The End of Neutrality?
LCFS, Technology Neutrality, and Stimulating the EV Market.

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Abstract

Widespread electrification of the transportation sector is a key component of most strategies for deep decarbonization of the U.S. economy. While the acceptance of EVs has grown dramatically over the last decade, much of this growth has been spurred by substantial support from public funds and other related policies. Major electrification on the time scales supported in many climate policy plans will require substantial investment spurred by policy. In this whitepaper we discuss the policy options for expanding the EV market. Our particular focus is on the potential role that a Low-Carbon Fuel Standard (LCFS) can play in supporting electrification. Standards like the LCFS are typically positioned as "technology neutral", and the LCFS itself relies upon a dense set of calculations and assumptions to rate a wide variety of fuels based upon their life-cycle carbon intensity (CI). The LCFS in California is currently directing hundreds of millions of dollars to the EV market in California. However, it is likely that for a LCFS to support the kinds of investments on a magnitude likely necessary to reach electrification goals, it may have to be altered in such fundamental ways as to no longer really function as a technology-neutral fuel standard.

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1 Introduction

A key element of most visions for achieving climate stabilization involves the widespread transition of the transportation sector to electricity via the adoption of electric vehicles (EVs). Governments around the world have set ambitious targets for EV adoption or set goals to phase out the sale of EVs entirely, often supporting these objectives with policies designed to encourage adoption. While the growth of the EV market over the last decade has been spectacular in percentage terms, EVs still remain a modest fraction of overall passenger vehicles.

One policy tool that has emerged to support EV growth in regions such as California is the Low Carbon Fuel Standard (LCFS). The LCFS allows suppliers of low carbon transportation energy to earn credits that are sold to producers of higher-carbon transportation fuels. It was initially positioned as a "technology-neutral" standard that scores a broad set of fuels based upon their life-cycle carbon intensity. While the LCFS was designed to promote low-carbon transportation, its original design was most easily applied to blends of lower-carbon fuel used in similar (internal combustion engine) vehicles. Adapting the LCFS to promote dramatically different transportation technologies, such as hydrogen or electricity, has therefore necessitated adopting a series of complex and arguably dubious assumptions that, if taken to a large scale, will fundamentally reshape and redefine the nature and function of the LCFS. To the extent that these assumptions create favorable conditions for specific fuels, the standard loses one of its main initial benefits: technological neutrality.

In this paper we discuss the policy challenges presented by a goal of rapid large-scale expansion of EVs. We focus on the market for passenger vehicles, which constitutes almost all of the EV industry for which there is currently useful empirical evidence. There are three channels in which EV adoption can be supported: operational (fuel) costs, up-front (vehicle) costs, and operational convenience. In each dimension the policy challenge is to establish or expand an advantage (or minimize a disadvantage) of EVs relative to conventional internal combustion engine (ICE) vehicles.

We then survey the standard policy options available for promoting the expansion of EVs, including carbon pricing, intensity standards (such as the LCFS), and subsidies provided by either general public funds or utility ratepayers. Each option has its particular advantages and disadvantages with regards to economic efficiency, transparency, and broad public appeal.

Notably, the LCFS in its purest form is a policy that targets the first of the three channels of EV support, relative fuel costs. For most fuels, the LCFS increases revenues for the producers of low carbon fuels and indirectly works to lower the retail prices of those fuels. The intent was to promote both the innovation and production of low-carbon fuels by providing subsidies that increase as the carbon-intensity of those fuels decline. However, in practice, while a small amount of the revenue generated by LCFS credits may translate into a fuel price reduction in the cases of fleet owners and perhaps those using public charging (if the owner chooses to pass along some of the credit value to the consumer), the vast majority of EV-generated revenue coming from residential charging does not generally translate to a fuel price reduction for EV users. Additionally, the LCFS in California has added several elements designed to reduce vehicle costs, by directing a large proportion of residential charging value to a statewide point-of-purchase rebate for EVS, and promote the provision of services that increase charging convenience, by allowing credit generation for unused fueling capacity for zero emission vehicles (ZEVs), namely EVs and hydrogen. While these measures arguably increase the appeal of EVs and ZEVs more generally, they also alter the nature of the LCFS in ways that carry unpredictable implications for the production of other types of low carbon fuels. For example, there are no specific rewards available for the sale of flex-fuel cars that would be analogous to those available for EVs, or for "blender" pumps that could facilitate more large scale usage of biofuels; any LCFS credit revenue directed toward these is completely at the discretion of the credit seller. Thus, where more distribution channels have opened for non-ZEV fuels, as in the case of renewable diesel, it has been on the strength of the LCFS incentive on the flow of fuels.

We conclude by summarizing what is known from the available academic and policy literature about the relative costs and effectiveness of supports flowing through the three consumer channels of fuel prices, vehicle prices, and convenience. Unfortunately given the early stage of the EV market, the empirical literature is relatively limited. One major takeaway is that future policies need to be designed in a way that better allows for credible policy evaluation so that the impacts of these policies can be understood. One key advantage of more flexible, market-based policies such as an LCFS is that they more easily accommodate course corrections as we learn more about the relative costs and benefits of different technology options.

If EVs are to be supported either through vehicle subsidies or through promoting convenience and accessibility through measures such as expanded charging networks, this leaves policy makers with one of two choices. Support for vehicle costs and charging networks could either be provided via policies specifically designed and directed for those purposes, or such support could be added to a LCFS at a magnitude and in a fashion that so alters the nature of that regulation that it no longer resembles or operates as an actual fuel standard.

2 The EV Policy Landscape

SUMMARY

- Policies promoting EVs target at least one of three elements.
  - Upfront (purchase) cost of the vehicle.
  - Operational (fuel) cost of the vehicle.
  - Convenience (supporting infrastructure) of vehicle use.
- In each case, the important margin is the cost or convenience of an EV *relative* to a conventional vehicle.
  - Pro-EV policies can either raise the cost of conventional vehicles or lower the cost of EVs (or both).
  - Policies lowering EV costs require funding sources, policies raising conventional costs raise funds.
- A Low Carbon Fuel Standard works by directing funds from producers/sellers of conventional fuels to producers/sellers of low-carbon fuels.
  - The LCFS raises the price of the average fuel, but by less than an analogous carbon tax.
  - The LCFS subsidizes the use of fuels that emit carbon, as long as they are less carbon intensive than the standard.

A wide set of factors, from financial considerations to convenience to a desire to make a personal statement, influence consumer vehicle purchase decisions and, specifically, the decision of whether to adopt an electric vehicle. Yet government policies related to light duty adoption focus almost exclusively on three possible margins of the consumer's decision.

First and foremost, government policy targets the purchase price of the vehicle. Even with the striking reduction in battery prices over the past decade, EVs remain more costly to build and purchase than conventional vehicles. As one illustration, the 2020 Nissan Versa and Leaf have roughly similar footprints, dimensions, cargo space and performance, although the Leaf has more user amenities.[1] Yet, the suggested retail price of the 2020 Leaf is $31,600, almost twice the suggested retail price of the Versa.

In the U.S., both federal and state governments offer targeted subsidies that aim the narrow the gap in purchase prices between EVs and their conventional counterparts. As part of the American Recovery and Reinvestment Act of 2009, the federal government offers a tax credit of up to $7,500 per vehicle.[2] The federal tax credit is supplemented by direct subsidies at the state-level. Two such examples are the Clean Vehicle Rebate Project and Clean Cars 4 All

[1] While not completely definitive about the comparability of the models, buyers of the Leaf often cite the Versa when surveyed as their "second choice".

[2] The credits are automaker specific in the sense that the value is linked to the the total number of qualifying vehicles sold by automaker. The credits phase out gradually once a given automaker has sold more than 200,000 EVs.

(formerly the Enhanced Fleet Modernization Program) in California, both of which provide rebates at or shortly after the time of purchase. In addition to direct subsidies, the purchase price of new vehicles is also indirectly subsidized through mandates such as the Zero Emission Vehicle Mandate in California and through other regulations such as the federal Corporate Average Fuel Economy standards, both of which raise the price of "dirty" vehicles and lower the price of "clean" vehicles.

Second, government policy directly and indirectly influences the operational costs of electric vehicles relative to conventional vehicles. While the upfront sticker cost of the vehicle may be the most salient cost at the time of purchase, consumers incorporate the costs of operation into their purchase decisions.[3] Reflective of the higher efficiency of an electric drive-train, electric vehicles tend to be less costly to operate than conventional counterparts. But, state and local taxes on transportation fuels and state regulation of electric utilities heavily influence the magnitude of the potential savings. Where taxes on gasoline are low or where residential consumers pay a high price for each unit of electricity they consume, the relative savings from an electric vehicle are modest. In the U.S., examples include California and the states in New England, where high residential electricity prices lead to modest operational savings from driving an electric vehicle, despite relatively high gasoline prices. In contrast, where fuel taxes are high and electricity prices are modest (e.g., in Washington and Oregon), the operational savings offered by an electric vehicle can be considerable. Rough estimates of the operational cost savings of driving an electric vehicle instead of a comparable conventional vehicle vary from a low of 10 - 20 percent savings per mile in the former states to upwards of 60 - 70 percent savings per mile in the latter set of states. Although lower or higher fuel prices might also impact the number of miles a vehicle is driven, such rebound effects, which might offset some of the operational cost savings or costs, are generally estimates to be rather modest in magnitude (see e.g., Gillingham (2014)).

