Headwinds and Tailwinds: Implications of Inefficient Retail Energy Pricing for Energy Substitution

By SEVERIN BORENSTEIN AND JAMES B. BUSHNELL*

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* Borenstein: Haas School of Business, University of California, Berkeley, CA 94720-1900, severinborenstein@berkeley.edu. Bushnell: Department of Economics, University of California, Davis, CA 95616, jbbushnell@ucdavis.edu. For outstanding research assistance and very helpful comments, we thank Sara Johns, Jenya Kahn-Lang and Dan Mazzone. For valuable comments and discussions, Mohit Chhabra, Alejandra Meija Cunningham, Lucas Davis, Tatyana Deryugina, Ari Gold-Parker, Catherine Hausman, Matthew Kotchen, Amber Mahone, Erin Mansur, Nick Muller, Allison Seel, James Stock, and participants in seminars at The Energy Institute at Haas-UC Berkeley. We also thank Catherine Hausman for sharing data on natural gas retail rates. This research was supported in part by the California Public Utilities Commission.

ABSTRACT: *Electrification of transportation and buildings to reduce greenhouse gas (GHG) emissions requires massive switching from natural gas and refined petroleum products. All three end-use energy sources are mispriced due in part to the unpriced pollution they emit. Natural gas and electricity utilities also face the classic natural monopoly challenge of recovering fixed costs while maintaining efficient pricing. In this paper, we study the magnitude of these distortions for electricity, natural gas, and gasoline purchased by residential customers across the continental United States. We find that the net distortion in pricing electricity is much greater than for natural gas or gasoline. In most of the country, residential retail electricity prices are well above social marginal cost (the sum of private marginal cost and unpriced externalities), while in some areas with large shares of coal-fired generation, prices are below SMC. We then analyze the impact of these pricing distortions on the incentive to adopt electric space heating, water heating, and vehicles in California. Combining our estimates of the gap between price and SMC for each of the fuels with a large survey of California households' energy use, we calculate the distribution of annual fuel costs for space heating, water heating, and electric vehicles under actual pricing and under counterfactual prices equal to SMC. We find that moving prices for all three fuels to equal their SMC would significantly increase the incentive for Californians to switch to electricity for these energy services.*

I. Introduction

Around the globe, strategies for mitigating the emissions of greenhouse gases (GHGs) are coalescing around a common blueprint that involves both decarbonizing the electric sector and transitioning as many energy-using activities as possible away from fossil fuels and into electricity usage. This process is known as electrification. In the United States, the first phase of this strategy is much more advanced than the second. While greenhouse gas emissions from the electricity sector have been declining steadily over the last two decades, emissions from the transportation and building sectors have continued to grow.[1]

The process of transitioning buildings and transportation away from their primary sources of energy, natural gas and petroleum, respectively, is at the forefront of climate plans, but faces significant barriers. The capital stock of existing vehicles and appliances is enormous and replacement is relatively slow under normal conditions. There are also potentially significant additional infrastructure investments needed to support the large scale expansion of electrification, particularly of transportation. At the same time, an enormous amount of existing infrastructure and other capital could become "stranded" if the consumption of natural gas and petroleum declines as rapidly as called for by some climate policies. Fortunately, technological advancements have recently closed much of the quality gaps between conventional vehicles and household appliances – a term we use to mean all in-home energy-using devices, including furnaces and hot water heaters – and their electric-powered counterparts, but some differences remain.

One additional challenge to the process of electrification that is obvious to economists, but surprisingly less prominent in policy discussions, is overcoming relative retail price disparities between the three fuels. For many US residents, electricity can be the most expensive of the three energy sources on a normalized basis. Furthermore, the advancement of the two-pronged electrification strategy could enlarge this gap. While low-carbon electricity production sources have rapidly declined in costs, most analyses predict that "deep" decarbonization will require costly investments in battery storage, transmission, and more exotic (and expensive) technology solutions, such as hydrogen for long-duration storage. In addition, while electricity may become more expensive as it gets cleaner, the demand reductions

[1] See `https://cfpub.epa.gov/ghgdata/inventoryexplorer/index.html`

produced by any success of electrification would almost certainly depress fossil fuel prices.

For economists, the logical solution to such a pricing gap would be carbon pricing either through a tax, cap-and-trade, or some other mechanism. This solution is complicated by the fact that there are existing taxes and other pricing distortions that have already caused fuel prices to deviate from marginal costs. The strict application of a pigouvian tax to account for the environmental externalities without accounting for pre-existing distortions could exacerbate rather than correct some of these pre-existing distortions.

