The Economics of Electric Vehicles

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Abstract

Electric vehicles (EVs) powered by renewable electricity are a centerpiece of efforts to decarbonize transportation. EV advocates also claim benefits from local pollution reductions, lower life-cycle costs to consumers, and improved energy security. We examine the theory and evidence behind these claims and evaluate when the market will produce the optimal path of EV adoption. Optimal EV policy is nuanced. While EVs driven in some locations reduce pollution, they increase pollution in others. While many consumers enjoy cost savings from EVs, some experience net benefits from choosing gasoline-powered cars, even after accounting for EV subsidies. And depending on the dynamic benefits of stimulating EV adoption today, optimal policy might front-load stimulus, even though the environmental benefits of EV adoption are likely to increase over time as electricity grids become cleaner. Reflecting these nuances, the policy landscape is complicated and often creates conflicting incentives for EV adoption in regions with ambitious adoption goals. We highlight several themes for policy design, including 1) promoting regional variation in EV policies that align private incentives with social benefits, 2) pursuing a time-path of policies that follows the trajectory of marginal benefits, and 3) rationalizing electricity and gasoline prices to reflect their social marginal cost. On the extensive margin, purchase incentives should ramp-down as learning-by-doing and network externalities that may exist diminish; on the intensive margin, gasoline should become relative more expensive than electricity (per mile traveled) to reflect cleaner marginal emissions from electricity generation.

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1 Introduction

Policymakers view electrification of the vehicle fleet as a central element to addressing major environmental, transportation and energy policy challenges. States and countries around the world have set ambitious long-run goals to transition away from internal combustion engines (ICEs), with targets for large-scale electric vehicle (EV) adoption[1] or timelines to phase out ICEs entirely.[2] However, EVs are not yet universally superior to ICEs, either economically or environmentally, leading to a complicated landscape of optimal policy.

This paper examines the economic rationale and policy implications of the complex suite of policies that currently affect EVs. Our goals are to clarify three aspects of the economics of EVs. First, we evaluate the private rationale for EV adoption by consumers. In many cases, the operational savings of EVs counteract higher upfront price of purchasing an EV. However, the operational savings of an EV relative to a gasoline-powered vehicle vary substantially across states, and even within states across different utility territories. We document the variation in the private benefits to EV adoption and highlight the role of regulatory policy.

Second, we consider external benefits of EVs that policy-makers offer as a rationale for intervention in the EV market. Potential social benefits of EV subsidies include a reduction in global and local pollution externalities, industrial learning-by-doing, network externalities relating to charging infrastructure, and enhanced energy security. We evaluate the relevance and potential magnitude of these claimed benefits through the lens of economic theory and, when available, empirical evidence.

Third, we discuss what the private and public economics of EVs imply about optimal EV policy. Using efficiency as a benchmark, we describe and assess the current landscape of EV policy. We consider the impact that the suite of existing policies has on private benefits of EV adoption, the degree to which existing policies can be expected to improve or diminish social welfare, and how (and why) current policies might work in concert to spur or to hinder EV adoption.

The latter of these three points is especially important for policy. EVs operate in a space at the intersection of environmental, transportation and energy issues and are viewed as an important element to addressing challenges in each area. Yet, policies to address these challenges are often formed in isolation from each other, leading to policies that may be uncoordinated and, in some cases, conflicting. As an example, high electricity prices that encourage individuals to adopt rooftop solar or make energy-efficient capital investments also make EVs more expensive relative to ICEs. Moreover, even within a single regulatory "silo" such as a public utility commission or department of transportation, policymakers often design EV interventions to satisfy the objectives of multiple stakeholders. Electricity providers, manufacturers, environmentalists, urban planners, consumer groups and environmental justice advocates each see the potential of fleet electrification as a way to achieve different end goals. The rhetoric and details of EV policies often echo this "coalition-building", at the cost of reducing the efficacy of achieving a single objective, like reducing emissions of greenhouse gases (GHGs).

The paper offers several lessons for optimal EV policy:

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[1] For example, Germany aims to have 6 million EVs on the road by 2030. In the U.S., California has also set ambitious targets 1.5 million zero emission vehicles (ZEVs) on the road by 2025 and 5 million by 2030.

[2] Recent pledges to phase out ICEs include those in France and the United Kingdom UK (by 2040), Norway (by 2025), China (2035) and India (by 2030).

1. Some market failures have external costs or benefits that are similar across locations in the US in the short- and medium-run. These included production spillovers, energy security and global climate change mitigation. When equating marginal costs and marginal benefits on these dimensions, a policy that is uniform across locations will likely arise.
2. Other market failures vary by geography, such as externalities arising from local pollution or network effects relating to density of local charging station infrastructure. To address these concerns, a decentralized approach to policy makes sense, and it may be optimal to delegate decision control to state and local authorities.
3. An important temporal component exists in the EV market. There are efficiency reasons to front-load stimulus in the EV market, as well as reasons to ramp the stimulus up gradually over time. To the extent production spillovers and indirect network effects associated with charging infrastructure exist, the dynamic effects of such investment increase the marginal benefits of taking action today. However, the pollution reduction benefits from driving EVs rather than ICEs will likely grow over time, as electricity grids shed coal and add renewables. Presently, an EV charged in the midwestern U.S. generates roughly as much pollution as a comparable ICE, but this is likely to change over coming years and decades. If environmental objectives are paramount, then optimal policy might exhibit spatial differences according to current grid composition and ramp-up incentives as electric grids become less pollution-intensive.
4. Current subsidy levels are difficult to justify based on the cumulative external benefits of environmental, energy security and network externalities relating to charging infrastructure. Economic justification for EV subsidies at recent levels relies on the presence of substantial non-appropriable learning by firms. Unfortunately, it is difficult to estimate the true extent of learning-by-doing, let alone determine the extent of non-appropriability.

In what follows, readers may notice that the order of subsection topics (e.g. discussion of the intensive versus extensive margin) is not symmetric across sections. We begin each section by discussing the topic that seems most salient or important. That the order changes between sections reflects a misalignment between the externalities (which mostly occur on the intensive margin) and existing EV policies (which mostly seek to influence the extensive margin). In Section 2 we discuss the (private) incentives facing consumers who are deciding whether to purchase an EV or an ICE. We then turn our focus to several potential externalities that relate to the production and use of EVs (Section 3), followed by a discussion of what these considerations collectively imply about optimal EV policy (Section 4). Section 5 concludes.

2 Private Economics of Electric Vehicles

Conventional wisdom is that EVs are more expensive to buy and less expensive to operate than gasoline-powered cars. The reality is more complex. In this section we explore the private economics of EVs through the lens of the consumer, separately discussing the three main cost components: up-front cost, operating costs and maintenance costs. We highlight three main takeaways related to the private benefits of EV ownership. First, EVs continue to operate at an up-front cost disadvantage, relative to conventional vehicles, although the purchase price gap between the two is closing as battery costs fall. Second, although for many users, this upfront cost disadvantage is offset by operational cost savings, the extent of these savings vary substantially across states and electric utilities. Finally, the nascence of electric powertrains implies that data on long-term maintenance costs for electric vehicles is still relatively limited – battery longevity and replacement costs remain a source of cost uncertainty.

2.1 Up-Front Cost

EVs are at a manufacturing cost disadvantage due to the need for an expensive battery instead of a cheap gasoline tank. Although battery costs have fallen significantly over the past decade, EVs remain more costly to produce than comparable conventional vehicles. According to Bloomberg New Energy Finance, lithium-ion battery pack prices fell by 85 percent from 2010-2018.[3] Synthesizing academic, industry and government estimates, Tsiropoulos et al. (2018) find disagreement as to specific date when EVs might reach cost-parity with internal combustion engines (anticipated price of roughly $90 per kWh). Although many estimates suggest price parity within the next ten years,[4] other industry participants question whether parity (with regards to both cost and range) will ever be possible with current technology parity within the next 15 years.[5]

In exchange for higher upfront costs, EVs offer a different bundle of attributes from ICEs, arising from the differentiation of the electric powertrain. Some of these difference may be preferred by consumers and reflected in a willingness to pay a premium for an EV. For example, EVs offer superior torque and acceleration, and do so more smoothly (no gears) and quietly (no combustion engine) than ICEs. On the other hand, battery constraints introduce some unappealing features of EVs relative to their ICE counterparts. The driving range of EVs is typically lower than the range offered by ICEs, limiting the usefulness for certain transportation needs (e.g. longer road trips). Batteries take more time to charge than it takes to fill a gasoline tank, even with frontier fast-charging technologies. The present inconvenience of within-trip refueling may be offset somewhat by the advantage of being able to recharge at home for consumers who have access to home charging infrastructure. In fact, the desire to increase the flexibility of EVs for longer trips partially offsets declining battery costs, as automakers increase the vehicle battery capacity to increase range. And major improvements to charging speed might require innovation beyond the current slate of battery technologies.[6]

The novelty of EVs cuts both ways in terms of consumer willingness to pay. For some consumers, EVs present an opportunity to engage in pro-social behavior, and yield utility in the form of warm glow or virtue signaling. For others, novelty may instead represent uncertainty about resale value, battery lifecycle and replacement costs, or availability of ongoing maintenance years into the future for models that may no longer exist. That EVs typically are available with limited trim options may also lead to poor matches with some consumers' tastes, forcing them either to select an EV with a suboptimal bundle of attributes or an ICE. The difference in upfront costs leads to a fundamental policy challenge. Ambitious aspirations for EV adoption are inhibited by the fact that EVs cost more, to which the standard response is to offer government-funded subsidies to bring EVs closer to price parity with conventional vehicles.

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[3] `https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/`

[4] See, e.g., (n.d.) that projects cost parity later this decade.

[5] `https://insideevs.com/bmw-talks-electric-car-cost-nightmare/`

[6] `https://www.bloomberg.com/news/articles/2019-01-06/before-the-electric-car-takes-over-someone-needs-to-reinvent`

2.2 Operating Cost

Conventional wisdom (and EV marketing materials) tout the operation cost savings associated with driving an EV. Yet, these savings can vary substantially across locations. Three factors determine the relative operating costs of EVs versus ICEs: the effective electricity price, the gasoline price, and the effective fuel efficiency of the propulsion system. Depending on these factors, the operating cost savings from driving an EV can be anywhere from positive and substantial to zero or even negative.