Lastly, some policies aim to make the experience of owning an electric vehicle more pleasant and convenient, attempting to remove potential non-pecuniary obstacles to purchase. Here, the range of targeted obstacles is fairly broad. One set of state and federal policies seeks to speed the construction and increase the density of public charging stations, through a combination of incentives and mandates. Although survey evidence (e.g., Hardman et al. (2018), Dunckley and Tal (2016)) suggests that most EV charging occurs at home, these policies seek to increase

[3] Busse et al. (2013), Allcott and Wozny (2014), and Sallee et al. (2016) document that future gasoline costs are largely incorporated into purchase decisions. Yet, less in known about how consumers electricity prices influence EV purchases. Evidence from Bushnell et al. (2020) suggests that electricity prices influence EV purchases considerably less than commensurate changes in gasoline prices.

the convenience of charging away from home as a way of reducing range anxiety or increasing the ability of EV drivers to travel longer distances.[4] Another set of policies seeks to offer a variety of conveniences to EV drivers. The most notable is the ability to drive in high-occupancy vehicle ("HOV") lanes without a second passenger. Consumers survey evidence (e.g., Jenn et al. (2020)) and evidence from used vehicle sales (e.g., Shewmake and Jarvis (2014)) suggest consumers in areas with substantial traffic congestion place a high value on single-occupancy HOV lane access. Similar incentives extend to (more modest) benefits such as decreased registration fees and dedicated parking.

To be clear, all of the incentives designed to encourage consumer adoption are partially motivated (rhetorically) by supply-side considerations as well, with the idea that stimulating consumer adoption will help kick-start the industry. For example, if consumers' lack of knowledge or experience is an impediment to adoption, increasing market penetration of electric vehicles might help overcome the information barrier. Alternatively, stimulating adoption might encourage manufacturers to offer a wider variety of EVs for purchase or enable manufacturers to capture learning externalities or economies of scale present in the nascent industry. [5]

2.1 Policy options

Although government policies influence different margins of a consumer's decisions, policies related to EVs can broadly be characterized into one of three categories: (1) emissions taxes (or tradeable permit systems) that levy a fee on emissions regardless of the source, (2) intensity standards that set a target within a particular segment (e.g., transportation fuels as in the case of the LCFS) of the market, against which products are measured and taxed or subsidized, and (3) targeted incentives for particular products.

2.1.1 Emissions and Fuel Taxes

An emissions tax offers the broadest scope for policy, levying a per unit tax on emissions regardless of the source.[6] Levied on transportation fuels, sellers are responsible for the carbon content of that fuel, which will eventually be combusted in on-road vehicles. If combusting a gallon of gasoline results in 20 lbs of CO_2 emissions, then at carbon price of \$20/ton of CO_2

[4] Empirical evidence (e.g., Springel (2017), Li (2017), and Li et al. (2017)) documents that EV vehicle adoption increases with the extent of the public charging network.

[5] See Muehlegger and Rapson (2021) for a deeper discussion of the economics of EV markets and policies.

[6] For expositional purposes, we focus on emissions taxes. A system of tradeable emissions permits shares the advantages (and economics) of emissions taxes, where the equilibrium price of permits allocated to achieve the welfare maximizing level of abatement is equal to the emissions tax set to achieve the same outcome.

sellers of gasoline would be responsible for a charge of \$ 0.20/gallon. Similarly, if combusting a gallon of biofuel results in net 4 lbs of CO_2, sellers of biofuel would be taxed at \$0.04/gallon. Ideally, the tax per unit of emissions is set so as to equate the benefit of additional emissions reductions to society with the cost of additional emissions reductions by polluters.

An emission tax (optimally set) offers several attractive advantages from a policy perspective. First, by virtue of the common tax per unit of pollution, more polluting sources or products are more heavily taxed than less polluting sources or products, in proportion to their relative emissions intensities. This technological-neutrality provide attractive incentives and disincentives directly linked to the cleanliness or dirtiness of a good or input. Levied on producers, firms incorporate the tax as an additional cost of production, which acts as an incentive to identify less-emission intensive production technologies or sources of inputs. Specifically, the tax encourages firms to make investments or change production in ways that are less costly on a per-unit of pollution reduction basis than paying the tax. To the extent that the tax is passed through to consumers in the form of higher retail prices, the tax further acts to discourage consumers from purchasing carbon-intensive goods, and in the case of fuels discourages consumption on the intensive margin.

Second, the scope of policy (covering a broad set of sources) provides a common disincentive to pollute across different types of products. A carbon tax applied to all of the transportation sector, for example, would levy a similar per-unit tax on the production of vehicles and the emissions associated with transportation fuels. The common disincentive provides identical encouragement to all segments in a sector to reduce emissions, rather than foisting the burden of emission reductions on a single segment (e.g., fuels or vehicles) of the industry. This "equality" ensures that a given amount of emissions reduction is achieved efficiently at lowest cost. In contrast, if industry segments face different incentives, some segments may reduce pollution at very high costs while others, facing less of an incentive, exert very little effort to reduce pollution. In this case, a similar level of emission reduction might be achieved at lower cost by asking less of the heavily regulated segment and more of the lightly-regulated segment.

Finally, an emissions tax is net positive from the perspective of public funds. Emissions tax revenues can be used to reduce other taxes (described as the "double-dividend" by environmental economists), rebated to consumers or, as is more often the case, allocated to support subsidies for green goods. From a fiscal perspective, of particular attraction is the taxation of goods with relatively inelastic demand, for which the market distortions are modest in relation to the amount of tax revenue generated. While emissions taxes have the potential to affect

Figure 1: Policies Influencing EV Adoption

<table>
<tr><th></th><th colspan="3"><u>Margins of Influence</u></th></tr>
<tr><td><u>Policy Options</u></td><td>Upfront Vehicle Cost</td><td>Fuel Cost</td><td>Infrastructure / Convenience</td></tr>
<tr><td>Emissions Tax</td><td colspan="3">Carbon Tax / Cap-and-Trade</td></tr>
<tr><td>Intensity Standard</td><td>CA ZEV Mandate, Federal CAFE Standard</td><td>Low Carbon Fuel Standard</td><td></td></tr>
<tr><td>Government-Financed Subsidy</td><td>Clean Vehicle Rebate Project, Federal Tax Credit</td><td>Gasoline Taxes, Subsidized EV Electricity Rates</td><td>Charging Station Subsidies, HOV lane access</td></tr>
</table>

the price of many types of goods, the most direct impacts likely fall on the price of relatively inelastic energy goods (e.g., electricity and transportation fuels). To be clear, though, the primary purpose of the emissions tax from a policy perspective is to provide a common, uniform incentive to reduce emissions, rather than the fiscal benefits.

2.2 Intensity Standards

Intensity standards share (partially) the spirit of emissions taxes. Applied to pollution, regulators set a standard ($\bar{X}$) which represents the target emissions intensity within a particular segment (e.g., transportation fuels). Each firm's production is benchmarked relative to this standard. In tradable systems like the ones examined here in the US, if a firm's products generate less pollution than the standard, the firm generates compliance credits. In contrast, if a firm's set of products generate more pollution than the standard, the firm generates a compliance deficit, which must be met by purchasing credits from firms with excess compliance credits. The requirement of firms to meet a shortfall through purchasing compliance credits ensures that the intensity standard will be met, within the regulated industry segment.

Similar to a system of tradeable permits, the number of firms in- and out-of-compliance influence the price at which the credits trade. If a lax standard is set, where most firms are in compliance, the price for credits will be low. But, if policymakers set an ambitious standard, the price of credits will adjust, so as to act as a sufficient subsidy to equate the supply and demand of compliance credits and meet the intensity standard.