In this paper, we examine the relative pricing distortions of the three primary energy sources most relevant to electrification policies: electricity, natural gas, and gasoline. For each of these fuels we develop an estimate of the social marginal cost (SMC) of supplying the fuel to residential customers and compare it with the relevant retail price faced by individual residential customers. In each case, retail prices can be inefficiently inflated by regulatory pricing structures (in the case of electricity and natural gas) or market power, and inefficiently depressed by a lack of accounting for environmental externalities. There are two aspects of pricing distortions in retail energy: the within-fuel gap between retail price and its SMC and the across-fuel "gap in gaps" that compares the relative signs and magnitudes of the mis-pricing between fuels. This latter pricing gap is particularly relevant for assessing the prospects for, and implications of, a large scale strategy of substituting from end-use fossil fuel combustion to electricity.

The paper is divided into two main sections. The next section describes our calculations of marginal prices and SMC for the three fuels. In Borenstein and Bushnell (2019), we find that significant pricing distortions arise in electricity, where prices can be up to 4 times SMC in some states, and 25% or more below SMC in other states. In much of the US, however, the distortions of regulatory rate design offset those of the omitted externality pricing, leaving prices fairly close to SMC on average. Residential natural gas prices, which include substantial margins designed to recover sunk infrastructure costs, are only modestly above SMC in much of the country due to negative environmental externalities that increase SMC. Gasoline, by contrast is largely underpriced relative to SMC, a gap that is most extreme in dense urban areas most vulnerable to local air pollution.

The degree to which any pricing gaps would change behavior will depend in part upon the availability of a reasonable substitute for any given appliance or vehicle. The second half of this paper applies the pricing findings from the first half to specific electrification goals in California, a state that is pushing the electrification policy perhaps harder than any other. We examine the degree to which the pricing distortions we document influence the economics of the fuels costs for electrifying space heating and water heating – which combined account for about 86% of residential natural gas use in California. We show that for both space heating and hot water heating changing the volumetric prices of electricity and natural gas from their current levels to SMC would greatly alter the economics of the energy choice for these primary residential uses. In both cases, current energy prices tilt strongly in favor of natural gas, but pricing at SMC would effectively eliminate that difference. We also do a rough comparison of the pricing distortions in California between gasoline and electricity in the context of two examples of vehicle substitution. Lower fuel costs are supposed to be one of the big advantages of electric vehicles, but at current rates in California – where we find gasoline is priced below SMC in most locations and electricity is priced well above SMC – we find the fuel cost advantage of EVs would increase by about $500 per year on average if each fuel were priced at SMC.

II. Estimation of Existing Pricing Distortions

In this section we develop estimates of both marginal retail prices and social marginal cost (SMC) for the three main residential energy sources: electricity, natural gas, and gasoline. Each energy source presents some specific issues in developing such estimates. Electricity and natural gas are both distributed by regulated utilities, and the regulatory rate-making process plays an important role in setting prices for residential customers. As we describe below, infrastructure and other fixed costs comprise a significant share of retail prices.[2] In some areas these costs are at least partly recovered through a fixed monthly charge component of a two-part tariff, but in all cases variable prices of electricity and gas are designed to also recover some share of these fixed costs. Gasoline, which is distributed at commercial retail stations, is sold exclusively at a variable price in a fairly competitive market that is under little economic regulation and that likely reflects some degree of market power.

[2]See Borenstein, Fowlie and Sallee (2021).

To develop externality costs for each fuel, we lean heavily on estimates developed by Nicholas Muller in the current version of his Air Pollution Emission Experiments and Policy (APEEP) model of air pollution damages, AP3.[3] These estimates account for damages from four criteria pollutants as well as CO_2. We do not account for externalities that are unlikely to differ significantly based on fuel type, such as the traffic congestion and accident externalities associated with driving, because they would not impact the net efficiency of fuel choice. We use Muller's parameters for the damage from criteria air pollutants, but we adjust the damage from CO_2 to be \$50 per metric ton.[4]

We do not include in our estimates the upstream emissions in the production or extraction of the energy sources or hardware for energy production. Emissions from extraction of fossil fuels are likely to be the largest of these factors, and are almost certainly greater for gasoline and natural gas than for electricity, because a large share of electricity is produced from sources other than fossil fuels. Thus, inclusion of upstream emissions would likely raise the gap between price and social marginal cost for electricity relative to gasoline or natural gas. Nonetheless, reliable estimates of the marginal impact of consuming any of the sources on upstream emissions are difficult to find, so we have omitted them at this point. Our estimates also do not account for tax breaks and subsidies for either fossil fuels or renewable energy. To the extent that these lower the wholesale prices of energy – which we use as an indicator of private marginal cost, as explained below – our estimates will understate the private marginal cost and therefore the social marginal cost.[5]

A. Previous evaluation of electricity price versus social marginal cost

In previous work, Borenstein and Bushnell (2019), we develop estimates of the marginal residential retail price and social marginal costs of electricity. Our sample covered the years 2014-2016. For comparability, we use these years for analysis of all three fuels. We summarize our methodology and results from Borenstein and Bushnell (2019) here.