In this section we will compare the cost of driving a variety of EVs and ICEs based on relative energy prices (which differ based on time and location) and fuel efficiency (which differ based on car choice). We use average gasoline prices over 2016 by state, aggregated from daily gasoline prices for each state reported by AAA. 2016 electricity prices come from Borenstein and Bushnell (2018), and originally sourced to Form EIA-861. For these calculations, we use the weighted-average fuel efficiency that is provided by the EPA and reflects implicit assumptions about highway versus city driving mileage.

The pattern of variation in electricity prices differs from that of gasoline prices in some important dimensions. First, gasoline prices are closely linked to the global price of crude oil, causing them to exhibit less variation in the cross-section and substantial variation over time. While it is true that gasoline prices can vary across space due to variation in fuel taxes, local environmental regulations or market power, this variation is dwarfed by temporal changes. Since 2005, the average price of gasoline nation-wide has fluctuated from roughly \$2/gal to \$4/gal following crude oil prices. In contrast, state-level gasoline price variation (with the exception of California) is generally within thirty to fifty cents per gallon.[7]

In contrast, retail electricity prices differ by utility district, mainly due to regulator decisions about whether to recover fixed costs via a fixed charge or by distributing them into variable rates and due to regulatory decisions covering cost recovery. Difference can be substantial - as in illustration, the top marginal retail electricity price for residential consumers in Pacific Gas and Electric's service territory (which covers West Sacramento) was 40 cents per kWh, almost four times higher than the 11.4 cents per kWh rate for a residential household living in the Sacramento Municipal Utility District service territory. Moreover, differences may appear both *between* and *within* utility districts. The EV customer in Pacific Gas and Electric's territory could either be on a time-varying EV rate or on a time-invariant increasing block rate, and this distinction can dramatically change the operating cost differences experienced by different consumers. Likewise, the increasing block usage thresholds differ by climate zone, again affecting the probability that a household finds itself on the highest rate tier when charging. Throughout this section we will be clear about which rate is being used for comparison.

Figure 2 shows the annual fuel savings enjoyed by a Nissan Leaf owner as compared to an identical owner (in terms of vehicle-miles travelled and driving behavior) of other popular vehicles. Vertical lines represent various electricity prices across the country, including different tiers at a major California utility, Southern California Edison. As one would expect, private savings from driving an EV are decreasing in the electricity price and increasing in the fuel intensity of the comparison gasoline-powered vehicle. The main observation here is that the range of savings resulting from actual differences in electricity prices could be substantial –

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[7] See, e.g., tax-inclusive gasoline prices reported by the Energy Information Administration at `https://www.eia.gov/dnav/pet/pet_pri_gnd_a_epmr_pte_dpgal_w.htm`

roughly $1,000 per year in savings for someone in Texas or Georgia who is choosing between a Leaf and a Toyota Camry (the most popular light duty car in the U.S.) – or slightly negative for customers with prices on the top SCE residential tier in California.

Actual savings will fluctuate to reflect changes in gasoline prices. For a decision between the Nissan Leaf and the Nissan Versa, these differences can be seen in Figure 3. Diagonal lines reflect gasoline prices at $2, $3 and $4/gallon. A $1/gallon increase in the gasoline price translates to $300/year in savings from switching to an EV. Horizontal placement on the graph reflects the effective electricity price for charging. For an EV owner in LA who's on the lowest residential price tier, the three dots show how savings will change over time, both due to changes in electricity rates and in the gasoline price. The differences can be substantial. While electricity prices didn't change much during that period, gasoline prices declined substantially from 2014 to 2016 before increasing substantially from 2016 to 2018. Those gasoline price changes are enough to change annual operating costs of an ICE as much as going from a Nissan Versa to a Ford F150 pickup truck.

Operational cost savings can influence consumers' decisions about which car to buy. To the extent EVs are cheaper to operate than ICEs, and to the extent that consumers are aware of these savings and incorporate them into their purchase decisions, one would expect the rate of EV adoption to be high. Evidence from the literature on gasoline car adoption tends to support the hypothesis that consumers value future cost savings at their time of purchase. When gasoline prices are high, consumers buy more hybrid cars and fewer SUVs. This intuition is tested and supported in Busse et al. (2013), Allcott and Wozny (2014), and Sallee et al. (2016). Yet, whether consumers incorporate electricity prices to a similar extent remains an open question. But, any results would need to be placed into the context of consumers who may experience range anxiety or envision the utility of EVs to be different from or complementary to ICEs. As an example, Davis (2019) documents the substantial gap between vehicle-miles traveled (VMT) in EVs as compared to ICEs - if EVs are driven less than conventional vehicles, on average, traditional estimates may overstate the potential benefits from driving an EV.

2.3 Maintenance

EVs have fewer moving parts than vehicles relying on an internal combustion engine. As a result, conventional wisdom is that EV owners will enjoy lower regular maintenance costs. A forward-looking buyer would rationally incorporate this benefit into his or her purchase decision. Yet, the short history of EVs limits our observable experience with maintenance costs, especially when considering larger, discrete maintenance expenses that are likeliest to occur as the vehicle ages. There are several papers that describe the differences between EV and ICE costs, but the quantitative aspects of these studies relating to maintenance appear to be either purely assumption-driven or based on references that we have not been able to track to an original source. Instead, we describe qualitative differences in ongoing maintenance costs before presenting new data from recent but imperfect sources.

There are three main categories of ongoing maintenance costs of cars: costs unrelated to engine technology, ongoing maintenence of the engine and/or drivetrain and major component replacement. The first category includes ongoing maintenance costs, such as insurance, tire replacement, electronics system repair, body work resulting from ambient conditions (e.g. salt in the wintertime). We see no reason why these costs would differ based on engine type, at least conditioning on driver behavior and vehicle replacement value.

But, the other two categories of maintenance costs will differ. For ICEs, ongoing engine maintenance relating to internal combustion is significant. Oil and filters need changing, along with spark plugs and other components in the ignition system. The simplicity of an electric drivetrain eliminates these costs.

The final category of costs – major component replacement – is experienced by cars with both engine types. EVs have batteries that are expensive and need to be replaced. While costs have declined significantly in recent years, replacing a battery still costs thousands of dollars. Whether the car owner pays for this directly or through a manufacturer's warranty, it is a substantial cost that is unique to EVs. On the other hand, ICEs don't have expensive batteries, but have transmissions and gear-boxes that eventually wear out and need to be replaced. Moreover, the presence of regenerative braking in EVs dramatically extends the usable lifespan of brake pads, also reducing costs for EVs relative to ICEs.

We now shift to the available data on costs. As noted above, battery replacement costs are large and have been declining rapidly over time. At the moment, the pack price-per-kwh is roughly $150. At this price, a 30 kwh capacity battery (roughly the size of a Nissan Leaf battery) would be $4,500, and a 75 kwh Tesla Model 3 battery would cost $11,250. The ICE analog of battery replacement is perhaps transmission replacement. A remanufactured transmission replacement costs in the range of $1,100 to $3,400.[8] This is no doubt higher for luxury brands. The point is, replacing a transmission has costs roughly the same order of magnitude as a battery replacement may cost to EV drivers in a few years.

What does the evidence say about costs overall? The best evidence that we were able to find on overall relative EV and ICE maintenance costs is from the Consumer Expenditure Survey. In the 2018 CES, there are only 23 EVs of model-year 2013 or later, as compared to over 23,000 ICEs. Over the first five years of ownership of these cars, ICEs and EVs had statistically indistinguishable average maintenance costs of $200 and $224, respectively. While these statistics don't appear to align with conventional wisdom, they are also the best available source, to our knowledge.[9] Moreover, the sample underpinning ICE maintenance costs is large, and these numbers can be viewed as credible. They are also small in magnitude, particularly when compared to fuel and electricity costs. Even if EVs were to halve the maintenance costs of ICEs, that would save drivers just $100 per year. Finally, these aggregate statistics gloss over information about intensity of use. EVs are driven substantially less than ICEs, and one may consider maintenance costs on a per-mile basis as being more relevant than maintenance costs per year.[10]

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[8] `https://www.transmissionrepaircostguide.com/`

[9] New York City released a report in 2019 (REFERENCE) about relative EV versus ICE maintenance costs in its vehicle fleet. In it, the reported annual amount spent on ICE maintenance was $1,286 as compared to $317 for EVs. However, this is not an apples-to-apples comparison. Their EVs were brand new (purchased in 2018), while the ICEs were bought in 2017 or earlier. Also, while the "estimated mileage" of both car types was the same, the use of vehicles was not reported and could have been different.

[10] Davis (2019) reports statistics from the *2017 National Household Travel Survey* that reveal annual average EV miles driven is 6,300 as compared to 10,200 for ICEs.

3 Market Failures in Electric Vehicles

Externalities arise when decision-makers do not internalize the full social costs (or benefits) of the decisions they make. The presence of externalities (both positive and negative) are regularly offered as justification for government intervention in the EV market, by po policymakers, industry participants and EV advocates. In this section, we describe the main externalities that might relevant, grouping the externalities into those created by the operation of EVs (the "intensive" margin) and those arising from the production or stock of EVs on the road (the "extensive" margin). For each of the externalities, we consider the efficiency rationale for policy - specifically, whether a price-based intervention, such as a tax or subsidy, might be a way to address a market failure.

3.1 Usage-based "Intensive" Externalities

3.1.1 Carbon Emissions

Greenhouse gas emissions from electricity generation, much like local pollutant emissions, vary based on timing and location of electricity demand. Unlike local emissions, however, GHG emissions contribute to a global stock that diffuses in the atmosphere and diminishes slowly with time. The methodology to compare the GHG footprint of EVs to ICEs is similar to the methodology described in the previous section. Graff Zivin et al. (2014) were the first to estimate the marginal emissions factor of EVs, articulating the (correct) intuition that marginal emissions may be very different from inframarginal emissions. That distinction is worth describing in some detail.

The electricity generation sector is comprised of many different technologies: wind, solar, hydro (run-of-river and dammed), nuclear, and various fossil fuel technologies such as coal, natural gas (combined-cycle gas turbines, combustion turbines) and even some petroleum "peakers". What matters when attributing pollution to a marginal additional load source like an EV is which generator "turns on" or ramps up production when demand increases. It cannot be the case that the marginal supply comes from a technology that would be producing electricity irrespective of whether the EV is plugged in. The marginal supply must be, almost by definition, "dispatchable"; i.e. it must be a source that can be turned on or off depending on market conditions. Typically this rules out intermittent sources of renewable supply such as wind (which produces when the wind is blowing, irrespective of demand conditions) or solar (which produces when the sun is shining, irrespective of demand conditions).