Ideally designed, an intensity standard applies a common disincentive to pollution. Like emissions taxes, intensity standards as conceived are "technologically-neutral," although often the neutrality is limited to a particular segment of the market such as transportation fuels. Formally, if a firm emits X units of pollution relative to the standard $\bar{X}$, and the equilibrium price for credits is given by P_c, a firm faces an effective per-unit tax equal to $P_c * (X - \bar{X})$, representing the cost of the compliance credits they need to purchase for each unit of production. Where a firm's emissions intensity (X) exceeds the intensity standard ($\bar{X}$), the intensity standard acts as an implicit tax. Set with equivalent stringency, an intensity standard creates a similar wedge between the price of dirty and clean goods as does an emissions tax. As a result, producers face very similar incentives to shift production away from dirty goods to clean goods and for innovation in lowering pollution intensity. But notably (and in contrast to an emissions tax), an intensity standard implicitly *subsidizes* production at firms with lower pollution intensities than the standard. If X is below $\bar{X}$, each unit of production generates $(\bar{X} - X)$ compliance credits which can be sold to more polluting firms. Thus, intensity standards impose smaller impacts on the average price of all the goods (clean and dirty) in a sector. This dichotomy, of imposing a strong incentive on producers to innovate and shift away from dirty inputs, while moderating the effect on the average prices paid by consumers forms one attraction of intensity-based standards for policymakers.[7]

Yet, one drawback is that, in contrast to emission taxes, an intensity standard is typically more narrow in scope, limited to a particular set of products within a specific segment of the industry. This has important implications for the cost efficiency of reducing pollution. If firms face standards of differing stringency, the cost and effort to reduce pollution will be higher in stringently regulated markets than in markets with lax standards. This inconsistency increases the cost of achieving a given level of pollution reduction, as low cost methods of pollution reduction are forgone as a result of less stringent standards.

Although above we describe an example of an emissions intensity standard, mandates are functionally equivalent. As an example, California's Zero Emission Vehicle (ZEV) mandate sets a standard for the ZEV share of a firm's vehicles sales. Tesla (and other companies) that sell a high proportion of ZEVs generate compliance credits. These credits act to subsidize ZEV production, as ZEV firms sell the credits to companies that are out-of-compliance with the standard set by the ZEV mandate.

From a fiscal perspective, binding incentive standards are revenue neutral, neither generating nor requiring tax revenue to support. By virtue of the transferability of the credits, "taxes"

[7] While moderating the average price impacts on consumers might be attractive for political reasons, the taxation of dirty fuels and subsidization of clean fuels limits the potential of an intensity-based standard to impact the intensive margin of vehicle miles travelled.

paid by firms out-of-compliance are directly transferred as "subsidies" paid to firms in compliance. This revenue neutrality can be attractive politically as an incentive standard does not compete with other policies for a jurisdiction's budget.

Finally, some policies share features of intensity standards while relaxing the binding nature of the credit system. One such example is the federal CAFE standard. The standard sets an automaker-specific benchmark based on the footprint of the fleet of vehicles sold. Over-compliance with the standard generates credits which can either be retained by the firm (and used in future periods) or traded to firms out-of-compliance. But, firms out-of-compliance have an alternative - they can opt to pay a fine rather than meet the target by purchasing tradeable credits from a firm in compliance. This caps the potential credit price, amounting to a per-vehicle tax proportional to the amount the firm's average fuel economy of its sold fleet fails to meet the CAFE standard.

2.3 Government-Financed Subsidies

The last set of policies are subsidies or taxes that are funded by or contribute to government budgets and are targeted at specific products. Examples of these subsidies abound in transportation policy, from vehicle subsidies to incentives for public charging station installations. As with emissions taxes or intensity standards, targeted subsidies can in principle create similar financial incentives for producers to shift production and innovative activity away from dirty towards clean goods or inputs.

But, from a broader perspective, these subsidies often lack the efficiency benefits of either an emissions tax or an incentive standard. Rather, the generosity of the incentive as well as which products are targeted are left to the discretion of the policy maker. In contrast to emissions taxes and intensity standards, targeted subsidies require the policy maker to pick and choose technologies in a way potentially unrelated to their emissions abatement potential. If the policy maker does not correctly foresee the set of policies or products with the greatest potential to reduce pollution at lowest cost, pollution reductions might be more costly to achieve. Further, from a fiscal perspective, targeted subsidies require funding support and, thus, compete with other policy objectives over (potentially) scarce government resources.[8]

Despite these disadvantages, targeted taxes or subsidies do offer an attractive feature for policymakers. By their nature, emissions taxes or intensity-standards like the ZEV mandate

[8] Targeted taxes can also be used to discourage pollution-intensive production techniques or pollution intensive goods and can be set in a continuous fashion that penalizes (or subsidizes) goods in proportion to their pollution-intensity.

are agnostic as to how an emissions reduction or an increase in EV penetration is acheived. Yet, policymakers often have multiple objectives when setting EV policy. As one common example, policymakers often hope to target benefits of policy towards disadvantaged socioeconomic groups. In the case of pollution, policymakers guided by environmental justice considerations might seek to ameliorate pollution faced by historically disadvantaged groups. For EV adoption, policies might seek to stimulate adoption amongst groups with low EV penetration rates.

This type of conditional targeting is easy (and fairly common) with a subsidy. In California, for example, the Clean Vehicle Rebate Project is means-tested - only households with incomes below cutoffs[9] are eligible to receive subsidies, with more generous subsidies available for lower income households. Clean Cars 4 All (formerly the Enhanced Fleet Modernization Program studied in Muehlegger and Rapson (2018)) extends this idea further, offering subsidies based on household income and whether a recipient lives in a "disadvantaged" community.

2.4 Policy Summary

Virtually all of the policies that directly or indirectly impact electric vehicle adoption can be categorizes as one of the options above. In figure 1, we arrange many of the most well-known policies that impact three margins discussed above into the three policy categories.

As illustrated, a emission tax spans all three industry segments as it sets a common tax on carbon emissions regardless of the source. Intensity standards, that impose a binding constraint within a particular segment, include California's ZEV mandate and the Low Carbon Fuel Standard, which set binding benchmarks for ZEV sales and for the carbon-intensity of transportation fuels respectively. Targeted policies include gasoline taxes, subsidized rates for electicity, and monetary incentives for electric vehicle purchases or charging station construction.

In figure 2, we summarize the efficiency and political tradeoffs amongst the three different types of policies. We evaluate each of the options based on how, for a comparable policy incentive, we would expect them to impact the cost of the dirty and clean fuels (or vehicles), the overall impact on the retail price of fuels, the revenue consequences of the approaches, whether the approaches create a consistent incentive across or within segments, and whether the approaches are easily tailored towards more targeted socioeconomic or distributional goals. Emissions taxes, at one end of the spectrum, offer an approach that creates a common incentive for all segments within the transportation sector to reduce emissions and generates fiscal

[9] Household income cutoffs for CVRP are $150k for single-filers and $300k for joint filers.

Figure 2: Assessment of Policy Categories

	Policy Options		
Evaluation Criteria	Emissions Tax	Intensity Standard	Government-Financed Subsidy
Raise cost of dirty fuels	Large	Small	None
Lower cost of green fuels	None	Smaller than subsidy	Large
Overall impact on fuel price	Positive	Variable, depends on fuel type & pass-through	Negative
Impact on public funds	Positive	Neutral	Negative
Technology-neutral	Yes, across segments	Yes, within segment	No
Easily targeted to demographic groups	No	No	Yes

Note: For expositional simplicity, we focus on targeted subsidies. A targeted tax would share similar attributes to a targeted subsidy with the exception that it would raise the price of dirty goods, lower the cost of green goods, and contribute to rather than draw upon public funds.

revenue. Targeted subsidies, at the other end, allow policymakers greater discretion to target the policy towards particular products or particular socioeconomic groups.

3 Low Carbon Fuel Standards and EVs

SUMMARY

- In California the LCFS transfers roughly $3 Billion per year largely through increased cost and prices of high-carbon transportation fuels.
  - The funds subsidize low-carbon transportation fuels.
  - Sellers of electricity earn LCFS credits based upon assumptions of displaced petroleum fuels and the magnitude of residential charging.
  - LCFS credits awarded for charging passenger EVs generated roughly $400 Million in 2019.
- Under the current prices and administrative values, the LCFS credit value for a kWh of electricity is roughly 3 to 4 times higher than the average wholesale cost per kWh of electricity (Borenstein and Bushnell (2018)).
- While most LCFS credits lower the costs of low-carbon transportation fuels, LCFS credit value for sales of electricity has been applied to a wide variety of expenditures. Most of the value has been applied as lump-sum payments to EV owners and some to infrastructure investment.
  - The application of LCFS value to purposes other than lowering the cost of the low-carbon fuel represents a departure from the primary LCFS paradigm, which aims to make high carbon fuels more expensive and low carbon fuels less so to promote the latter.
- While most LCFS credits are generated through the production and sale of low-carbon fuels, credits have also been awarded for investment in EV-supporting infrastructure such as charging stations.
  - Infrastructure credits are only available for selected fuels (e.g. electricity and hydrogen, but not biofuels).
  - Awarding credits for infrastructure investment could in theory dilute the pool of LCFS credits and lower their value, although a regulatory cap on infrastructure credits limits the extent to which this is the case.
  - There are no rigorous quantitative estimates of the carbon savings create by infrastructure investments.
  - The scale of current infrastructure awards has been modest and therefore is unlikely to have impacted LCFS prices to date.