[3]See https://public.tepper.cmu.edu/nmuller/APModel.aspx and Clay, Jha, Muller and Walsh 2018.

[4]This is in line with the Biden administration's interim finding on the Social Cost of Carbon. See `https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf`.

[5]Our estimates also do not incorporate the distortions that might replace the ones that we identify here to the extent that price is lowered to equal SMC and a revenue shortfall results.

Retail Prices

To construct estimates of marginal residential retail electricity prices we combine data from the Energy Information Administration (EIA) Form 861 (Energy Information Administration, 2017) and the Utility Rate Database (URDB) (National Renewable Energy Laboratory, 2017). The EIA 861 reports total customers, sales and revenues for each major electric utility by customer class, including residential. The average residential price can therefore be calculated by dividing total revenues by total sales. The URDB provides, among other things, information on the fixed component of a two-part tariff for utilities that apply them. We multiply the fixed charge by the number of customers to calculate the revenues derived from fixed charges. We then subtract this fixed charge revenue from total revenue, and then divide by total sales to calculate an average marginal price for residential customers. In some areas this average will mask additional heterogeneity in marginal customer prices if the utility applies an increasing or declining block rate-structure. However, the "step size" in these rate structures is relatively modest for all but utilities in California, and even California electricity rates have undergone a significant compression of the prices across tiers in recent years. See Borenstein and Bushnell (2019) for more details.

Using this process we derive prices for about 2100 utilities over 3 years serving virtually all residential customers in the US.

Private Marginal Costs

The private marginal costs of electricity are primarily derived from wholesale pricing data published by Independent System Operators (ISOs).[6] The ISOs operate wholesale electricity markets across the bulk of the US electric system and calculate locational-marginal prices (LMPs) at least hourly. The LMPs are calculated as the shadow cost of meeting one more unit of demand in a given location including the bid-in marginal cost of generation as well as the shadow cost of transmission congestion and other operating constraints. In other words, ISOs calculate and apply a textbook definition of the marginal cost of supply that includes almost all relevant operating constraints.

We match each utility in our dataset with the three nearest ISO pricing "hub" locations

[6] We use the term ISO here to refer to both Independent System Operators and Regional Transmission Organizations.

that captures the hourly marginal cost of electricity in a regional location. The primary component of the hourly marginal cost of electricity for each utility is the (inverse distance-weighted) average of these three prices.[7]. These prices, however, are for delivery of electricity to the local interface between the high-voltage transmission network and the lower-voltage distribution networks. Moving the electricity from this interface to the residential customer creates additional costs, because some of the electricity is dissipated as heat. We account for these line losses to then determine the marginal cost of supplying electricity to the residential customer.

Externality Costs

Many sources of electricity generation produce some or all of the criteria pollutants covered in the AP3 model, as well as CO_2. Detailed emissions data from every major emitting power plant are collected by the USEPA's continuous emissions monitoring system (CEMS) and published quarterly by the EPA Environmental Protection Agency (2018). We adapt procedures developed in Holland et al. (2016) that map electricity demand at a given location to output from given power plants. The general procedure converts emissions from the CEMS to monetary damages using values taken from the AP3 model. We aggregate these hourly emissions damages by summing the damages from all plants in a region for a given hour. We then regress the hourly emissions damages from each region on the level of demand, or "load", in the region in which the plant is located as well as other neighboring grid-connected regions. In our case we divide load within a region ('own region') and in neighboring regions ('other-region') into terciles to generate a piecewise linear estimate of the relationship between load and the emissions located in a given region.