For EVs, Graff Zivin et al. (2014), Archsmith et al. (2015), and Holland et al. (2016) all use variants of a methodology that attempt to empirically estimate the emissions profile of generators that "are on the margin". Archsmith et al. (2015) extend that methodology to allow renewables (such as dammed hydro) to be part of the marginal supply mix. They also include upstream ("life cycle") emissions that are associated with the extraction and transportation of inputs.[11] Ambient temperature is also an important determinant of the efficiency of EVs, both due to declines in charging and discharging efficiencies experienced in very cold temperatures. Tamayao et al. (2015) runs scenarios that assume a range of potential emissions factors as the

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[11] While natural gas is the cleanest fuel at the point of combustion, it has a much higher upstream emissions factor than coal or gasoline. Coal, by comparison, is often extracted very close to its point-of-use, and is transported quite efficiently from a GHG perspective.

basis for the EV side of the EV-ICE comparison. The GHG profile of ICEs depends mainly on features of the car and driving patterns, but there is less heterogeneity in fuel source. Life cycle emissions of gasoline have been studied extensively and vary primarily based on the location and extraction technology of the crude oil inputs.

The conclusions of the above studies are qualitatively similar. EVs tend to provide some GHG savings relative to ICEs in areas where natural gas is on the electricity generation margin, but tend to be more GHG-intense if coal is on the margin. GHG emissions from EVs are substantially higher in areas with cold winters, which in the case of the midwest U.S. coincides (at present) with a higher likelihood of coal being the marginal generation fuel. Archsmith et al. (2015) estimate that a Nissan Leaf generates roughly $425 worth of life cycle GHG savings when driven in California instead of the Nissan Versa, its ICE equivalent. That's a 20 percent life cycle GHG savings in California, compared to 5 percent nationwide and -10 percent in the midwest, each of which is consistent with results from Graff Zivin et al. (2014), Tamayao et al. (2015), and Holland et al. (2016).

One challenge with retrospective analyses in this context is the dynamic nature of electricity supply and EV technology itself. As the electricity generation sector moves away from coal and towards renewables (potentially with storage) and natural gas, the GHG profile of electricity supply will improve. Moreover, improvements in EV technology may improve energy efficiency of the electric drivetrain, particularly in cold temperatures, thus reducing GHG emissions conditional on any source of electricity generation. While this vision is appealing and may represent one of the most promising avenues to widespread decarbonization of developed economies, we are far from a situation where EVs are powered by renewable electricity. Regional policy-makers should monitor marginal emissions factors in their regions, and national and international policy-makers should acknowledge the spatial heterogeneity in potential benefits and costs of promoting EVs. For example, at the moment it is counterproductive to subsidize EVs in regions where coal is on the margin, such as the midwest U.S. Moreover, arguments relying on economies of scale, learning-by-doing or market transformation must be tempered by the possibility that environmental damages of EVs when fueled by coal exceed the damages from ICEs. Scale-related benefits, which we discuss in section 3.2, will be most efficiently achieved by promoting EVs in areas where they provide benefits rather than costs.

3.1.2 Local Pollution

Combustion of fossil fuels contributes, directly and indirectly, to the stock of harmful pollutants in the air. These pollutants inflict damage to valuable resources such as human health, the built infrastructure, crop yields and the ecosystem. Human exposure is the primary driver of damages, and this leads to two main factors that affect the extent of local pollutant damage: the quantity and type of fuel combusted and its proximity to population centers in relation to wind patterns. These two factors suggest considerable potential differences in the local emissions impacts of gasoline-powered cars as compared to EVs. Combustion of gasoline occurs at the location of the car when it is driven, thus exposing the population to pollutants in proportion to population and traffic density. In contrast, the combustion associated with EV propulsion is disconnected from travel in both time and space.

As with carbon emissions, the local pollution associated with charging an EV depends on the emissions of the marginal generating unit, the unit that would not have otherwise been generating electricity had the EV not been plugged in. Typically in the United States, the marginal generation source will be coal or natural gas due primarily to the ability to expand production on demand. In 2018, roughly 63 percent of electricity in the United States was generated from either coal or natural gas, down from 70 percent in 2014.[12] To the extent EV-induced fossil generation occurs in close proximity to population centers, it may expose people to health damages that exceed those from driving gasoline-powered cars. But, due to the spatial integration of electricity markets, the marginal generating unit could be geographically distant from the EV as well. So, the maximum local pollution benefit to driving an EV (relative to ICE) will occur when the car is located in an already-polluted and densely populated area, and where the marginal electricity generating unit is either clean (e.g. dammed hydro or natural gas) or located far from population centers.

This intuition is reflected in Holland et al. (2016), who assess the local environmental benefits of EVs relative to ICEs. Large benefits accrue to driving EVs in cities where the ambient air quality is poor and where the electricity grid is powered by relatively clean electricity (e.g. Los Angeles, California). Where coal is likely to be on the electricity generation margin and is upwind of population centers, driving EVs can actually increase net local pollution (e.g. the entire U.S. midwest, northeast and southeast).

Pollution has also been linked to many potential channels of social harm, including decreased labor productivity (Graff Zivin and Neidell (2012) and Chang et al. (2016)) and impaired cognitive performance (Archsmith et al. (2018)). It is challenging to incorporate all channels in analyses such as Holland et al. (2016). Nonetheless, policymakers have long recognized the importance of pursuing reductions in ambient air pollution. These efforts have combined with market forces to contribute to substantial changes in the composition of the electricity generation sector in recent years. Relative to past, recent estimates suggest a reduction in the local pollution impacts of electricity production (Holland et al. (2020)). This research suggests that, even in the very recent past, the relatively poor record of local pollution from upstream EV emissions is improving. As the electricity grid continues to become cleaner, EVs will as well. However, criteria pollution rates from ICEs is not static either. Fuel economy is improving conditional on vehicle mix, although composition of the fleet continues to shift towards more fuel-intense vehicles (SUVs and light trucks).

Despite EVs receiving the label "zero-emissions", that is currently true only at the tailpipe, even after accounting for the rapid growth in renewable electricity generation. Policy-makers must consider both tailpipe emissions and the effects of EV-induced upstream combustion when assessing the extent of true local damages. EVs should be promoted on the basis of local pollution benefits to the extent that overall harm is reduced by the shift from ICEs to EVs. This may at times place the incentives of local policymakers (who care about local pollution in their city) at odds with those of regional policymakers (who care about the air quality near a potentially-large number of upstream electricity generation facilities). Moreover, optimal policy will vary over time and space according to the composition of the grid and the proximity of people to emissions sources. Local pollutant benefits of EVs are greatest in dense urban centers where the electric grid is clean such as Los Angeles and other cities in the western U.S. In contrast, in locations where the marginal unit of electricity comes from more pollution-intensive sources or from sources upwind of major urban areas, local pollution benefits are low

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[12] U.S. Energy Information Administration

or even negative.

3.1.3 Congestion and Accidents

Drivers exert additional negative externalities by increasing congestion or through accidents. While both externalities relate primarily to vehicle miles travelled, congestion externalities are magnified in heavily trafficked routes during congested periods of time and the externalities imposed by a driver is positively correlated with the weight of the vehicle driven.[13] To a first-order approximation, replacing an EV with an comparable ICE should have relatively little overall impact on the externality. But, some policies designed to encourage EV adoption, such as single-occupancy access to HOV (carpool) lanes, might impose externalities by reducing the utility of these lanes. In addition, there is growing evidence of portfolio effects, as suggested by Archsmith et al. (2017), within a household's set of vehicles. If marginal households purchasing EVs also tend to purchase larger vehicles in an attempt to diversify the portfolio of vehicles-owned, incentives to encourage adoption may increase the dispersion of the vehicle fleet weight distribution and increase accident externalities.

3.1.4 Energy Security

We follow Metcalf (2014) by defining energy security as "the ability of U.S. households and businesses to accommodate disruptions of supply in energy markets."[14] Energy security advocates express concerns about the level of imported energy, mainly crude oil. Traditionally, there are two sources of these concerns. First, much of the global crude oil supply comes from nation states with geopolitical interests that may be in conflict with or not well-aligned with U.S. interests. Concerns arise from the idea that U.S. oil purchases enrich these potential adversaries, and that the pursuit of U.S. interests will be compromised as a result. Second, there is a precautionary concern relating to potential wartime scenarios. In the event of a global conflict, the U.S. may not have control over valuable key energy inputs, and therefore would be practically or strategically impaired by supply disruptions. Separately, energy security is often also bundled into advocacy narratives that favor clean energy technologies despite there being no a-priori reason why energy security interests are furthered by clean energy, or vice versa (Borenstein (2012)).

Widespread substitution away from gasoline-powered vehicles towards EVs would reduce reliance on crude oil in favor of electricity and, by extension, the inputs that generate electricity. Implications for U.S. energy security are in flux as a result of the U.S. becoming a major oil and gas producer. In 2017, the U.S. energy production was roughly 90 percent of energy consumption, and net U.S. energy imports reached their lowest levels since 1982 and are rapidly declining.[15] As a result, energy security interests may now be less relevant than ten or twenty years ago or, to the extent they remain relevant, they may be at odds with the interests of domestic oil and gas producers. We briefly mention several interesting considerations at the nexus of energy security and EV-induced demand reductions for gasoline in the U.S.

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[13] Weight-based externalities are well documented in Anderson and Auffhammer (2013), Jacobsen (2013), and Bento et al. (2017)).

[14] The Congressional Budget Office 2012 adopts a similar definition, from which Metcalf's is derived.

[15] `https://www.eia.gov/energyexplained/?page=us_energy_home`, `https://www.eia.gov/todayinenergy/detail.php?id=35532`

Domestic considerations. The shale revolution has transformed the way that the U.S. interacts with global oil markets. For the last several decades, the U.S. has imported between five-to-ten million barrels per day (BPD) of crude oil and, until very recently, has exported roughly zero.[16] Since 2014, U.S. crude oil exports have increased from nearly zero to over three million BPD, while at the same time maintaining import levels at roughly 7 million BPD. The U.S. is therefore becoming increasingly petroleum-independent. It remains both an importer and exporter of petroleum because different refiners specialize in processing particular crude streams, and there are substantial differences in the type of crude available in different locations. The U.S., for example, tends to produce light crude but has substantial refinery capacity intended for heavy crude. Changes in refining technology in recent decades have shifted the fraction of imports towards Canada and Mexico, and away from the Middle East. Nonetheless, heavy and light crude are traded in a global marketplace that links their prices according to supply, demand and the ability to substitute between them.