State and local policy makers in the U.S. and beyond are looking to Low Carbon Fuel Standards (LCFS) as a policy instrument for reducing GHG emissions in the transportation sector. California implemented its LCFS in 2011, setting a target of a ten percent reduction in carbon intensity (CI) values for transport fuels used in the state by 2020 from 2011 levels, as part of its climate policy. The target has since been updated to a 20 percent reduction below 2011 levels by 2030. Oregon fully implemented its LCFS, the Clean Fuels Program (CFP), in 2016, seeking to reduce CI values of Oregon transportation fuels by ten percent from 2015 to 2025. Washington State failed in several legislative attempts to pass a LCFS before passing one in 2021, to begin in

2023 and reach 20% below 2017 levels by 2038. Other jurisdictions with, developing, or considering an LCFS-like program include British Columbia (in effect since 2011), Canada and Brazil (under development and in effect, respectively), and Colorado (initial feasibility analysis).

While the LCFS regulation is now moving forward, its history is not without controversy. There have been legal challenges linked to the way it differentiates fuels originating in different locations. As we discuss below, the implementation of an LCFS requires a combination of detailed modeling and strong assumptions about the usage of the fuels. There have also been extensive debates about the models and assumptions used to establish the carbon intensities of different fuels used for compliance, particularly aspects linked to the indirect land use effects caused by biofuels. Opponents have raised concerns about the efficiency of the regulation and its potential impact on fuel prices, while proponents tout the potential to boost clean transport energy development.[10] Concerns contributed to the continued debate over the LCFS mechanism in some states, notably Oregon and Washington, that eventually passed LCFS legislation.

Importantly, the LCFS was built around a paradigm of reducing the carbon content of transportation fuels compared to reference fuels such as gasoline or diesel. Initial scenario analysis featured several possible compliance profiles, some heavily depending on using an increasing amount of low carbon fuel in ICE vehicles, and others laying out a larger role for other vehicle technologies, such as natural gas, hydrogen, and electricity. However, because the program as implemented did not focus on direct incentives beyond the fuel itself, it was not likely to be enough to promote the adoption and usage of alternative fuels such as natural gas, hydrogen, and particularly electricity that required investments in new vehicles and delivery infrastructure. In any event, the LCFS has expanded from a mechanism solely impacting the prices and costs of fuels, to one that also incentivizes infrastructure investments for particular alternative fuels - but not others - as well as direct GHG capture. While impacts thus far are small, the change has in turn transformed the way in which carbon prices are calculated and transmitted within the operation of the regulation.

3.1 The California LCFS

The California Low Carbon Fuel Standard was initially implemented in 2011, amended in 2013, re-adopted in 2015, and extended in 2019 to set targets through 2030. The LCFS sets a carbon intensity (CI) standard percentage reduction from the petroleum-based reference fuel that decreases each year. Implementation involves classifying all fuel volumes into a fuel pool defined

[10] See, e.g., `https://thelens.news/2021/03/10/lcfs-debate-continues-in-senate-committee/`

by the reference fuel used or displaced and setting a nominal CI standard for each fuel pool. The reference fuels are diesel, E10 gasoline, and, from 2019 forward, jet fuel.[11] The LCFS falls within a general regulatory framework known as intensity standards. It regulates the carbon intensity (e.g., gCO2e per megajoule) of transportation fuels, rather than the total amount of CO2 released through fuels.

As with all intensity standard mechanisms, the LCFS implicitly subsidizes the sales of fuels that are "cleaner" that is, lower in carbon intensity than the standard, and pays for the subsidy through charges imposed on fuel that is "dirtier" than the standard (CI rating above the standard). Sales of individual fuels rated at a CI below the standard generate credits, and fuels rated at a CI above the standard generate deficits, in amounts proportionate to volumes, with credits and deficits accruing on emissions relative to the standard. The LCFS requires annual compliance by regulated entities; all incurred deficits must be met by credits generated by production of low-carbon fuels or purchased from a credit market. The units of LCFS credits are dollars per metric ton of CO2e. LCFS credits can be banked without limit, allowing over-compliance under less stringent standards to help cover increased obligations as the standard grows more stringent, and they are fungible - meaning credits generated in any fuel pool are treated equivalently.

One of the attractions of policies like the LCFS to the policy community is that these subsidies and charges can work to partially offset each other; this, plus the fact that the charge or subsidy falls only on emissions relative to the standard, dilutes the pass-through of the implied carbon cost to retail fuel prices. For example, currently in California LCFS credits are valued at a little under $200/ton of CO2e, while credits under California's cap-and-trade program are valued at a little under $20/ton. Despite the fact that the LCFS carbon price is an order of magnitude larger than the price in the cap-and-trade program, the impacts of the two charges on retail fuel prices for conventional gasoline is roughly the same (about 18 cents per gallon). This consequence of the LCFS has also been criticized by environmental economists, who note that the dilution of the carbon cost works to encourage more fuel consumption than would arise under alternative instruments such as a carbon tax. In an extreme case, the subsidy of "cleaner" fuel could spur consumption growth to the point where the quantity of fuel that is consumed overwhelms the reduction in the carbon intensity of the fuel and carbon emissions can increase. With conventional fuels, this extreme case is unlikely as it would require extremely price-elastic fuel demand. However, the overall point that, relative to other regula-

[11] Alternative jet fuel can generate credits, but petroleum fuel is not charged deficits. Thus alternative jet is another pool of credits for offsetting on-road petroleum use.

tions, the LCFS can encourage consumption of fuels has continued to raise concerns in some circles.

Within the EV context, the negative consequences of the subsidy effect are linked to the question of how much conventional travel, and therefore fuel consumption, is displaced by the EV vehicle miles travelled (eVMT) induced through heavy subsidies. At one extreme, if EV subsidies induce eVMT from a household that previously relied exclusively on mass transit, the GHG savings are negative. At the other extreme, if every mile driven in an EV displaces a mile in an ICE vehicle, the GHG savings would be a function of the relative carbon intensities and fuel efficiencies of the two technologies. The LCFS framework adopts this latter approach, assuming that each eVMT offsets an amount of petroleum blend fuel used in a representative conventional vehicle.

3.1.1 Carbon Intensity: The Foundational Metric

The complicated process of calculating the carbon intensity (CI) of each fuel (or activity) is a foundational element of the LCFS. The reasons for the complexity are twofold. First there has been a desire to include GHG emissions from as much of the "lifecycle" of a fuel's production as possible. This tendency toward lifecycle measures is an offshoot of the wide use of biofuels to comply with the regulation. Since the tailpipe GHG emissions of biofuels are not that different from those of petroleum-based fuels, any GHG benefit from the use of biofuels requires consideration of the carbon captured while growing feedstock crops.[12] Once the door to considering one aspect of a fuel's lifecycle - crop production - was opened, it was natural to consider other aspects of the lifecycle - ranging from emissions from fuels burned in the refining process to the GHG impacts of "indirect land use change" (ILUC) such as deforestation stimulated by higher demand for croplands.

The second complication with developing and applying a CI score within an LCFS is that assumptions are necessary to link the carbon intensity (grams per megajoule) of a given fuel into a metric (tons of CO2e) that is directly comparable across fuels. The issue is that different fuels are used in different vehicles under different conditions and therefore create different GHG impacts. A "low carbon" fuel used in a very fuel inefficient vehicle could still produce a relatively large amount of GHG. In order to make different fuels directly comparable, the LCFS maintains a series of formulas representing assumptions about aspects of the fuel use, such as

[12] Carbon cap-and-trade programs, which typically encompass a much broader set of carbon emissions, usually treat biofuel emissions as zero-carbon, essentially assuming that the lifecycle emissions are zero. In principle lifecycle accounting methods could also be used under a carbon tax or carbon cap system, but to date they have not been.

the average mileage (joules/mile) of vehicles using a specific fuel.

The depth of complexity in this process is reflected in the CI scores awarded to a fuel such as "renewable" or captured, methane. The production of renewable methane results from the capture of methane from some location, such as landfill sites or animal-waste ponds at farms, that would otherwise emit methane directly to the atmosphere. Capturing methane therefore creates climate benefits, under the condition that its release was unregulated to begin with. In order to translate that benefit into a metric comparable with a gallon of ethanol, the LCFS makes an assumption about what would have happened to the methane if it had not been used in transportation, as well as how much methane is needed for a given mile of transport. When the resulting CI score of this fuel is negative (e.g. consuming the fuel in a vehicle creates climate benefits), sellers of renewable methane indeed benefit from the fact that most natural gas powered vehicles are assumed to be *less* efficient than their conventional counterparts, and in this way "sequester" more carbon per mile.