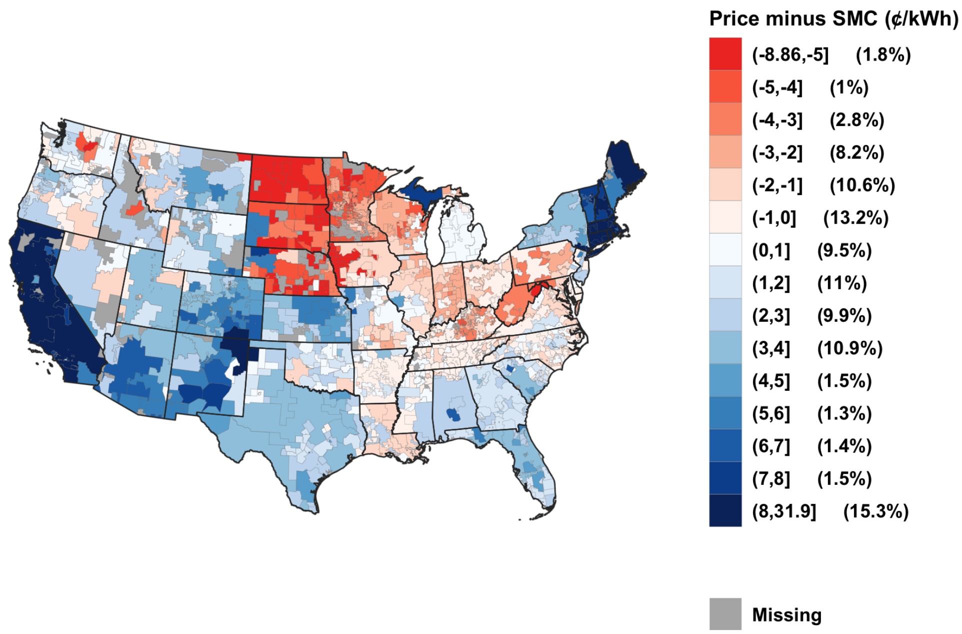
The damages associated with electricity consumption in a given region at a given time is derived by summing the coefficient values that attribute the share of a region's hourly emissions damage to load in a specific region. For example, roughly \$12 of the \$13 per marginal MW of the CO_2 damages from power plants in California is attributable to electricity consumption in California, and consumption in California is responsible for about \$5 of the \$30

[7] A small number of utility regions do not have ISOs, and transparent prices are therefore not available. For these utilities we apply the "system lambda" value reported to the Federal Energy Regulatory Commission in the FERC form 714 Federal Energy Regulatory Commission (2017). See the appendix of Borenstein and Bushnell (2019) for more details.

per marginal MW of the CO_2 damages created by power plants in the non-California west.

Both private marginal cost and externality costs vary hour to hour in the electricity industry. For the purposes of this analysis, however, we aggregate these hourly marginal costs into quantity-weighted averages.

Results



Note: Percentages in parentheses are share of residential electricity customers in each category

Figure 1: Electricity Marginal Price Minus Social Marginal Cost (per kWh)

The results of these calculations – averaged across 2014, 2015, and 2016 – are presented in Figure 1 and in Table 1. Figure 1 shows the wide range of differences between price and social marginal cost across the country and the percentage of customers in each of the bins. For 15.3% of residential customers, including most of California and much of New England, average residential retail price exceeds social marginal cost by at least eight cents per kWh. Nearly half of customers, however, face a retail price that is within two cents of SMC, the lightest colors on the map. There is also a swath of areas, mostly in the upper Midwest, where price is significantly below SMC, though only about 6% face a price more than three cents below SMC.

	Mean	StDv	Min	P25	P75	Max
Retail Variable Price (P, ¢/kWh)	11.46	3.00	2.38	9.73	12.13	41.18
Private Marginal Cost (¢/kWh)	3.72	0.70	2.43	3.18	4.10	6.26
External Marginal Cost (¢/kWh)	6.20	2.38	2.53	4.55	8.81	11.91
Social Marginal Cost (SMC, ¢/kWh)	9.92	2.50	6.06	8.05	12.39	15.42
P-SMC (¢/kWh)	1.54	4.04	-8.85	-1.02	3.14	31.86
(P-SMC)/P	0.09	0.29	-2.70	-0.10	0.28	0.77

N=1756 (utility-states). Statistics are sales-weighted.

Note: Each observation is the average for one utility-state over 2014-2016.

Table 1—: Electricity Averages of Prices and Marginal Costs (2014-16)

Table 1 summarizes the variation of electricity prices and costs across the utilities in our sample. Electricity prices and costs vary substantially more over space than do the other fuels studied in this paper. Electricity prices are also uniquely volatile over time; variations of over an order of magnitude can be experienced within a single day.[8] In this paper we restrict our analysis to the differences between longer term average prices and costs, because our focus on the customer choice of durable, energy-using appliances and vehicles.

While figure 1 presents the geographic variation of the gap between price and SMC, it is harder to see the overall distribution and relationship to usage. Figure 2 shows a scatterplot of the gap versus each utility's average annual residential sales (in log scale). The graph shows that there are many more utilities with prices well above SMC than well below, and some of those are among the largest utilities in the country.

B. *Natural gas price versus social marginal cost*

Our analysis of residential natural gas pricing closely follows the approach we use for electricity.