As VMT shifts away from gasoline and towards electricity as the power source, it reduces domestic demand for gasoline, a co-product produced by refining petroleum. This will create both level and compositional pressures in the market. At a time when petroleum supply in the U.S. is expanding, a decline in oil demand will cause the U.S. to import less and export more, placing downward pressure on the global oil price. This highlights the contrasting effects on energy security proponents (who would applaud such a shift) and owners of crude oil reserves (whose assets are worth less in such a scenario).

The compositional implications are also potentially interesting. Conditional on refinery design, the refining process will convert crude inputs into products such as lubricants, jet fuel, diesel, gasoline, etc. in roughly fixed proportions. As demand for one of these co-products shrinks, the quantity margin of adjustment is constrained due to the Leontief nature of refining outputs. One might then expect either a glut of gasoline at very low prices and/or an increase in the price of the other co-products (or both).

Global considerations. The global implications of the current energy boom in the U.S. are expansive. One of the primary concerns articulated by energy security advocates relates to geopolitical stability, and it is unclear to these authors whether a glut of crude accompanied by very low global oil prices improves or diminishes stability. On one hand, under that scenario oil-rich countries would experience a significant decline in their financial resources. This may inhibit their ability to pursue interests that conflict with those of the U.S. On the other hand, one could argue that the wealth derived from oil resources has facilitated political stability within oil-rich countries. In a counterfactual world with lower oil prices, these countries may find it increasingly difficult to meet the expectations of their citizens, potentially planting seeds of civil unrest along the lines of what led to the Arab Spring.[17]

While admittedly outside of the scope of energy security, there may also be global environmental consequences stemming from this U.S. shift. As global oil prices fall, cleaner energy substitutes will become increasingly (relatively) expensive. Fast-growing emerging economies faced with a decision between these energy alternatives will increasingly be tempted to choose oil-derived fuels. This "macroeconomic rebound effect" is discussed in Gillingham et al. (2016)

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[16] For a sense of scale, the U.S. consumed an average of just over twenty million BPD of petroleum in 2018 and is steadily increasing.

[17] While many of the grievances of Egyptian protesters centered on political freedom and state abuse, economic factors (high unemployment, food-price inflation and low wages) played an important role.

in the context of energy efficiency standards, and the logic extends to this setting.

3.2 Stock-based "extensive" externalities

The stock of EVs or charging stations might also generate external benefits, such as learning-by-doing, knowledge spillovers in production, or network effects related to charging infrastructure. These types of benefits are notoriously hard to separate from economies of scale that arise from contemporaneous production or models of graduate technological diffusion without meaningful externalities. Yet, economics provides some guidance as to the conditions under which they are likely to be relevant for EV policy. Broadly, we categorize these spillovers along two dimensions: (a) whether the benefits that accrue can be appropriable by the firm, and (b) whether the benefits arise from the global stock of vehicles or the stock of vehicles operating in a local region.

We focus our attention on four potential ways in which the production volumes might generate impacts: (1) network externalities related to the stock of EVs and the charging station network, (2) learning-by-doing and within-firm economies of scale, (3) spillovers in production knowledge within the industry, and (4) spillovers arising from the use of shared (e.g., battery) technology.

3.2.1 Learning-by-doing and within-firm economies of scale

Learning-by-doing reflects potential benefits from experiential learning on a firm's production. In the classic sense, learning-by-doing describes a number of different mechanisms that share the same outcome; as the firm's cumulative production experience increases, its future production costs fall. The firm might refine its production process; its workers might become more skilled; or it might develop gradual expertise in managing inputs. In each of these cases, as the firm's cumulative experience in the past allows it to produce units at lower cost *in the future*.

Learning-by-doing is distinct from economies of scale, whereby a firm's production costs decline with *contemporaneous* output. With economies of scale, the cost reduction might arise from higher volumes allowing the firm to, for instance, better manage inventories or negotiate more aggressively over the cost of inputs.

Empirically separating economies of scale from learning-by-doing is challenging. In many settings with falling costs, production increases over time as does cumulative production experience. To our knowledge, no one has quantified the extent of learning-by-doing for EV manufacturers, although learning-by-doing has been documented in other manufacturing industries, most notably by Benkard (2000) in the context of aircraft manufacturing.

Despite the difficulty in empirically distinguishing the two mechanisms, learning-by-doing and economies of scale share an important feature for policy. The benefits of both accrue *internally* to the firm. If a firm's cumulative experience or contemporaneous production rises, it is able to reap the benefits of lower costs. Here, there are no external benefits that are left uncaptured by the firm making production decisions that might naturally motivate subsidy to encourage (in this case) production. So long as the firm has access to well-functioning capital markets and there are no other market failures that prevent the firm from capturing the benefits, learning-by-doing and within-firm economies of scale are not market failures and thus do not justify intervention from the perspective of economic efficiency.

3.2.2 Spillovers across firms

In contrast to learning-by-doing, spillovers reflect benefits from production or cumulative experience that extend beyond a firm's boundaries. Importantly for policy, spillovers generate benefits external to the firm, and hence might justify policy to encourage production or adoption. However, the nature of the spillovers plays a central role in whether government intervention is appropriate and, if so, the appropriate magnitude of such an intervention. In what follows we distinguish between spillovers in production techniques that accrue within the EV manufacturing sector and spillovers that accrue as a result of shared technology across different end-uses (e.g., lithium-ion batteries).

Productivity gains associated with production of vehicles may arise from labor specialization, agglomeration of EV manufacturers and parts manufacturers or cumulative production experience. As with within-firm learning-by-doing, empirical quantification of these benefits is difficult. Nonetheless, even in cases where the benefits from labor specialization might be large, estimates of the impact of cumulative industry experience are modest. Thornton and Thompson (2001) estimates the within-firm benefits of experience exceed the external benefits of cumulative industry experience by an order of magnitude for liberty ships, a setting where we might expect the benefits of labor specialization to be relatively large. While knowledge spillovers in production might also exist within the auto industry, to the extent that labor specialization or production expertise arise from the production of all vehicles, the benefits of this set of spillovers have likely been captured over the past century of manufacturing experience.

Meaningful spillovers may plausibly arise as a result of either innovation or "external economies of scale" described by Bartelme et al. (2018) for shared technologies, such as batteries. Transportation is the most quickly growing sector of the battery market, and in recent years has rapidly outstripped consumer electronics as the main user of Lithium-Ion batteries. Focusing on just that battery technology , Tsiropoulos et al. (2018) documents a 26% annual growth rate over 2010 - 2017, with the lion's share of the growth coming from the transportation sector. In 2010, virtually all Lithium-Ion battery production (measured in total battery capacity) was for consumer electronics. In 2017, 60% of Lithium-Ion battery production was deployed in EVs. At the same time, production costs have fallen significantly, from over $400 per kWh of storage capacity in 2013 to under $200 per kWh in 2017. Future projections, summarized in Tsiropoulos et al. (2018), disagree as to specific date when EVs might reach cost-parity with internal combustion engines (anticipated a price of roughly $90 per kWh), but even the least optimistic forecasts suggest cost parity within the next 15 years.

Battery production and use, spurred by deployment in EVs, may plausibly foster innovation in battery chemistry, characteristics or costs. These innovations might consequently increase the value of batteries for EV manufacturers or for manufacturers that use rechargeable batteries for other uses, such as consumer electronics. In fact, there is a long history of beneficial innovations within the battery industry, whereby innovations that improve battery operation for one use are subsequently adapted for other uses. Despite the needs of different battery-powered electronics, many common innovations, such as energy density, the ability to quickly recharge and battery longevity are valued for many different uses. Central to arguments justifying intervention on these grounds is that the benefits of such innovation accrue external to the firm identifying the innovation. If battery producers are able to capitalize the innovation through intellectual property, they face efficient incentives to engage in research and development. Even if the capture of intellectual capital is imperfect, it is unclear whether offering incentives for EV adoption are the most cost-effective strategy for stimulating battery (or other technological) innovation - inframarginality of EV buyers blunts the efficacy of incentives to stimulate innovation.

3.2.3 Charging Infrastructure and Efficiency

Network effects arise when increases in the existing stock of a good leads to an increase in the value of the good to prospective consumers. Network effects may be "direct" or "indirect". In the context of EVs, direct network effects exist if the marginal utility of an EV owner is increasing in the number of other EV owners, whereas indirect network effects might arise through the availability of an important complementary good: charging infrastructure.

Charging infrastructure takes two forms. Level 2 chargers supply 220V and can allow for charging at a rate of up to nearly 20kW, though most Level 2 charging stations max out at a third of that level. The fixed cost associated with installing these stations is modest (on the order of several thousand dollars) as are distribution utility requirements to update transformer and delivery infrastructure. Level 2 chargers are already commonplace – as a point of reference, roughly 57,000 level 2 charging stations have been built in California. They are typically constructed in locations such as parking lots, commercial and retail locations and multi-unit apartment buildings. In contrast, fast-charging (or Level 3) stations supply the fastest re-charge available today. They cost in the range of $100,000 and can provide a nearly full charge in under 30 minutes. Fast-charging stations are more likely to be built along highways to facilitate longer-distance trips between cities.

It is unclear whether market failures arise in this context. As in the case of learning-by-doing, network effects do not inherently imply a market failure. Just as firms might appropriate the benefits of learning-by-doing, benefits of network effects may also be captured by firms. For example, Microsoft benefited from enormous network effects, but the market failure that arose was due to market power, not the inability of Microsoft to internalize the benefits of the network effects. In this setting, one such example is Tesla's charging network. Tesla's network for fast-charging stations provides a unique benefit to buyers of Tesla vehicles, and as such, Tesla has every incentive to build out the charging station network optimally.

However, network externalities may arise when multiple technology platforms exist (such as the different charging standards used by EV automakers), or if market participants are unable to internalize the benefits that arise from the network effects. In the case of the former, there are currently three "standards" for fast-charging connectors adopted by EV automakers: CHAdeMO, Combined Charging System (CCS) and Tesla.[18] To the extent that standards are incompatible, governments have long played a regulatory role in aligning standards.[19] Yet, in some cases, market forces create strong incentives to achieve compatibility and obviate the need for government intervention.[20] For EVs, automakers want to design vehicles that are either compatible with a prevailing standard or to offer adapters to allow their vehicles to used across charging platforms. As one such example, the version of the Tesla Model 3 sold in Eu-

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[18] Broadly, Asian automakers have used CHAdeMO and U.S. legacy and European automakers have used CCS.