This example illustrates an idiosyncracy of the LCFS when it is applied to fuels that could be used for applications outside transportation. The LCFS credits fuels used in transportation under the assumption that they displace conventional transportation fuels, and ignores any other potential alternative value. However, since methane (or natural gas) is also used in electricity generation, home heating, and industrial applications, the consumption of renewable methane in a vehicle eliminates the possibility that this methane could have been used elsewhere. Until recently LCFS credits have only been available to methane that is "booked" against gas used in vehicles, and therefore renewable methane earns a much higher price in the transport sector than it would if used in one of these other sectors.[13]

3.1.2 Setting Carbon Intensity for EVs

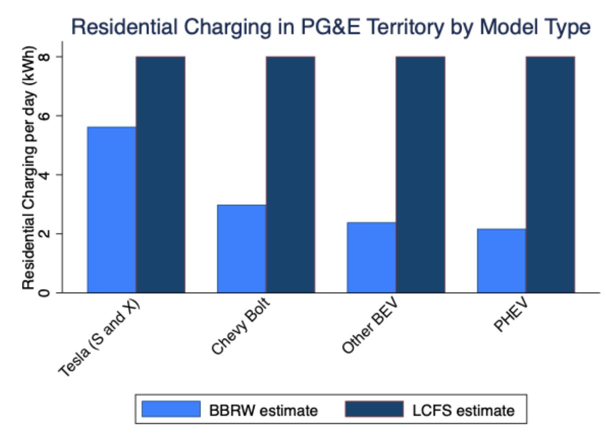
The previous sections allude to the fact that crediting a reduction in carbon content of liquid fuels used in the same kinds of vehicles in (more or less) the same way as conventional fuels is more straightforward than extrapolating the approach to new fuel/vehicle types. Calculating the amount of LCFS credits produced through the sale and consumption of electricity in an electric vehicle also requires:

(i) The amount of electricity used for vehicle charging.

(ii) The carbon intensity of the electricity used for vehicle charging.

[13] More recently, renewable methane that generates electricity can also be "booked" against electricity used for EV charging. Biogas used to make renewable hydrogen can also be credited as a transport fuel or input to fuel production.

Figure 3: Comparison of Residential Charging Load Estimates



(iii) The amount of electricity required to produce a unit of travel (e.g. eVMT) and the amount of carbon (gasoline) displaced by that eVMT.

There is little direct measurement of any of these factors. In most cases an administrative value based upon analysis and assumptions made by the California Air Resources Board, the agency overseeing the implementation of the regulation, is applied. Below we briefly summarize the assumptions made about each of these factors and the resulting values assigned for purposes of generating LCFS credits.

i *Quantity of Electricity used for Charging*.

At first glance, it may be somewhat surprising that even the *amount* of electricity going into vehicles is in most cases not currently directly measured. This is because most households do not separately meter the electricity going into vehicles from that going toward other household uses. According to recent LCFS figures, roughly 85% of EV credits for passenger vehicles are assigned for unmetered home charging. Until recently, the amount of home charging was estimated based upon the observed charging of a small sample of households who chose to install separate meters for charging their EV. All other homes with EVs were assumed to charge at a level equal to that of the average of the sample of directly metered households in the same utility area. There are strong reasons to believe that this is a highly biased sample of EV charging. Recent estimates from Burlig et al. (2020) indicate that actual home charging may be less than half as much as the values currently assigned to EV-owning households (figure 3).

Figure 3 highlights another shortcoming of the current load estimation approach - it makes no accounting for the model or type of EV and instead assumes all vehicles charge equally. If these estimates are correct and apply broadly in other utility regions, the amount of LCFS credits generated and awarded for EV charging may be close to twice the amount warranted by actual EV usage.[14] As discussed below, the LCFS in California now includes measures that provide additional incentives to directly measure residential vehicle charging, so presumably the share of unmetered charging could decrease going forward. The implication of this result is that EVs are likely being driven far less than LCFS assumes them to be. In addition, some surveys of transportation usage Davis (2019) imply that the average EV is driven considerably fewer miles than the average conventional vehicle. If EVs are being driven less, they are also presumably not displacing as much conventional fuel as the regulation gives them credit for. If EVs are not being driven less, it raises the question of where they are being charged. The LCFS as currently structured appears to over-compensate for residential charging. If the LCFS assumptions about *total* charging are correct than credits for away from home charging are massively under-represented.

ii *Carbon Intensity of the Electricity*.

The ARB uses two distinct potential types of values for the CI score of the electricity. For "generic" charging the ARB uses a value of 82.92 gCO2e/MJ, which is based upon an annually updated estimate of the average carbon intensity of all electricity consumed in California. This value could be misleading to the extent that the marginal electricity used for a vehicle may be of higher (or lower) carbon intensity than the overall average. This is because the production of electricity entails a mix of fuel sources, some of which (e.g. nuclear and solar) are producing at their maximum output whenever possible. The key metric for the attribution of additional carbon emissions is the *change* in total power sector emissions resulting from an increase in charging demand. The marginal carbon emissions rate could also depend upon the time of day, as well as other system conditions such as the amount of renewable electricity generation.

The ARB now allows entities to use CI scores that deviate from the average grid, in ways that reflect actual or "booked" electricity associated with charging. An entity can claim "smart charging" credits that are more reflective of marginal emissions, when hourly metered data for electricity going into a vehicle are available. The CI score associated with this electricity varies by the hour and is calculated based on CPUC data. The ARB also now offers the ability for some electricity to claim a CI value lower than the grid average (often a CI score of zero) if book-and-claim accounting establishes a contract for electricity of the appropriate CI, and the

[14]The original regulation foresaw the phaseout of crediting for unmetered residential EV charging around mid-decade, but regulatory amendments removed that stipulation, allowing continued use of CARB's estimates of residential unmetered charging, already in effect to that point. The regulation also indicates use of the best available informaiton to make the estimate for metered residential charging to be applied to unmetered charging, but does not supply information on how the metered estimate is made.

low-CI electricity can be shown to offset vehicle electricity charging.[15] The intent of allowing these categories of classification appears to be to reward, in the case of smart charging, timing of charging to match lower marginal emissions on the grid, and in the case of zero or other low carbon electricity credits, the procurement of this electricity by firms that sell either power for vehicles or, in the case of metering via the use of onboard telematics, the vehicles themselves.[16]

While the low-CI electricity initiative has unlocked access to further EV credit values for firms in EV supply chain, the logic applied to attribute carbon savings to such firms is questionable. For renewable electricity to be the marginal source of electricity in EV charging, said charging would have to be occurring simultaneously (and geographically co-located) with the curtailment of renewable energy sources due to some kind of "over-generation" condition. Even in California, such curtailments are relatively minimal.

iii *Electricity used and Gasoline displaced for a mile of travel*

The LCFS subsidizes the sale and usage of some types of energy. The justification for an environmental payment for using energy is that the use of the subsidized fuel displaces some amount of "dirtier" fuel. As discussed above, each eVMT is assumed to displace a conventional ICE VMT. In the case of EVs, this means that, while the "mileage" of different EV models varies (just as the mileage of ICE vehicles does), the LCFS necessitates an assumption about the efficiency of a representative EV relative to a representative ICE vehicle. This value, called the *Energy Economy Ratio* (EER), is set at 3.4 for light-duty electric vehicles.[17] In other words, a joule of electricity used for transportation is assumed to be consumed in a vehicle that is 3.4 times as efficient (in joules/mile) as the ICE vehicle whose VMT is assumed displaced by the eVMT.

The EER, as a ratio, is dimensionless. However, the GHG credit calculation requires a conversion of each type of energy (kWh of electricity, gallons of gasoline, mcf of methane) into a common unit of energy before the ratio can be properly applied. This conversion uses the *Energy Density* (ED) of each type of fuel. These factors are combined with the carbon intensity (CI) of each form of fuel, to produce the following credit "obligation" formula for kWh sales (in grams of CO2e).

[15] Contracted low-CI electricity must be either generated within the California Balancing Authority or meet CPUC REC deliverability requirements(ARB 2019). In the case of zero-CI electricity, the source must be renewable, excluding biomass, biomethane, geothermal, and municipal solid waste.

[16] After recent amendments, automakers, utilities, or other entities involved in home charging, can earn credits on the increment of CI savings below the grid average, if they provide the necessary telematics information to isolate home charging, and the residential electricity is non-metered.

[17] The detailed regulation is described in https://ww2.arb.ca.gov/sites/default/files/2020-07/2020_lcfs_fro_oal-approved_unofficial_06302020.pdf

$$(\frac{\text{CI}_{ev}}{EER_{ev}} - \text{CI}_{standard})xED_{ev}xEER_{ev}$$

Since the CI of electricity is lower than that of the standard, this "obligation" is negative, meaning that the above formula reflects the credits earned for each kWh of electricity that is estimated to go into an EV. If the kWh earn the zero CI classification, then the credits generated would equal the CI of the standard times the ED of electricity and the EER of 3.4. Under the current regulation this equates to .00113 tons/kWh, which at a credit price of $200/ton equates to about 22 cents/kWh. For reference that the wholesale cost of electricity is roughly 5 cents/kWh and the retail price in California is about 20 cents/kWh (Borenstein and Bushnell (2018)).

