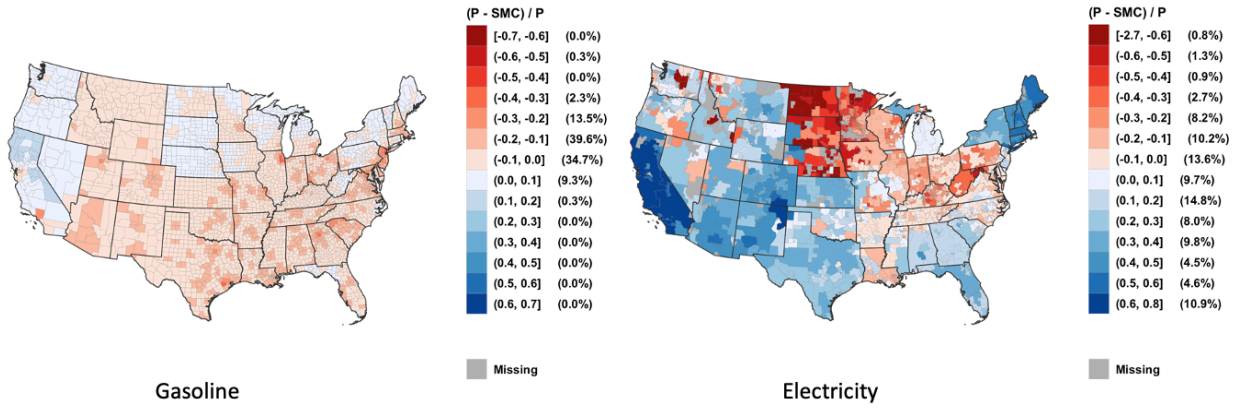

Figure 4: Relative Price Deviation from Social Marginal Cost

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 US 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. Figure 4 illustrates the mis-pricing of gasoline and electricity as a percentage of the retail price.[9] There is large regional variation in the separation between price and SMC, particularly for electricity and gasoline, but by this metric electricity prices again stand out as uniquely inefficient. While gasoline is over-priced (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 for less than 50 percent of the population were within 20 percent of SMC and nearly 30 percent of the population faced prices more than 30 percent above SMC. Again, these figures understate the severity of mis-pricing of electricity as these multi-year averages mask monthly and even hourly variation in SMC.

4.3 Non-Carbon Externalities

Another consideration of potential public cost of electrification is the degree to which electrification changes the amount and incidence of non-carbon 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 a potent greenhouse gas, remains a concern in residential applications and can claw back some of the climate benefits of reduced fossil fuel combustion

[9] The mis-pricing is defined as the ratio of marginal price (P) minus social marginal cost (SMC) over P.

(Pistochini et al., 2022).[10]

Similarly, while analysis of the net benefits of electric vehicles often consider the local air pollution benefits (e.g. Holland et al. (2016)), less attention has been given to the significant non-pollution externalities associated with passenger vehicle use. Typically, the list of major vehicle externalities focuses on traffic congestion, accidents, GHG emissions, and local pollutants (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 that of the air pollutants (Parry et al. (2007)), with the costs of accidents somewhere in between. The GHG emissions have typically been the smallest of the major auto-related externalities, but most studies have used what may be today considered modest social costs of carbon.[11]

EVs already offer GHG advantages in the U.S. that are likely to grow, if not as fast as some would prefer. Many studies find benefits from reductions in local pollution from electrification as well, but there are reasons to suspect those advantages may decline. Emissions of local pollutants are notoriously concentrated in older vehicles, and emissions from newer ICE vehicles that comply with air quality regulations are increasingly small. Further, recent analysis has found that particulate emissions from tire wear is now a larger threat than that from the tailpipes of newer gasoline and diesel powered vehicles (OECD, 2020).

The issue of tire wear highlights a 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 4,500lb Tesla S, to the 6000lb Ford Lightning, up to the enormous 9,000lb Rivian R1T and GMC Hummer. These reflect weights ranging from 1000 to 3000lbs higher than their ICE counterparts.

Vehicle weight plays an important role in tire wear, thereby contributing to the severity of tire-related particulate emissions (Emissions Analytics (2022)). In addition, weight is one of the important considerations in the severity of accidents. Anderson and Auffhammer (2013) found

[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.

[11]For example, while Parry, et al. (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.

that an additional 1000lbs 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 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 et al. (2021)).

4.4 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), 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 lower even in areas with extremely high electricity prices (Borenstein and Bushnell (2022)). To the extent that lower marginal costs spur driving "rebound," the external costs of accidents, tire wear, and traffic will increase, and climate gains will be potentially mitigated. Of course, EVs are not pure substitutes for ICE vehicles and some attribute differences, notably range, may increase the convenience costs of driving. Research on electric VMT is preliminary and the results are mixed,[12] so it is likely too early to conclude that widespread electrification would increase VMT. However, it is certainly a distinct possibility in the long run due to lower operating costs, and during the transition due to government subsidies that are likely expanding the overall size of the vehicle fleet.

Policy influences are of course crucial in this regard. While countries such as Norway have incentivized EVs largely by increasing the costs of owning and using ICE vehicles, the U.S. has applied a combination of tax-credits and other public subsidies for EVs. This latter approach will not only leave existing non-climate externalities unaddressed by electrification, but may very well ex-

[12] Davis (2019) finds 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. **?** find surprisingly low increases in residential electricity use by EV owners, but with substantial heterogeneity by vehicle type.

acerbate 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 (**?**). Such policies, along with a renewed regulatory focus on vehicle weight, or the chemical composition of tires, will likely become more urgent as fleets electrify (**?**), whether we reach 100 percent electrification or not.

5 Conclusions

Of the 97.3 quadrillion Btu of primary energy inputs to the U.S. economy in 2021, less than 40 percent (36.7 quadrillion Btu) went to electricity generation.[13] 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 U.S. economy. While even the most aggressive plans do not forsee electrifying some 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 if "just" of 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. While large uncertainties remain over both the costs and the benefits of such policies, the cost of 100 percent electrification using today's technologies would almost certainly exceed even more extreme forecasts of the social cost of carbon.

Commitments to full electrification therefore represent a bet that technological advancement in the production and distribution of zero carbon electricity dramatically reduces the costs of those activities. For electrification to be the appropriate policy for all applications, this cost reduction would have to exceed those experienced in other low carbon approaches as well as 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 en-

[13] https://www.eia.gov/energyexplained/us-energy-facts/

ergy use is powered by electricity but each of those shares are 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 move to target 100 percent electrification through rigid mandates and bans therefore 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. This risk is greater the shorter the transition period that is imposed. The second risk is the foreclosure of opportunities for more efficient, lower cost pathways to decarbonization that either exist today for some applications or may emerge as broadly applicable as technology advances.

Therefore it is important that policies pursuing zero carbon electrification retain some flexibility either 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 to 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 towards more efficient pricing of services offered by electric utility companies.

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