[19] Classic examples include voltage regulation and infrastructure standards for electric utilities.

[20] Li (2017) simulates the welfare impacts of standardizing the charging platform, finding that standardization increases welfare through both increased adoption and a more cost-effective charging network.

rope is built with a CCS connector so as to allow owners to take advantage of the existing fast-charging network.

Market participants can be expected to internalize the benefits of network effects so long as there are low barriers to entry and firms are able to achieve sufficient scale. To illustrate this point, consider the case of a firm owning a single fast-charging station along an interstate. The number of EVs (and the profits of that charging station) depend on the density of the broader network, and specifically, on whether there are other firms that build fast-charging stations along the same interstate. Here, a meaningful network externality might exist. Yet, a large well-capitalized entrant will build at a scale that internalizes these network effects by, for example, constructing a string of fast-chargers along a route. Market forces will strongly push towards the latter outcome. Tesla's supercharger network provides one such example. Economists do not traditionally view economies of scale as a market failure as firms have every incentive to achieve necessary scale. Simply the presence of network effects in this industry are neither necessary nor sufficient conditions for market failure.

However, there may well be multiple equilibria in this industry, which has implications for potential market failure. Consider the discussion in the previous paragraph as being local (in an equilibrium sense) to current supply and demand conditions. An alternative equilibrium may exist which a far higher level of both EV adoption and charging infrastructure. A market failure exists if welfare is higher at the alternative equilibrium and if a hurdle exists that inhibits the market from reaching that alternative. We can't reject whether such a high EV - high charging equilibrium exists, and indeed, it very well may. However, there is little empirical guidance to inform us as to whether welfare is higher or lower in such an equilibrium. The environmental benefits would certainly be high, but the cost to build out the charging network and transform the electric grid will also be high. The relative magnitude of these costs and benefits is highly uncertain. One source of uncertainty comes in the form of foreclosing future potential climate solutions. Over-building infrastructure will reduce the expected benefits of exploring alternative transportation emissions mitigation pathways, such as hydrogen, direct air capture, cellulosic ethanol, other yet to be identified technologies or even re-envisioning the role of cars in the urban environment.

4 Current Policies and Economic Efficiency

EVs exist at the intersection of transportation, energy and environmental policy, and as such, EV policies attempt to address potentially-numerous objectives. In this section, we discuss how the interconnected transportation, environmental and energy policy landscapes relate to the private and public economics of EVs. We will assert that market failures are the legitimate justification for government interventions that strive to improve market outcomes. We will describe many of the most prominent EV-related policies and then discuss the extent to which they can (or cannot) be justified on the grounds of correcting market failures. Distributional objectives are also important, and although they fall outside of the purview of economic efficiency, we will touch on them as well.

We begin by discussing optimal policy from the perspective of addressing market failures from the previous section that might justify intervention. We then provide an overview of the current policies in place and highlight how the suite of existing policies spur, or in some cases hinder, EV adoption and affect the economic efficiency of outcomes.

As described above, externalities arise when decision makers do not internalize the full social costs (or benefits) of the decisions they make. Typically, economists focus on pricing as the most direct way to correct externality-driven market failure, with the goal of inducing the decision-maker to incorporate the social costs or benefits associated with different courses of action into his or her decision. Before discussing the role that taxes and subsidies might play in addressing potential externalities, we highlight three broader lessons that are common across the externalities from the previous section.

First, an externality only arises when the benefits of an agent's decision accrue to other parties. If the agent is the residual claimant on the benefits of deploying an additional EV, there is no externality-based market failure and no justification for a production or sales subsidy. For example, if learning-by-doing in production accrues entirely within the boundaries of the firm, then a forward-looking firm will anticipate the benefits and fully-internalize the additional learning benefit from production. Similarly, one commonly stated rationale for subsidies are to help automakers achieve necessary economies of scale in production. However, absent a clearly articulated reason why a sufficiently-capitalized firm wouldn't avail itself of economies of scale, there is no market failure that would justify subsidies. In contrast, if the learning-by-doing creates spillovers outside the firm, arising perhaps from a labor force that moves between automakers or intellectual property that benefits all automakers, subsidies might play an important role in leading firms to produce the socially optimal quantity. Network externalities create similar spillovers if, as fleet size increases, charging station infrastructure is further developed. Here the private economics of the consumer's decision fail to capture the broader benefits from a growing EV fleet.

The second point related to the intertemporal nature of subsidies. As discussed above, network externalities and production spillovers on the extensive margin, to the extent they are relevant, likely exhibit diminishing marginal returns.[21] This suggests that if initial subsidies are justified, the subsidies should taper as the external benefits of production or purchase diminish in magnitude.

Finally, the externalities described above vary with regards to their spatial scope. For those where the externality extends across a wide set of geographies or firms, a one-size fits all policy might be appropriate. For example, if meaningful spillovers exist with respect to production experience or intellectual capital, it doesn't necessarily matter whether EVs are produced in location A or location B. But, for others, local variation in the external costs or marginal benefit of abatement suggest decentralized policy might be much more effective. Network externalities depend on the local confluence of EVs and charging stations, and in such a case decentralized policy is likely a better match with the local externalities created by EV fleet expansion. As an illustration, if the effects of adding additional charging stations or EVs in a "saturated" market like the San Francisco Bay Area are modest, resources that encourage firms or consumers in these areas to further expand EV adoption might be unjustified on network externality grounds. Or the addition of an EV to a location where the external costs of local pollution are relative high might be preferable from a welfare perspective.

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[21] Benkard (2000) and Thornton and Thompson (2001) document diminishing marginal returns in aircraft and shipbuilding manufacturing to experiential learning. Similarly, early adoption of EVs might spur charging station investment (and vice versa as suggested by Li (2017) and Springel (2017)), but the marginal external benefits decline as fleet size increases or charging stations become pervasive, the external benefits decline.

In light of the three points above, we can evaluate the role of policy to address externalities on the "intensive" and "extensive" margins. Externalities on the intensive margin arise from how much an EV is driven, and when and where that driving occurs. Pollution externalities are a function of the relative pollution intensities of EVs and traditional vehicles.[22] Although the GHG contribution of a conventional vehicle is space-invariant (the same ICE vehicle emits the same amount of carbon whether it is located California or Minnesota), the GHG contribution of an EV depends on the marginal carbon-intensity of electricity generation in that area. Likewise, the impacts of local pollutants depend on the size of the impacted population. In the simplest case, if consumers are well-informed, the most direct intervention would be to tax the externality-generating outcome at marginal external cost, since these costs would vary, so does the optimal price. In the case of a carbon externality, we would tax gasoline and electricity based on their relative carbon-intensity. In doing so, the "tax" on electricity used by an EV would not only reflect carbon-intensity of the regional electricity grid, but also diminish as the electric grid shifts toward lower-carbon forms of generation. Local pollutants suggest localized policy to tailor the fuel taxes the externalities imposed on the local community. For local pollution, the two products would be taxed at the marginal external costs generated by either the tailpipe emissions from the conventional vehicle or the emissions from the marginal electricity generating plant, again varying locally depending on the population impacted.

The optimality of a tax as a policy instrument assumes that consumers are well-informed about fuel prices and forward-looking with respect to fuel costs when choosing what type of vehicle to purchase. Although recent evidence suggests that conventional vehicle buyers are aware of gasoline prices and forward-looking (incorporating future fuel costs) when deciding which vehicle to purchase[23], Ito (2014) describes consumers who are aware of the average electricity price they face, but poorly understand increasing marginal block prices often employed by regulators. If consumers consider the average price of electricity rather than the marginal price of electricity or misperceive the costs of fueling an EV, they may over- or under-estimate the costs of operation of an EV, leading to over- or under-utilization. To date, we do not have clear empirical evidence as to whether EV buyers are forward-looking to the same degree as buyers of conventional vehicles.

Subsidies to the upfront purchase price of EVs play a similar role Pigouvian taxes on electricity and gasoline prices. To the extent that there are externalities that arise on the "extensive" margin from the stock of EVs on the road, efficient policy justifies the use of a tax or subsidy to the upfront purchase price. As with the "intensive" externalities described above, the nature of the externality affects whether a common policy or local policy is preferable, depending on whether the marginal societal costs or benefits vary by geography. For instance, the local nature of network externalities suggest a decentralized approach preferable to a one-size fits all approach.

Yet, subsidies to the upfront purchase price may also play an important role in addressing externalities on the *"intensive"* margin, by inducing consumers to select fuel efficient vehicles. In particular, if consumers are poorly informed or underestimate the savings associated with operating an EV, they may be less willing to accept the higher upfront cost of an EV as compensation for future savings. As noted in Allcott et al. (2014), taxing electricity and gasoline at

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[22] As noted by Davis (2019), to the extent that fuel taxes generate tax revenue earmarked for road infrastructure, one might also imagine taxing the mileage of EVs to reflect the wear imposed by the EV on roadways.

[23] Busse et al. (2013), Sallee et al. (2016)

their marginal external costs may not lead to the first-best outcome. To the extent that buyers are myopic, they will tend to adopt fewer EVs than if they were forward-looking. Even if the price of electricity and gasoline reflect the full social costs of the use of the fuels, consumer myopia would generate a externality on the *extensive* margin equal to the net present value of the stream of externalities generated on the intensive margin, potentially justifying subsidies to the upfront EV price.

We now turn our attention to various policies that are in place in the U.S. to promote supply and demand in the EV market. These policies pursue a wide range of goals, with some stating more or less clearly precisely what market failure the policy seeks to address. State and federal tax credits (in concert with non-monetary incentives) encourage consumer adoption. California's Zero-Emission-Vehicle (ZEV) Mandate and CAFE standards create incentives to promote supply. Indirect network externalities associated with charging infrastructure investments are addressed through direct subsidies for construction of charging stations. We discuss this policy landscape briefly with the goal of identifying the stated rationale when possible, and ascertaining the extent to which those stated or presumed rationale can be justified by market failure. A general principle in what follow is that policies that are not justified by a market failure lead to costly distortions and imply that the same environmental and market outcomes could be achieved at a lower cost. In our view, the aspiration to cost-minimize ought to be central to any environmental policy that policy-makers wish to scale or see replicated elsewhere.