3.2 Infrastructure Credits

In 2018, the LCFS was amended to allow for credit generation from zero emission vehicle fueling infrastructure, namely hydrogen refueling stations for fuel cell vehicles and DC fast chargers for EVs. The fueling infrastructure had to be put into public service in or after 2019. Infrastructure crediting for ZEVs was the first allowance for LCFS credit generation not directly tied to actual low carbon fuel use, and was crafted in response to an Executive Order instructing ARB to recommend ways to use the LCFS program to assist ZEV infrastructure build-out. EV fast charging infrastructure credits are limited to 2.5% of deficit generation from the prior quarter; hydrogen has a similar limit. ARB also sets credit generation potential per charger to try to stay within a bound of its installation costs. Infrastructure credits are issued based on what would have been earned had unused charging capacity been in use. The infrastructure credits awarded at a given facility decline as operating capacity - and LCFS credit generation for actual fuel flows - increases. Thus more infrastructure credits can be earned at stations that support little actual charging, than at those with high volumes of charging. Applications for EV fast charging infrastructure credits are open until 2025.

3.3 Advanced Credits

As of mid-2020, the LCFS was amended so as to harden the program's credit price ceiling by drawing on residential electricity credits expected to be generated in the future. In the case of lack of compliance with the standard once parties have pledged already-generated credits to a clearinghouse credit sale at year's end to cover any remaining outstanding deficits, ARB releases to the large utilities the necessary "advanced credits," which are then sold to regulated parties that need them for compliance. The regulation stipulates a limit on the allowable amount of such "advanced credits" and a schedule for their "repayment" to the program (by ARB withholding the predetermined amount of residential electricity credits generated in a future year). The idea behind the system was to create a mechanism to shore up the program's "soft" credit price ceiling while enhancing near-term incentives for vehicle electrification. This mechanism, if deployed, will mean additional carbon savings relative to a stricter standard in the future will be needed for compliance, as some fuel flows are then diverted to repaying the advanced credits.

3.4 Disposition of LCFS credits for Electricity Sales

There are two issues related to the disposition of LCFS credits for electricity sales: who earns the credits and how the credit revenue is spent. Both have evolved under the LCFS to reduce the chances for electricity sales to go uncredited altogether while expanding the list of who can earn electricity credits,[18] and adding additional restrictions to credit revenue use.

Initially, electric service providers - utilities or provider of electric charging infrastructure - earned the credits, unless explicit agreements were made to transfer credit ownership to others. Explicit agreements allowed credit generation rights to transfer to charging station owners or homeowners. There were no restrictions, at least from the ARB, on how revenue from LCFS EV credits was used. In 2012, the program was amended to give charging station and fleet owners first claim on public charging EV credits, with the utility able to opt-in to claim credits if others didn't act. The utility remained the credit generator for residential charging. This narrowed the scope for potential LCFS credits being "stranded" due to inaction. The 2012 amendments also directed credit sales revenue to be used in ways that would benefit current EV customers, provide rate options to encourage off-peak charging, and educate consumers on EV benefits. Further amendments in 2016 loosened the first criterion so that sales revenue must benefit current or future EV customers, made the list of eligible non-utility credit generation entities for light-duty vehicles - charging stations and EV fleet owners - more explicit,[19] and closed the loop on the potential for stranded credits by having all unclaimed electricity credits default to the utility.

[18] Electricity is an opt-in fuel in the LCFS, meaning it is not explicitly regulated because its CI was deemed to meet last-year targets from the outset.

[19] The amendments also expanded the list of EV types that could claim credits to include off-road sources, such as electric forklifts and electric guideway (e.g., light rail)

This system resulted in a patchwork of programs statewide to spend LCFS EV credit value. For the utilities regulated by the CPUC, expenditure programs had to be approved and details are in the public sphere. One utility, SDG&E, used EV revenue from 2017-2019 for an annual rebate to registered EV owners in its utility area. The remaining CPUC utilities (PG&E and SCE) instituted post-purchase EV rebates.[20]

Additional LCFS amendments in 2019 created the possibility for low-CI electricity credits, as well as a framework to substantially shift EV credit revenue toward a single statewide point-of-purchase rebate program. Residential charging at grid-average CI generates "base credits," with the electricity provider earning the credits. Low-CI residential electricity generates "incremental credits" based on the gap between the grid-average CI and the charging electricity CI.[21] For metered electricity, the entity with control over the metered data is eligible to earn the credits, meaning EV manufacturers in the case of no at-home metering.

Residential "base credits" provide the funding for the statewide point-of-purchase rebate program, called the *California Clean Fuel Reward*. Investor-owned utilities must funnel 67% of residential base credit revenue towards point-of-purchase rebates. Publicly-owned utilities have lower percentage contributions that vary by utility size, and edge up in 2023. The maximum amount of the rebate will increase with EV battery size. The funds support a rebate of $1500 per vehicle that started November 17, 2020.[22]

Other utility EV credit value programs are closing out. Amendments made in 2020 added an equity dimension to EV credit disposition. Starting in 2022, utilities must earmark a proportion of the remainder of the EV base credit value (called "holdback credits") for use in projects that support transport electrification targeted at disadvantaged or low-income communities, rural areas, and/or low-income individuals. The rest of the revenue from EV credits - including incremental credits earned for low-CI electricity used at residences - is subject to the same spending restrictions as before.

[20]For SDG&E, annual per vehicle rebates for EV owners were $200, $500, and $850 for 2017-2019, respectively. The other utility one-time post-purchase rebates ranged from $450 to $1000. In the case of SMUD, the EV owner could opt for a one-time $599 cash incentive or a Level 2 charger.

[21]Non-residential low CI electricity credits do not have these categories.

[22]https://ww2.arb.ca.gov/news/carb-and-california-electric-utilities-partner-offer-consumers-1500-electric-cars.

4 Survey of Empirical Evidence

SUMMARY

- An EV purchase subsidy that reduces the purchase price by 10 percent increases EV demand by 10-35 percent.
  - Effect of subsidies appears to be larger for low- and middle-income buyers
  - Effective subsidies imply that potential buyers are not (yet?) willing to pay market prices for EVs
- Car buyers are willing to pay nearly $100 today for $100 in future fuel savings.
  - Substantial operating savings of EVs vs gasoline cars ought to stimulate demand in areas of the U.S. where electricity prices are low
  - Evidence from early adopters indicates that high gasoline prices may stimulate EV demand more than low electricity prices
  - Drivers do not adjust their miles traveled much in response to higher gasoline prices. Whether the same is true for EVs (e.g. in California where many EV drivers pay high electricity prices) remains to be seen
- There is insufficient evidence to substantiate claims that higher density of EV charging infrastructure stimulates demand for EVs
  - Credible estimates must overcome a ‘chicken and egg’ problem, and more (and better) research is required to convincingly assess such claims.

The extent to which LCFS can promote GHG abatement via EVs depends on its ability to shift incentives on three margins: up-front cost relative to gasoline alternatives, relative usage expense, and convenience. There is a growing body of academic research seeking to quantify the effects on these margins. On the other hand, the EV market is young, and high-quality research often requires retrospective analysis that spans a high volume of cars over a long period of time. For this reason, we continue to rely on evidence of consumer behavior in the context of gasoline-powered vehicles. There are many questions still in need of deeper study. In this section we review the state of peer-reviewed empirical evidence that exists today, refer to works-in-progress (mainly by the authors) that has not yet reached the journal submission phase, and identify gaps in our knowledge that require more research.

4.1 The importance of purchase incentives

Up-front purchase incentives, mainly in the form of government subsidies, are an important policy lever for stimulating EV adoption. Several papers estimate the impact of these incentives on demand for hybrid, electric or alternative-fuel vehicles.

Some insights can be gleaned from research on hybrid adoption. Both Gallagher and Muehlegger (2011) and Chandra et al. (2010) exploit the timing and coverage of U.S. state and Canadian province hybrid vehicle incentives, and estimate that a $1000 tax incentive was associated with 31 to 38 percent increase in hybrid vehicle adoption. These are enormous effects. They may reflect the importance of incentives on early adoption of hybrids, or perhaps they stem from particularities of the markets being studied. Estimates of the response to EV subsidies are substantially lower.

A 10 percent subsidy-induced decrease in EV purchase price leads to a roughly 10-35 percent increase in EV adoption, according to existing evidence in the U.S. Li et al. (2017), Li (2017), and Springel (2017)) estimate demand elasticities for early EV adopters in the range of 1-2. Clinton and Steinberg (2017) estimate an 11 percent increase in EV registrations for every $1000 in subsidies. They don't report an elasticity in the paper, but at $30,000 purchase price their estimates imply an increase in demand of 33 percent in response to a 10 percent price decrease. Muehlegger and Rapson (2018) examine the effect of subsidies on low- and middle-income EV demand. They also find a 33 percent increase in demand from a 10 percent subsidy.[23]

Some caution is warranted when considering extrapolating these results to future EV demand. Research on past programs may not provide a good guide as to the impact or fiscal costs of meeting ambitious EV adoption targets for two main reasons. First, past incentives for alternative vehicles rarely offer the quasi-experimental variation necessary for clean causal identification. In virtually all cases, the decision to offer an incentive may be correlated with underlying demand for EVs. States with populations predisposed to purchase EVs are more likely to offer incentives, confounding estimation of the causal impact of incentives on vehicle adoption. For example, Californians have a high underlying appetite for EVs, and California offers among the most generous EV incentives in the country. Even in settings where subsidies are plausibly exogenous, such as in the case of the program studied by Muehlegger and Rapson (2018), other features of the setting may make it difficult to generalize to other states or populations. Second, the populations that have adopted EVs thus far may not exhibit the same price sensitivity as subsequent target populations. It helps to have studies that examine EV demand in low- and middle-income populations, such as Muehlegger and Rapson (2018); but there is always a possibility that car buyers in regions that have not been exposed to EVs to the extent that, say, California has, will be very different. Of particular interest are households living in multi-unit dwellings. For these drivers, availability of in-building charging infrastructure may be a far more effective inducement than up-front discounts to the purchase price.