Retail Prices

As with electricity, aggregate data on residential revenues, customers, and quantities are available by utility from the EIA (form EIA-176), but further adjustment is needed to derive marginal price. Fixed monthly charges are also quite common in natural gas. Thus, as with electricity, we subtract estimated aggregate fixed charges from total residential revenues and

[8]In Borenstein and Bushnell (2019) we contrast the relative inefficiencies of the static nature of retail electricity prices to those created by an inefficient *level* of average prices. In much of the central U.S. the lack of time-varying retail pricing is the larger distortion, but the larger distortion on the west coast and northeast is due to extremely high average electricity prices.

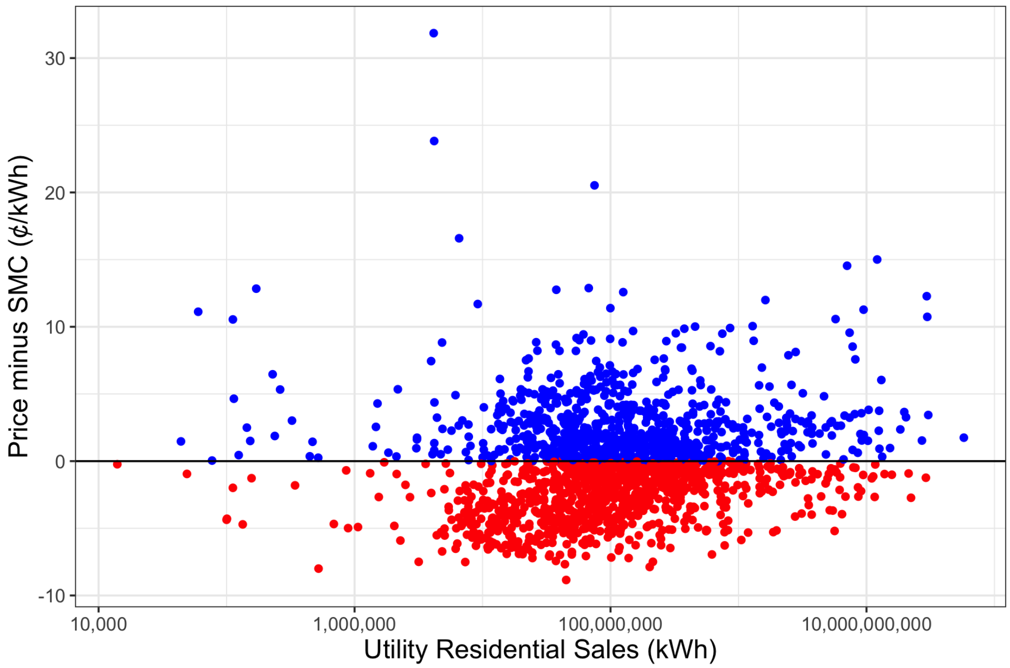


Figure 2: Electricity Price Minus SMC versus Average Annual Residential Sales (by utility)

divide by quantities to get an estimate of marginal retail price. To implement this approach, we started from the data on residential fixed charges collected by Catherine Hausman for Hausman (2019). We then hand-collected data from additional gas utilities to get to the total data set we use, which covers 97% of all residential customers with natural gas service. About half of all residential households in the US have natural gas service.

Private Marginal Costs

The private marginal cost of natural gas delivered to the home is nearly entirely attributable to the marginal cost of acquiring gas for the utility's distribution system. Every state has one or more "city gate" locations at which gas in the pipeline is priced. We use city gate prices as the marginal cost of supplying natural gas. We make one adjustment to to the city gate price, which reflects the gas that is lost or stolen in the distribution process, known as "Lost and Unaccounted For" gas (LAUF). Utilities report LAUF to the EPA for their entire distribution system. We adjust the marginal cost of supply for the proportion of gas that is lost in the distribution process, as reflected in the LAUF.

Externality Costs

The primary pollution externalities from residential combustion of natural gas are CO_2 and NO_x. In addition, some natural gas, which is nearly all methane, leaks out from the distribution pipes. There is significant disagreement about how well LAUF reflects leaks, as discussed in detail in Hausman and Muehlenbachs (2019). They argue that while LAUF is a noisy measure, it is correlated with actual leaks. We use LAUF for the proportion of gas that is leaked in the distribution system and assume a global warming potential (GWP) for these methane leaks of 34, *i.e.,* we assume that 1 pound of natural gas leaked into the atmosphere has a climate change cost that is 34 times greater than 1 pound of CO_2.[9] It is worth noting that residential distribution involves more miles of pipe per unit of energy delivered than distribution to commercial and industrial customers, so very likely the share of gas that leaks in residential distribution is higher than the overall utility average.