4.1 EV Purchase Incentives

State and federal tax credits are motivated by the fact that, both currently and for the anticipated future, the upfront cost to purchase an EV is higher than the upfront cost to purchase a comparably-sized gasoline-powered vehicle. State and federal subsidy programs are the primary policies aimed at influencing the consumer purchase decision. Federal subsidies of up to $7,500 per new EV were made available as part of the American Clean Energy and Security Act of 2009. These subsidies are tied to battery capacity and are capped at the manufacturer level, with up to $1.5 billion in tax credits available for consumers of each manufacturer, phasing-out after an automaker sells 200,000 electric vehicles. A wide array of state and local incentives have been available, with the most typical being rebates or tax credits, high-occupancy vehicle lane access, and/or free or subsidized charging (more on this in the next subsection). Through 2017, roughly 700,000 EVs claimed a total of an estimated $4.7 billion in federal subsidies have been paid to EV buyers nationwide. The future status of these subsidies is being debated presently both at the federal level (where some favor eliminating subsidies and some favor expansion), and at the state and local level.

State governments have also been active in setting up financial incentives for EV adoptions. By 2014, over half of the states had some sort of EV incentives in place. These ranged from point-of-sale subsidies to high-occupancy vehicle (HOV) lane stickers, sales tax waivers, registration fees (waivers or taxes), parking preferences, charging infrastructure subsidies and more. The largest state program in the U.S. is the California Clean Vehicle Rebate Project, which offers new EV buyers $1,500-$2,500. In 2016 it put in place means-testing to stimulate lower-income EV adoption. In addition, some funds generated by the low carbon fuel standard (LCFS) are redirected to California electric utilities to subsidize EVs.

From the standpoint of economic efficiency, subsidies address two potential sources of market failure, stock-based externalities arising from network effects or spillovers and (potentially) the present discount value of usage externalities if buyers are not forward-looking with regards to future energy costs. Not withstanding concerns of economic efficiency, empirical research finds that subsidies can be effective at stimulating demand for alternative fuel vehicles. Gallagher and Muehlegger (2011) show that demand for hybrid vehicles was dramatically increased by the presence of sales tax waivers. In low- and middle-income subpopulations, subsidies appear to be effective as well (Muehlegger and Rapson (2018)). These results are consistent with estimates of the EV demand elasticity, which in all studies (to our knowledge) exceed -1 (Li et al. (2017), Li (2017) and Springel (2017)).

The extent to which subsidies induce "additional" EV purchases is an important determinant of cost-effectiveness and welfare effects of a subsidy policy. In the case of most EV subsidy programs, both subsidy-induced EVs and those that would have been purchased irrespective of the presence of a subsidy are subsidy-eligible. There is no foolproof way to target subsidies only towards buyers for whom the subsidy is the determining factor in a purchase decision. Due to this information asymmetry, the cost per additional (subsidy-induced) vehicle depends on the size of the market that would have been realized in a subsidy-free world, which is unobservable. The demand elasticity summarizes much of what is needed to predict what would have happened in this alternate, subsidy-free world. On one hand, a high demand elasticity will induce more EV purchases for a given amount of subsidy, thereby implying a higher degree of additionality than if demand were less elastic. On the other hand, as the proportion of subsidy-induced vehicles grows, the implication is that in a subsidy-free world the size of the EV market would have been that much smaller. To the extent subsidies are larger than the socially-optimal value, an expansion of subsidy-induced demand reduces welfare.

To demonstrate these points, we consider the implied proportion of EVs sold under the existing federal and California subsidy regimes that is additional.[24] Table 1 present these estimates. In Panel A we report the implied fraction of battery electric vehicles (BEVs) that were "additional" under different assumptions about the demand elasticity. Consistent with intuition, more elastic demand corresponds to a higher fraction of the market that is subsidy induced. An elasticity of -1.5 implies that the vast majority of BEVs would have been purchased even had the subsidies not been present. This is particularly true for Teslas. At the higher end of the elasticity range, -3.5, it still appears that most Teslas were likely not subsidy-induced purchases; but 64-77 percent of non-Teslas were. The other side of this coin is the implied subsidy per induced BEV, which decreases as demand becomes more elastic (moving left to right in the table). If most BEVs would have been purchased irrespective of subsidies, the implied subsidy cost per subsidy-induced purchase must be large. If 80 percent of Teslas in California would have been purchased without subsidies (and assuming 100 percent subsidy uptake), then the average subsidy expense per subsidy-induced Tesla would be over $50,000. Even at higher elasticities, the effective cost per subsidy-induced BEV substantially exceeds the face value of the subsidy itself.

Setting aside efficiency considerations, many policymakers and industry enthusiasts are interested in how to achieve various EV adoption goals (e.g. 1.5 million EVs on the road in

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[24] The main elements of this calculation are data on actual EV purchase prices, California and federal EV subsidy amounts (which we assume to be $2,500 and $7,500 for California and federal subsidies, respectively), and data on the number of EV sales. We perform the calculations separately for Teslas to acknowledge the fact that Teslas are much more expensive than the vast majority of other EVs sold during the period of our data (before the end of 2018).

California by 2025). Archsmith et al. (2021) estimates the relative importance of up-front purchase prices versus non-monetary EV attributes, such as battery range, the availability of EV pickup trucks, and charging station density. They concludes that EV market share in 2035 will be determined more by non-monetary factors than by subsidies. In their analysis, the first $500 billion in cumulative nationwide EV subsidies is associated a 7-10 percent increase in EV market share in 2035, an effect that diminishes as subsidies increase. For those aspiring to achieve upwards of 50 percent EV market share by that time, subsidies may help but will likely play a secondary role to more intrinsic determinants of demand.

4.2 Policies Affecting Intensity of Use

As of this writing, there is an active debate about how much EVs are driven. Electric vehicle miles traveled (eVMT) is a measure of the utility that drivers of EVs receive and speaks directly to the potential environment benefits provided by EVs. The absence of direct measurement and data collection leaves researchers and policy-makers only with indirect approaches to estimate eVMT. Survey responses are inconclusive. Responses from the 2017 National Household Travel Survey indicate that EVs are driven just over half as many miles per year as gasoline cars (Davis (2019)). Surveys from California produce an estimate of eVMT that is more-or-less the same as gasoline cars (Hardman et al. (2018)). The current alternative to surveys combines household-level electricity billing data with address-level vehicle registration data to estimate household charging load. Using that approach, and adjusting for fuel economy and away-from-home charging, Burlig et al. (2021) estimate that eVMT in Northern California from 2014-2017 is roughly 6,700 miles per year. That result aligns closely with Davis (2019), but there is more to learn. Factors such as selection into EV ownership, improvements in battery range, geographic variation, and the degree to which EVs are substitutes (versus complements) to gasoline cars are poorly understood and may all affect the intensity of use of EVs.

Relative to the popularity of up-front purchase incentives, fewer policies directly target the operational costs of driving an EV. Rather, the operational cost savings of driving an electric vehicle are strongly influenced by regulated electricity prices and gasoline taxes (and, of course, the underlying demand for transportation). The former are set with many objectives in mind, including cost recovery, encouraging residential solar PV adoption, and achieving redistributional objectives. Gasoline prices, to the extent they are influenced by the government, are set primarily with an eye towards funding transportation infrastructure. Anticipated fiscal shortfalls, due to declining gasoline consumption, have led a number of states to levy registration charges on electric vehicles and for state governments to form committees to consider mileage fees. Legislation on mileage tax pilot program has been enacted in California, Indiana and Oregon and is currently pending in Hawaii, Massachusetts, New Hampshire, and New York.[25] Beginning in 2020, Electric vehicle drivers in Utah will elect to pay either an annual registration fee or an mileage-based road charge.[26]

Setting socially-optimal incentives on the intensive margin requires setting Pigouvian taxes equal to the marginal external costs of gasoline and electricity. This would imply that the private savings from electric vehicle operation would equal the marginal external benefits per mile of an electric vehicle relative to a conventional vehicle. Figure 4 plots state-level per-mile

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[25] http://www.ncsl.org/research/transportation/ncsl-transportation-funding-finance-legis-database.aspx

[26] https://www.udot.utah.gov/main/f?p=100:pg:0:::1:T,V:5090

fuel cost savings against the environmental benefits or costs calculated from Holland et al. (2016) for two comparison pairs. Panel A compares the Ford Focus Electric with Ford Focus ICE and Panel B compares the Nissan Leaf with the Toyota Prius. Perfect alignment of policy with Pigouvian taxes would imply equality between the private savings and the relative environmental benefits. Although there is a positive correlation between the private savings and environmental benefits, the private savings depart substantially from those that would induce efficient usage. As an example, the private savings for electric vehicle drivers in California are lower than the privates savings for EV drivers in North Dakota, despite the fact that using an electric vehicle rather than a conventional vehicle generates environmental benefits in the former and environmental costs in the latter. More generally, Holland et al. (2016) note that in most parts of the country, electric vehicles impose environmental costs relative to conventional vehicles. Yet, with the exception of a handful of Northeastern states, electric vehicle drivers enjoy savings relatively to drivers of conventional vehicles (when the Prius is used as a comparison vehicle).

4.2.1 Electricity Prices

Electricity is the "fuel" of EVs, and so the cost of traveling a mile in an EV is directly linked to the price paid for electricity. A vast literature exists already describing efficient electricity pricing, and we will not revisit it all here. However, some aspects that discussion are relevant to understanding why the cost of operating EVs is so dramatically different in some places than in others.

Recall from Figures 2 and 3 that electricity prices exhibit substantial variation from location to location. Even within a single state, California, households living just a mile apart may pay electricity prices that differ by as much as 400 percent. These differences exist because electricity prices are set through a regulated rate-setting process that accommodates many different ways of recovering costs. The rate-setting process is guided by several objectives. The costs of building and maintaining the electric grid must be covered, and these fixed costs comprise a large fraction of the total costs of an electric utility. (Indeed, the magnitude of fixed costs relative to variable costs is the reason why electric utilities are a natural monopoly and subject to regulation in the first place.) Regulators typically also seek to protect consumers. To some, this may mean minimizing the average price per kilowatt-hour consumed; to others, it may mean providing electricity from the cleanest possible sources; and to others still, there may be a distributional motivation, such as to keep prices low for low-income consumers.

These oft-competing priorities have different implications for retail electric prices. Where (variable) retail prices are high, it is typically because fixed costs are being recovered via volumetric charges. Some utilities charge a fixed monthly fee that must be paid irrespective of how much electricity is consumed. The price per kilowatt-hour in those districts is typically lower since it comes closer to reflecting the wholesale costs of generating and delivering electricity. Many utilities, for example investor-owned utilities in California, recover fixed costs through volumetric charges and also have increasing block rates such that high users pay higher prices on the margin. These differences lead to dramatic variation in how much it costs to charge an EV battery.