Finally, we note that the fact that subsidies are effective at increasing EV demand consti-

[23] The rate of subsidy pass-through is also an important policy parameter. All evidence points to full pass-through, both in the context of hybrid cars (Sallee (2011), Gulati et al. (2017)) and EVs (Muehlegger and Rapson (2018).

tutes a 'glass half-full, glass half-empty' paradox. On one hand, policymakers likely view high responsiveness of EV demand to EV subsidies as a positive. Their policies are working! However, the same result can be viewed through a different lens. To the extent EV subsidies are effective, and indeed perhaps responsible for the majority of EVs on the road today in the world, this means that the EV market would be substantially smaller without those subsidies. From that viewpoint, attempts to expand EV adoption into the mass market will prove to be difficult due to the fact that relatively few customers appear willing to pay unsubsidized market prices EV technology. This implies that large ongoing subsidy bills will be necessary to meet ambitious adoption goals. Under such a scenario (which we view as entirely plausible), the main justification for subsidies today ought to be to bring down EV costs in the future. Unfortunately, there is little theory that predicts governments will be more effective at reducing long-run EV costs than private firms. Moreover, it is almost impossible to estimate that causal effect of subsidies on future costs. This more pessimistic scenario reinforces the wisdom of maintaining viable low-carbon transportation options beyond EVs.

4.2 The dual roles of energy costs

Energy costs affect two important consumer decisions: whether to adopt an EV in the first place, and how much to drive it conditional on adoption. In this section we will review the state of evidence on each of these margins. The bulk of empirical work in this area studies consumer behavior relating to gasoline-powered cars, but we nonetheless view it as relevant to the EV market. The authors of the present study are writing what we believe is the first study of the effect of energy costs on EV adoption, and we will mention preliminary results from that study in this section as well.

There is a growing consensus in the academic literature that car buyers incorporate future fuel costs in their willingness to pay for fuel economy at the time of purchase. This makes sense, because energy costs and fuel economy determine how costly it is to drive a mile in the car. To the extent buyers are forward-looking at the time of purchase, all else equal, they will be willing to pay more for a car with lower future operating costs. To compare finding across different papers, results are typically reported in terms of how much a car buyer is willing to pay at the time of purchase for $100 in present value of future fuel savings.[24]

[24] "Present value" adjusts for the fact that a dollar received in the future are less valuable than a dollar received today. Future receipts must be discounted in order to compare them to a payment made today. An appropriate discount rate in this setting would be the interest rate at which car buyers can borrow money. Over the course of the studies we discuss, a discount rate of 4-5 percent would be reasonable.

Four recent papers find that consumers are willing to pay between \$70 and \$100 more for a car today if it saves them \$100 in (present value of) future fuel expenses, where \$100 is referred to as 'full valuation'. Busse et al. (2013) find full valuation in the new and used car markets in the U.S.; using different data and methodology, Sallee et al. (2016) find full valuation in the used car market; Grigolon et al. (2018) find nearly full valuation (\$91) in the European new car market; and Allcott and Wozny (2014) estimate that car buyers are willing to pay \$76 at purchase for \$100 in future savings.

Notwithstanding this evidence, controversy remains. Policymakers across the political spectrum appear to be stuck on the idea that consumers are "myopic", meaning that they are not willing to pay today for future savings. This can be seen in assumptions of strong consumer myopia that they build into their cost-benefit analyses. For example, both the Obama (2016) and Trump (2018) EPA analyses of Corporate Average Fuel Economy (CAFE) Standards assume that consumers are willing to pay only \$15-\$25 up front for \$100 in (present value) future fuel savings.

The valuation parameter is important for the EV market and prospects for EV adoption, since electricity prices vary dramatically state-by-state. Potential EV buyers on a standard residential electricity tariff in most of California are likely to be paying upwards of \$0.30 per kWh to charge their EV, as compare to roughly \$0.10-\$0.15 per kWh in most of the rest of the country. These electricity price differences translate directly into cost per mile traveled by EV, making EVs far more costly to drive in California than in the rest of the mainland U.S.

The authors of this study have a working paper (Bushnell et al. (2020)) that estimates how gasoline and electricity prices affect demand for EVs. We examine EV adoption behavior by households on either side of electric utility boundaries in California, where many municipal retailers sell electricity at prices far below those charged by the main investor-owned utilities in the state. We find that high gasoline prices have a much larger effect on EV demand than high electricity prices, at least among the relatively early adopters that we study (2014-2017). More research is needed, particularly as EV adoption extends into the mass market, where financial considerations may be more important than "warm glow" that motivates many early adopters.

Several papers also examine how VMT (intensity-of-use) is affected by cost-per-mile. The highest quality evidence finds that a 10 percent increase in cost-per-mile induces a roughly 0-2.5 percent decrease in VMT.[25] Taken in total, these results imply that drivers may not adjust

[25] Knittel and Sandler (Forthcoming) find a 1.5 percent decrease, but with substantial differences across vehicles. Hughes et al. (2008) find a 0.3-0.8 percent decrease in recent years. Gillingham (2014) find a 2.3 percent decrease from evidence in California. For a review of this literature, see Gillingham et al. (2016).

their VMT very much in response to cost-per-mile incentives. However, direct evidence about the effect of electricity prices on eVMT would be informative.

4.3 The role of EV charging infrastructure

It is often claimed that high EV charging station density stimulates EV adoption in nearby neighborhoods. However, it is extremely challenging to assess these claims. Researchers must disentangle a 'chicken-and-egg' problem to determine the direction of causation. In neighborhoods with lots of charging stations and EVs, are the charging stations there in response to many prospective customers, or was it the presence of the charging stations that induced demand for EVs in the first place? Li (2017), Springel (2017), and Li et al. (2017) attempt to answer this question. Readers of this literature are left with the impression that investments in EV charging infrastructure are a more cost-effective at stimulating EV adoption than EV purchase subsidies.

There is much more research needed to substantiate such a conclusion. To disentangle the 'chicken-and-egg' problem and understand the causal effect of charging station density on EV adoption, researchers need a variable (a so-called 'instrument') that *independently* affects charging station density *but is otherwise uncorrelated with EV demand*. Ideally, there would be a policy that affects the supply of charging stations in some places but not others. Unfortunately, such variation has not been used yet in the empirical assessments. Instead, and understandably, the literature attempts to estimate the relationship using either instruments that are likely to be correlated with EV demand, and therefore not suitable to break the chicken-and-egg problem.

In the absence of credible estimates of the parameters of interest, theory can offer some insight into the relationship. We offer three intuitive themes that are common to the empirical research. First, network externalities operate largely at the local level, rather than the industry-level. Although charging infrastructure in a distant metro area might make purchasing an electric vehicle marginally more attractive, the local charging network is much more relevant and valuable to a prospective buyer. Likewise, a large EV fleet in California might have little impact on the decisions of a firm building charging stations in the Midwest. Like the externalities arising from local-pollution, a one-size-fits-all approach is unlikely to be successful, since it will over-encourage adoption in some areas while under-encouraging it in others.

Second, if the network effects from each new EV on the road diminish as EVs become more common, incentives are most valuable at the early stages of market development, and diminish as the incremental network benefits from further increases in the fleet decline. 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.

Third, compatibility plays an important role in facilitating network effects. Open standards (in this case, charging stations that work with a wide range of vehicles) more readily generate network effects across manufacturers. In contrast, closed standards (such as Tesla's charging network) generate benefits only for Tesla drivers and provide benefits that can be captured by the manufacturer, limiting the external benefits that justify incentives for charging stations. Li (2017) simulates that a common charging standard would both increase demand for EVs (by facilitating network effects) *and* decrease the number of charging stations (by reducing overlap of currently-incompatible networks).

What does this mean for LCFS? To the extent LCFS funds are used to subsidize charging infrastructure investment, there would be enormous societal benefit to deploying those funds in a manner that allows for credible ex post analysis of its effects. In the absence of more credible evidence, it is unwise to rely heavily on EV charging investments as drivers of EV adoption. While we may end up learning that such a causal relationship exists, we have little confidence drawing such a conclusion from the existing literature.