Using Muller's AP3 model, we estimate the monetary costs of these emissions, and then add these externality costs to the estimated private marginal cost to create the social marginal cost per MMBTU of natural gas.

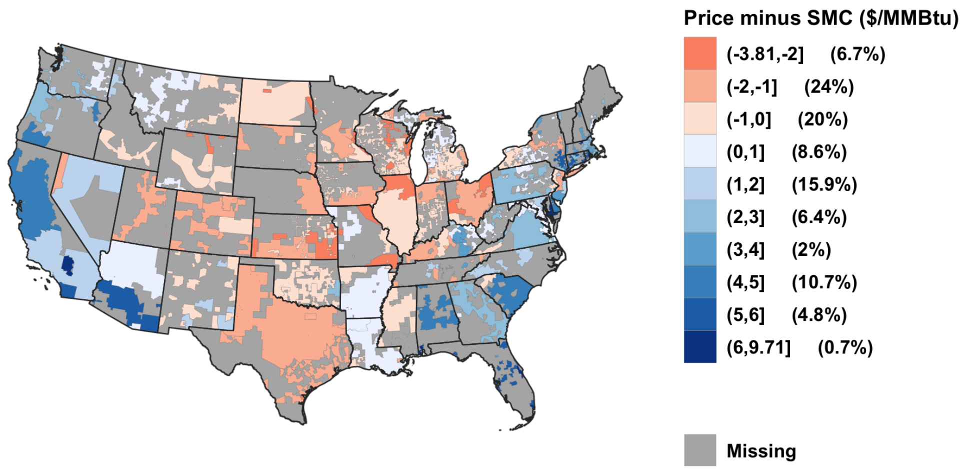
Results

The results of these calculations are presented in Figure 3 and in Table 2.[10] Figure 3 shows the differences in the standard units of natural gas, price per MMBTU. These are not the same units as for electricity, so these maps are not yet directly comparable. But Figure 3 shows that the general pattern of deviations from SMC is similar to electricity, with higher prices relative to SMC on the coasts and lower in the middle of the country. In order to compare the results to electricity, below we convert energy units from MMBTU to kWh.

As with electricity, we also present the scatterplot of the gap between price and SMC across utilities of differing size. Figure 4 shows less tendency for the larger gaps to be among the largest utilities, but again illustrates that the gaps with price greater than SMC are much larger than the gaps with price less than SMC.

[9]This is also very close to the GWP implied by the Biden administration's interim finding on the Social Cost of Carbon. At a 3% discount rate, it finds the average of the social cost of CO_2 emissions to be $51 and the average of the social cost of methane emissions to be $1500 per metric ton, a multiplier of 29.4.

[10]The large geographic areas of the country that show as missing are due in part to the fact that much of the low population density areas of the US do not have natural gas service and in part to the need to collect these data manually. The utilities shown account for 97% of all residential natural gas customers in the country.



Note: Percentages in parentheses are share of residential natural gas customers in each category

Figure 3: Natural Gas Marginal Price Minus Social Marginal Cost per MMBTU

	Mean	StDv	Min	P25	P75	Max
Retail Variable Price (P, $/MMBtu)	8.36	2.05	4.53	6.90	9.28	17.18
Private Marginal Cost ($/MMBtu)	4.65	0.52	3.17	4.43	4.91	8.61
External Marginal Cost ($/MMBtu)	3.55	0.52	2.74	3.16	4.00	4.95
Social Marginal Cost (SMC, $/MMBtu)	8.19	0.70	6.78	7.75	8.67	11.65
P-SMC ($/MMBtu)	0.16	2.23	-3.80	-1.28	1.26	9.40
(P-SMC)/P	-0.04	0.26	-0.84	-0.18	0.14	0.57

N=189 (utility-states). Statistics are sales-weighted.

Note: Each observation is the average for one utility-state over 2014-2016.

Table 2—: Natural Gas Averages of Prices and Marginal Costs (2014-16)

C. Gasoline price versus social marginal cost

Unlike electricity or natural gas, gasoline is not sold in a market subject to direct economic regulation or exhibiting attributes of natural monopoly. Still, we can take a similar approach to establishing the relationship between price and social marginal cost. The literature on optimal gasoline taxation generally assumes that the ex-tax retail price of gasoline is equal to its private marginal cost of supply.[11] This assumption potentially biases estimated PMC upward to the extent that refining or retailing of gasoline exhibits any market power, which

[11]See, for example, Parry and Small (2005) and West and Williams III (2007).