Many of the efficiency considerations relating to electricity pricing are explored in detail in Borenstein and Bushnell (2018). We will not revisit them in depth here except to restate the main observation: efficient electricity pricing is achieved when the price of electricity is equal to its social marginal cost. That is, the price must equal the cost of generating electricity plus (or minus) the societal costs associated with things like pollution damages (or benefits). Notice that this efficiency rule does not depend on how the energy is ultimately used. The efficient price reflects all of the upstream economic considerations and any downstream externalities.

It follows that charging different prices for different end-uses of electricity is inefficient. This observation is at odds with the apparent preference that regulators exhibit for charging different electricity prices depending on the end-use. Electricity customers with solar PV on their rooftops face a different electricity rate structure than their no-solar neighbors. Owners of EVs in many jurisdictions have access to electricity rates that are only available to customers who own EVs. This is inefficient. If EV owners are allowed to consume cheaper electricity than other consumers, there will either be over-consumption of EV miles-traveled or under-consumption of other electricity powered goods. The aspiration should be electricity that is priced to reflect its social marginal cost for all of its potential end uses.

4.3 Supply-Side Incentives

The federal and state governments also use a suite of policies to encourage automakers to offer electric vehicles. The Zero Emission Vehicle (ZEV) mandate was adopted in 1990 by the California Air Resources Board as part of a suite of policies intended to reduce transportation sector emissions. The ZEV Mandate sets a manufacturer-level target for percent of sales required to be ZEV. Over time, the mandate was adjusted to accommodate cost realities and technical challenges, reflecting an intention to help to stimulate commercialization on the margin. While the overarching goal appears to be environmental, the intermediate goals allude to potential market failures on the supply side.

Corporate Average Fuel Economy Standards require that car manufacturers meet a weighted average level of fuel economy. CAFE was first enacted in the U.S. in 1975, shortly after the OPEC oil embargo. Initially, CAFE standards sought to reduce dependence on foreign oil, reflecting aspirations to improve energy security. In recent years the stated rationale has expanded to include environmental and paternalistic objectives. The vast majority of the cost-benefit justification of recent CAFE rules relies on an assertion that consumers are myopic and therefore make privately sub-optimal car purchase decisions. Most of the remaining stated benefits come from environmental improvements, and one might reasonably assume that the apparent desire to correct for behavioral anomalies in this context is as much motivated by an intention to improve environmental outcomes as it is to improve private outcomes. In the 2012 CAFE rules, EVs are assigned credits according to their MPG-equivalent rating, allowing electric fuel economy to be compared to that of ICEs. In the 2016 rules, EVs began to earn multipliers in the CAFE formula.

Both of these supply-side incentives act to reduce the cost of EVs and increase the cost of ICEs. In many ways, supply-side policies might create similar incentives on the extensive margin to up-front EV subsidies, by lowering the effective price of EVs relative to comparable ICEs. Supply-side policies offer an advantage over up-front subsidies in that they are designed to be self-funded and, therefore, not require government fiscal support. However, the incentives they create do not mimic those of an optimal Pigouvian tax on energy. The optimal tax would reduce miles travelled as well as the number of cars on the road, and give automakers the proper incentive to invest in vehicle efficiency. Supply-side incentives do nothing to align private and social costs on the intensive margin nor do they yield the optimal number of cars on the extensive margin. However, by shifting automakers to supply EVs, they may stimulate innovation as well.

4.4 Charging Infrastructure Incentives

The vision to extend EV ownership to all confronts the obstacle of access to EV charging for people without driveways and garages, and for drivers needing to take trips whose distance exceeds the battery range. Significant resources are being deployed to stimulate construction of EV charging infrastructure. As of mid-2018, 17 states provided subsidies to reduce the cost of chargers for installers. These incentives again range from tax exemptions to subsidies. Volkswagen is directly and indirectly (via the diesel scandal settlement) funding significant investments in charging infrastructure. The largest portion of these are being allocated to California, where settlement funds from NRG are also being used.[27] The California Public Utilities Commission (CPUC) is at present considering a variety of infrastructure buildout plans by investor-owned utilities and much of the $157 billion currently earmarked by the Biden administration for EVs will be directed towards charging infrastructure.

From an efficiency perspective, as described above, much of the necessary investment in charging infrastructure is likely to happen through market forces. Yet, subsidies for charging infrastructure may still play a role if they are more cost-effective at stimulating EV adoption than direct purchase subsidies. Several economics papers have attempted to empirically quantify the effect of charging infrastructure on EV demand (see e.g., Li (2017), Springel (2017), and Li et al. (2017)). This is a particularly challenging empirical problem as there are two possible directions of causality: dense charging infrastructure may stimulate EV adoption, but a high market share (or anticipated market share) of EVs might induce higher investment in charging infrastructure. The best evidence to date (Li et al. (2017), Springel (2017), and Li (2017)) attempts to disentangle these effects using grocery stores, EV subsidies and government-sponsored infrastructure subsidies as instruments, respectively. These papers have been highly influential in guiding EV policy, as they find large impacts of charging station density on adoption, and stimulating adoption tends to be a primary objective of policymakers at present. That said, the exclusion assumption in these papers is that these instruments are uncorrelated with unobservable determinants of EV demand. Moreover, these papers analyze the EV industry during its earliest stages. If the network effects from each new charging station diminish as density increases, incentives are most valuable at the early stages of market development. Li (2017) offers empirical evidence of diminishing marginal benefits - a 10 percent increase in level 2 charging stations is associated with a 0.8 to 1.2 percent increase in the likelihood of adoption. Finally, there is growing evidence that the majority of day-to-day charging occurs at home, rather than at public charging stations.[28] While this doesn't necessarily speak to the utility of expanding the fast-charging network, it calls into question the public benefit of deploying government resources towards more public level 2 charging stations. Our view

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[27] `https://www.cpuc.ca.gov/General.aspx?id=5936`
`https://www.arb.ca.gov/msprog/vw_info/vsi/vw-zevinvest/vw-zevinvest.htm`

[28] Survey evidence in Dunckley and Tal (2016) documents that the vast majority of EV owners in California charge either entirely at home (50 percent) or at home and work (20 percent).

is that there remains a high marginal benefit of designing future charging station rollouts in a way that facilitates ex-post program evaluation. This will help to provide random or quasi-random variation with which to identify the causal effect of charging stations on EV adoption in the current environment. Ideally, it would help to quantify the costs and benefits of different types of charging infrastructure (e.g., level 2 vs. fast-charging) as well as the costs and benefits of different location choices (e.g., public urban, public interstate, and charging stations at multi-unit dwellings).

5 Conclusion

The multi-faceted EV policy landscape reflects the complexity of the transportation and energy sectors in the economy. EV policies are often crafted to pursue a wide array of social and environmental objectives. In this paper we review the economic intuition behind various market failures and policy objectives, and explore how these align with the articulated goals of existing policies. What we find is a mixed bag. Many market failures are location- and time-specific, and addressing them with a one-size-fits-all policy (such as the federal EV subsidy) is unlikely to create efficient incentives for EV adoption, use, or environmental benefits.

Benefits from EV-induced pollution reductions exhibit substantial spatial heterogeneity based on regional differences in electricity grid composition. These benefits are thus likely to increase over time, in step with grid decarbonization. A clear implication is that EV subsidies cannot be justified based on environmental benefits in regions where coal electricity generation persists. Over time, as electricity is decarbonized, the net benefits of EVs will change, and a sensible time-profile would reflect these realities.

Extensive margin externalities also vary over time and space. Non-internalized learning-by-doing in production or (non-internalized) network effects relating to charging infrastructure may justify policy intervention in the early stages of EV market development; but intervention based on these market failures will optimally diminish over time. On the margin, this would imply near-term subsidies where current network externalities might be significant. However, at the time of this writing, the level of apparent conviction about the need to subsidize charging infrastructure seems out of step with theory and evidence. While network *effects* undoubtedly exist in the realm of charging infrastructure, it is far less clear that these effects are *external*. It is likely that a well-capitalized firm would internalize network effects in charging infrastructure, as demonstrated by Tesla's supercharger network. This observation offers a note of caution for policymakers considering the promotion of investments in irreversible infrastructure.

Finally, the growing prominence of social and environmental justice goals in environmental policy is noteworthy. While these authors admit a preference for more equitable outcomes in the economy, cost-efficacy is also an important consideration. Artificially stimulating demand for EVs in an area where the private benefits are low creates a distortion that is disproportionately large relative to alternatives. Those EV owners would be better off if they were to receive the cash equivalent of the EV subsidy, rather than the subsidy itself. In an economy with scarce resources and a vast array of policy objectives, policy-makers should seek to identify ways to deploy public resources that maximize net benefits, which requires avoiding the creation of conflicting incentives.