5 Conclusion

The electrification of transportation constitutes a transition of immense scale. There were fewer than 350,000 EV sales in the U.S. during 2019, out of total auto sales of 17 million. While costs of EVs are declining and acceptance of the technology has grown dramatically over the last decade, a 2 percent EV market share implies that a shift to majority EV transportation is still in its earliest phase. While the adoption of EVs would likely continue to expand (at least modestly) absent aggressive policy support, major electrification on the time scales supported in many climate policy plans will require substantial investment spurred by policy. In this white paper we have summarized and discussed the three channels that policies typically influence: vehicle cost, operating (or fuel) costs, and infrastructure support. To date, the most substantial policy support of EV adoption has been directed at vehicle costs through tax credits and a variety of other direct and indirect subsidies such as a ZEV mandate operating in several states.

Despite the growing number of jurisdictions embracing electrification as a core greenhouse gas mitigation strategy, and devoting considerable public and private funds in the pursuit of this strategy, there are significant gaps in our knowledge about what margins most significantly impact EV adoption. Therefore, we still do not know which policies are most likely to successfully expand EVs on a significant scale, or even whether it is, in fact, even optimal to do so. A major reason for these gaps in knowledge is the fact that, for the most part, policies supporting EVs have not been implemented in way that makes them amenable to rigorous policy evaluation. Simply put, policy evaluation requires being able to compare groups exposed to these policies to similar groups that were not. Subsidies and infrastructure investment, where they have been applied, have been rolled out simultaneously and broadly, making it very difficult to perform an empirical assessment of the causal relationship between policy support and EV adoption. There are a handful of studies that have attempted to exploit the variation over time, or geography, of tax credits, fuel prices, and infrastructure expansion, to measure the impacts of these factors. While the research designs are not ideal, some preliminary lessons have emerged.

First, as with conventional vehicles, purchasers of EVs are responsive to fuel prices. When and where gasoline prices are high, consumers are more likely to favor EVs. In fact, consumers appear to be much more sensitive to gasoline prices than they are to electricity prices when choosing whether to buy an EV. This is probably due to the fact that electricity rates are often complicated and not well understood, even by relatively sophisticated consumers. In parts of California it is more expensive to power an EV per mile than a reasonably fuel-efficient gasoline car; and yet California is the epicenter of the U.S. EV market.

Second, EV purchase subsidies have been a key driver of EV demand in the U.S. Based on the estimated effectiveness of federal and state EV incentives, it's likely that over 30-50 percent of the EVs currently driven in the US would not have been purchased without subsidies. There are two important policy implications that follow from this result. On one hand, EV subsidies will likely be an effective (and essential) component to future adoption of EVs. On the other hand, the essential nature of EV subsidies reflects an unwillingness of car buyers to pay current market prices for EVs. Why this may be the case holds the keys to shaping effective EV policy in the future. If EVs simply do not provide people with the type of transportation services that they desire, then it calls into question whether a full-scale EV transition is feasible (or even a good idea). Alternatively, perhaps we are still so early in the EV transition that potential buyers need to learn more about EV technology, and allow time for it to improve (e.g. cost, range, charging networks) before considering it a genuine substitute to gasoline cars. The advantage of more technology-neutral carbon policies is that they allow policy makers to keep their options open, and allow consumer preferences and market forces to determine which technologies are best suited to meet society's transportation and environmental needs.

Third, EV infrastructure lags far behind the distribution and retail channel coverage of gasoline. Drivers on long-haul trips with EV technology currently have inferior refueling options, and it would not be surprising if many prefer non-EV technology until that situation improves. Moreover, people without parking at their place of residence (e.g. multi-unit dwellings) would require access to charging elsewhere. Some research has shown that funds invested in charging networks induces more EV adoption than vehicle purchase rebates. However, this research necessarily deals with the early phase of the EV market and is constrained by the lack of policy and investment variation necessary to cleanly isolate the effect of charging infrastructure from other factors.

The policy resources needed to dramatically expand the share EVs are potentially enormous. The research described here estimates that a 10% decrease in the purchase price increases EV sales by 10% to 35%. Electrification of even 20% of the US fleet would require an increase of roughly 1000% over the 2019 EV market share, seemingly requiring a significant reduction in current EV costs *and* major continued subsidies. This raises a central policy question about the support of electrification: where do these funds come from?

Broadly speaking there are two options: from general tax funds or from the petroleum based transportation sector. Subsidies and tax-credits drawn from general public funds could continue to fund both infrastructure investment and vehicle purchases. A gasoline or carbon tax can provide support in one or two ways. Such a tax (or carbon price) would make conventional vehicles more expensive relative to EVs by raising their costs. If the funds raised through the tax are further directed to EV subsidies it can further influence adoption. An intensity standard - the most prominent examples here are ZEV mandates and the LCFS - similarly charges the high-carbon technology and automatically direct funds to subsidize EV adoption.

In many ways, the differences between an emissions charge and an intensity standard are differences of optics and priorities. With a carbon tax, the main point is to set a price on carbon and let firms and consumers decide how to change their behavior in response. The funds raised is a secondary effect. With the LCFS (or a ZEV mandate) the point is to explicitly mandate lower carbon sources (low carbon fuel or vehicles), and the mechanism that achieves the mandate is an implicit tax on higher carbon sources that in turn funds the lower-carbon technologies. The differences between "taxes" and "standards" is therefore sometimes overblown. Fundamentally both act as taxes - either implicitly or explicitly - on dirty inputs. The main difference is that a standard pre-commits the funds collected via the tax to a set of offsetting green inputs.

To date, public messaging around standards has also successfully avoided being pejoratively labelled as "taxes." However, it is not clear how long this success can be maintained. Cap-and-trade programs were once considered politically easier to implement than taxation largely because they imposed implicit, rather than explicit taxes. This advantage faded as opponents were able to successfully frame such efforts as "cap-and-tax" programs.

What both approaches do share are elements of technology neutrality. The value of technology neutrality is largest when there is large uncertainty about the ultimate identity and mix of fuels and technological solutions that can best achieve policy goals. Such policies reward compliance based upon estimates of how much carbon savings they provide, rather than by how they provide it.

This report has focused on the potential for a specific intensity standard, the low-carbon fuel standard (LCFS) to significantly boost EV adoption. There is a paradox inherent in relying upon a technology-neutral standard as a prominent source of funds for advancing a specific technology, EVs. In order for a LCFS to direct sufficient revenues to the channels that appear necessary to promote substantial EV adoption, it needs to changed in such a fundamental way as to no longer really be a technology-neutral standard. In other words, it is possible to imagine how the mechanism of a LCFS - raising revenue from sellers of high carbon fuels - can direct significant resources to EV purchases and infrastructure - but in doing so it departs substantially from its original design paradigm of supporting low-carbon *fuels*.

California's LCFS has started down this path by both awarding credits for activities other than selling low-carbon fuels (such as installing charging stations) and by directing revenues from electricity sales toward vehicle rebates, rather than lowering the electricity price paid for charging vehicles. By contrast, the program contains no analogous incentives for biofuels infrastructure, such as the installation of e85 pumps. The resources directed to light duty EVs amount to roughly 10% of the $3 Billion currently raised annually by the LCFS, under a series of extremely generous administrative rules and assumptions that favor EVs. Policymakers have begun to treat the LCFS as a means for directing resources to preferred technology solutions, such as ZEVS in California, setting the policy on a path different from the science-based, technology-neutral fuel standard it was originally positioned to be.

From a policy perspective this transformation of the LCFS may be considered a feature rather than a bug, at least for supporters of EVs. California leadership has decided upon EVs as policy priority and is working to steer its existing climate policies toward that goal. The complicated and subtle ways in which the LCFS now raises funds and directs them toward a preferred technology solution may in the end make it a more durable and acceptable policy tool than one that works in a more explicit and transparent fashion. In the process, however, it will likely reduce the rewards for innovation in other solutions that are either more widely applied today or readily put to use, and may have an important role to play in future low-carbon transportation, particularly beyond the light duty sector in focus here.

One last potentially important factor through which a LCFS can provide support is through the price of electricity itself. Somewhat ironically, high electricity prices are a both barrier that a LCFS in its "pure" form would be well positioned to address and the one aspect of electrification that has not benefited from the LCFS to date. While research on California has indicated that electricity prices have less salience than gasoline prices for purchasers of EVs, this may be short-lived. The price of electricity does have an impact and there is reason to believe that EV drivers will become aware of it over time.

The importance of electricity prices could also be larger outside of California, for two reasons. First, electricity prices are considerably less complex in most US states than in California; and, second, *if* the assumptions supporting the credit values of electricity in California are taken at face value, the carbon savings from using electricity in an EV should be enough to offset the complete cost of electricity. A zero-cost fuel could have considerable salience in promoting the attractiveness of EVs. Therefore one role for a LCFS that has been largely untapped may be to deploy it in the way it was originally designed, as means for subsidizing the price of low-carbon fuel.

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