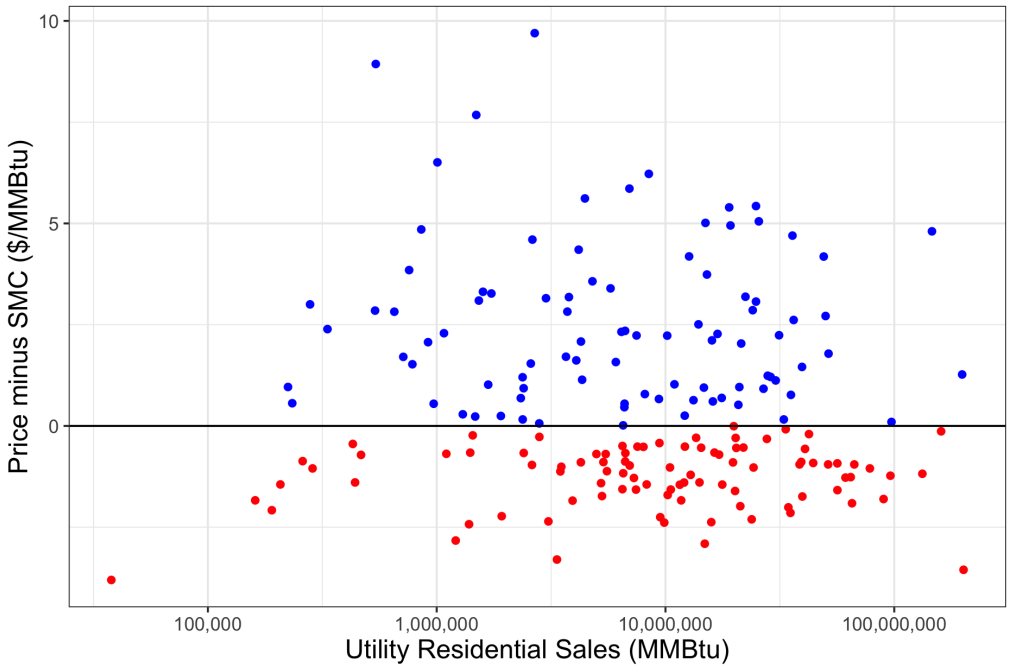


Figure 4: Natural Gas Price Minus SMC versus Average Annual Residential Sales (by utility)

seems especially likely in retailing due to spatial differentiation. Concerns about market power are particularly relevant to our analysis of technology choice in California, presented in the next section.[12] On the other hand, the standard assumption potentially biases estimated PMC downward to the extent that taxes are passed through to retail price less than 100%, *i.e.,* that suppliers bear some of the burden of gasoline taxes, though this seems less likely in the long run.[13]

Retail Prices

We take the state-level average retail price of regular grade gasoline as the benchmark for this analysis, because that is the most common type of gasoline sold in the US.

Private Marginal Costs

We assume that private marginal cost is equal to the ex-tax retail price minus $0.13. We arrive at this adjustment by assuming that taxes are fully passed through and calculating

[12]See Borenstein (1991), Petroleum Market Advisory Committee (2017), and Borenstein (2020).

[13]Chouinard and Perloff 2004 suggest that federal gasoline taxes are passed through about 50% to consumers, but state gasoline taxes are borne virtually 100% by consumers. Doyle Jr and Samphantharak (2008) finds that 70%-100% of tax adjustments are passed through to retail even in the short run, while Marion and Muehlegger (2011) find full pass-through on average, but suggest that the short-run pass-through varies with the degree of supply constraints.

an average margin above private marginal cost. To be exact, we take data from the Energy Information Administration on the 2016 US average retail price of ($2.14) and subtract an estimate of private marginal cost. Our estimated PMC is the sum of the EIA's 2016 average wholesale rack price ($1.39) plus average federal and state taxes ($0.45), an estimated average local tax ($0.02) and an estimated retail marginal cost ($0.16).[14]

We collect state and federal taxes for the years 2014-2016 from the Energy Information Administration. For all states except California, we assume that, plus $0.13, is the entirety of the gap between price and private marginal cost. California, however, during this time also had both a cap-and-trade program for greenhouse gases and a Low-Carbon Fuel Standard (LCFS), a tradable carbon intensity standard for transportation fuels. We incorporate the California cap-and-trade program by taking the average auction prices for each year, assuming that these prices were fully incorporated into retail price, and translating the cap-and-trade price per metric ton of CO_2 into a price per gallon of gasoline.[15] We obtain prices for LCFS compliance certificates from Stillwater Associates[16] and translate these prices into impact on gasoline prices using the cost calculator from the California Air Resources Board.[17].