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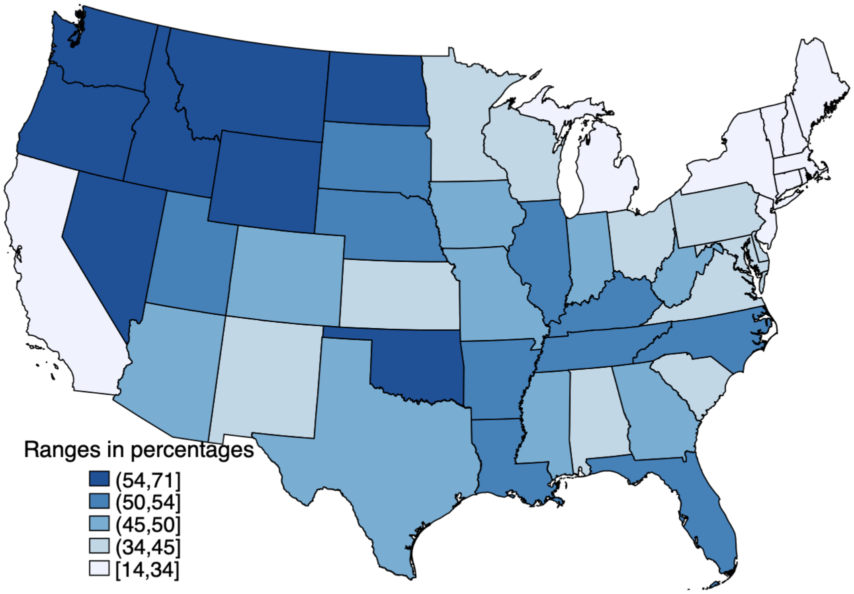
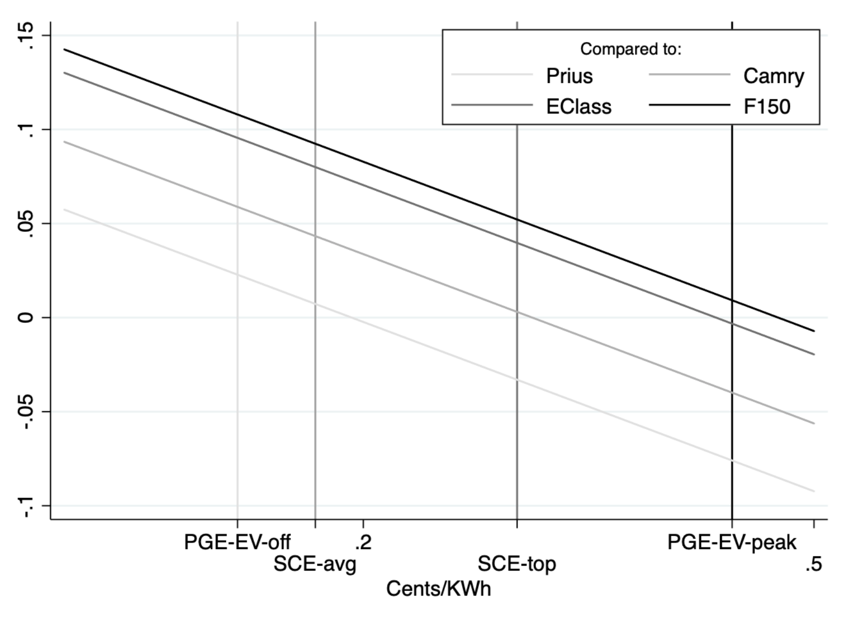
Figure 1: Implicit variable cost savings per mile for EV relative to ICE



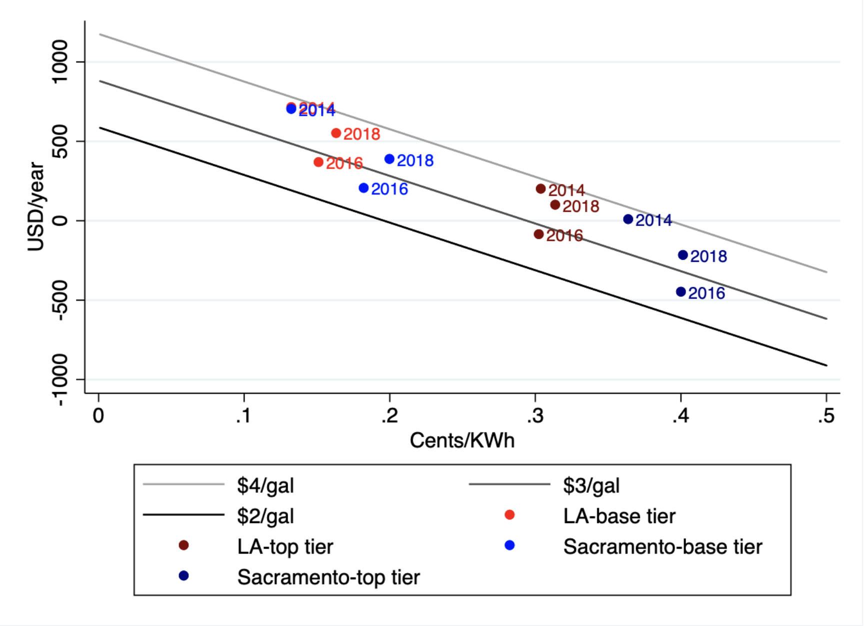
The graph compares the per mile variable fuel cost of the 2019 Nissan Versa (ICE) to that of contemporary Nissan Leaf (62 kWh battery). The Nissan Leaf runs 100 miles on 31kWh and the selected Nissan Versa earns 34 MPG according to the official estimates by the US Department of Energy. State-level marginal electricity prices were calculated using the estimates from Borenstein and Bushnell (2018) using total sales at the ZIP code level as weights. Retail gasoline prices (Regular) were calculated from monthly averages posted by AAA.

Figure 2: Annual Fuel Saving by Nissan Leaf



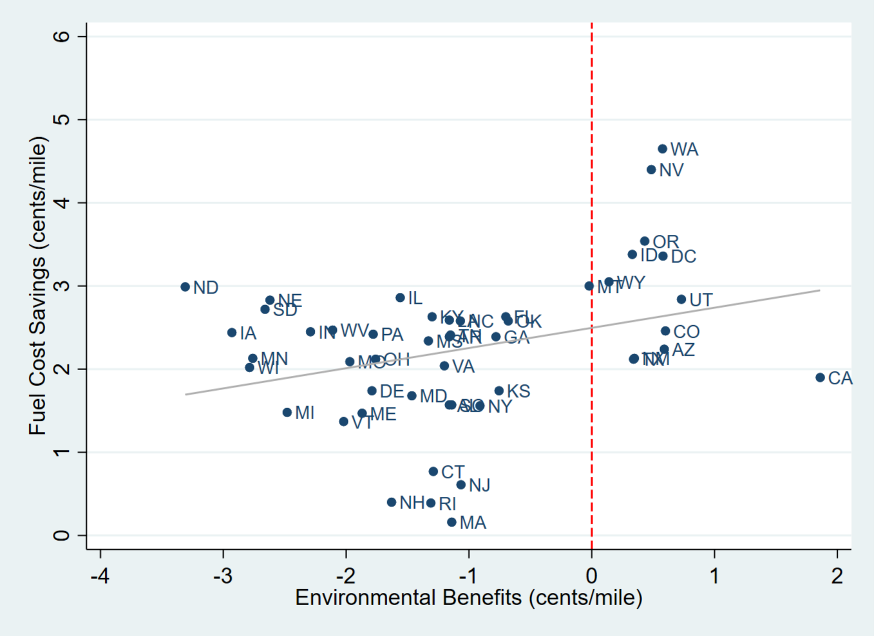
The graph compares the annual fuel cost difference of a 2019 Nissan Leaf to various popular ICEs. The Nissan Leaf (62kWh battery pack) runs 100 miles on 31kWh, as compared to the fuel economy of the selected 2019 Toyota Prius (52 MPG), Toyota Camry (32 MPG), Mercedes E-Class (23 MPG) and Ford F150 (21 MPG) according to the official estimates by the US Department of Energy. The retail gasoline price is assumed to be $3.00 per gallon.

Figure 3: Annual Fuel Saving by Nissan Leaf: California Utilities

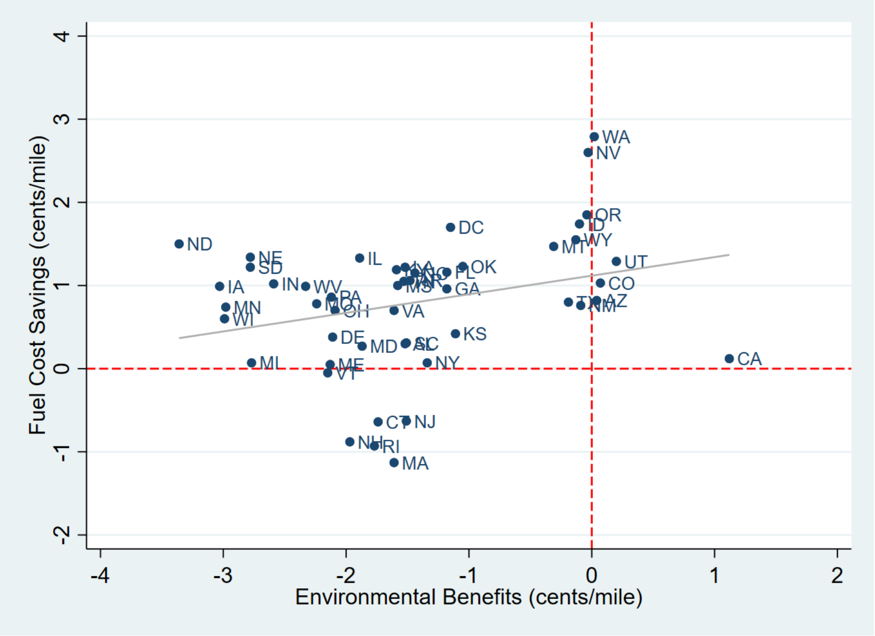


The graph compares the annual fuel cost of the 2019 Nissan Versa (ICE) to that of contemporary Nissan Leaf (62 kWh battery). The Nissan Leaf runs 100 miles on 31kWh, and the selected Nissan Versa earns 34 MPG, according to the official estimates by the US Department of Energy. Dots represent savings by year for a driver living in LA, buying electricity from Southern California Edison and gasoline from LA-Long Beach.

Figure 4: Private Fuel Cost Savings vs Environmental Benefits



Panel (a): Ford Focus Electric vs Ford Focus ICE



Panel (b): Nissan Leaf vs Toyota Prius

The scatter plots compare the per-mile fuel cost savings and per-mile pollution benefits or damages for a Ford Focus Electric and Ford Focus ICE (Panel A) and a Nissan Leaf and Toyota Prius (Panel B). Per-mile fuel cost savings calculated by authors based on state-level marginal electricity prices from Borenstein and Bushnell (2018) weighted by total sales at the ZIP code level, and retail regular-grade tax-inclusive gasoline prices posted by AAA. Pollution damages are calculated based on estimates from Holland et al. (2016).

Table 1: Subsidy Additionality

		Price Elasticity of Demand		
		-1.5	-2.5	-3.5
Panel A: Fraction BEVs Subsidy-Induced				
Tesla:	California	0.19	0.30	0.39
	Rest of U.S.	0.15	0.23	0.31
Non-Tesla:	California	0.46	0.65	0.77
	Rest of U.S.	0.36	0.52	0.64
Panel B: Implied Subsidy per Induced BEV				
Tesla:	California	$ 51,727	$ 33,227	$ 25,365
	Rest of U.S.	$ 68,355	$ 43,153	$ 32,402
Non-Tesla:	California	$ 21,509	$ 15,448	$ 13,028
	Rest of U.S.	$ 27,945	$ 19,156	$ 15,522

Note: Calculations assume a) $7,500 in federal new BEV subsidies, b) $2,500 in California new BEV subsidies, and c) that all subsidy-eligible purchases receive the subsidy.