Externality Costs

We follow Holland et al. (2016) for calculation of the air pollution externalities due to burning gasoline in light duty vehicles. The only change we make to their calculations is to assume a social cost of CO_2 emissions of $50/ton rather than $41/ton as they assume. Like Holland et al. (2016), we ignore externalities from congestion and accident risk, instead assuming that they are unchanged by whether the vehicle is powered by an electric or internal combustion engine. We do the calculation of price minus social marginal cost first in the

[14]The estimates of local taxes and retail marginal cost are works in progress. Data on local gasoline taxes from the Energy Information Administration are incomplete, and we have not found another source that covers all counties and other local tax authorities. Retail marginal costs are based on an assumption of $0.06/gallon for delivery from the rack (See https://www.thetruckersreport.com/truckingindustryforum/threads/how-much-does-it-cost-to-transport-a-gallon-of-fuel-to-a-retail-gas-station.223454/), $0.06 credit card processing fee (2.5% fee on $2.26), and $0.04 for marginal labor costs. Still, adjustments to this margin up or down by $0.10 per gallon would not qualitatively change our findings.

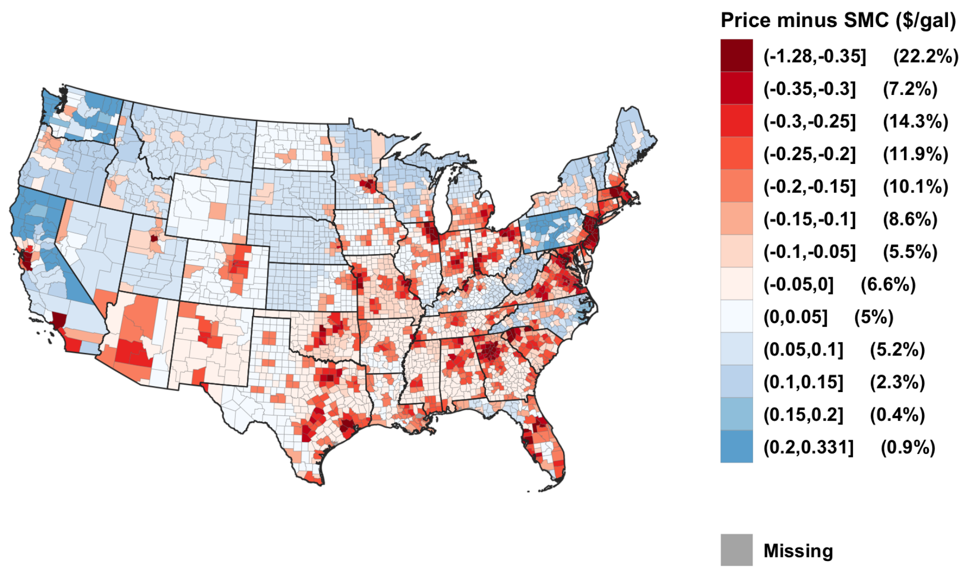
[15]For calculating the price impacts of both cap-and-trade and the LCFS, we assume that all gasoline fuel sold in California is 90% pure gasoline and 10% ethanol, consistent with reporting from the California Energy Commission.

[16]https://www.stillwaterpublications.com/membership/

[17]See https://ww3.arb.ca.gov/fuels/lcfs/dashboard/creditvaluecalculator.xlsx

familiar units of dollars per gallon. In the next subsection, we translate them into cents per kWh for comparison across the fuels.

Results



Note: Percentages in parentheses are share of population in each category

Figure 5: Gasoline Price Minus Social Marginal Cost per Gallon

The results of these calculations are presented in Figure 5 and in Table 3. Figure 5 shows the differences in the standard gasoline units of price per gallon, which again is not directly comparable to the earlier maps, as well as the population following in each bin. The only areas in which the price of gasoline is substantially above SMC are areas with very low population densities. Overall, approximately 14% of the population lives in areas where the price of gasoline is above SMC. The darker reds that correspond to most of the major metropolitan areas demonstrates that burning gasoline among high population density is particularly harmful, and is not reflected in retail prices.

We again also present a scatterplot of the gap between price and SMC, but in this case by county rather than utility. Unfortunately, we do not have data on county level sales, so we sort based on county population. Figure 6 shows clearly that the gaps of price below

	Mean	StDv	Min	P25	P75	Max
Retail Variable Price (P, $/gal)	2.49	0.20	2.23	2.34	2.57	2.92
Private Marginal Cost ($/gal)	1.87	0.12	1.70	1.76	1.95	2.15
External Marginal Cost ($/gal)	0.86	0.26	0.49	0.72	0.93	1.82
Social Marginal Cost (SMC, $/gal)	2.73	0.32	2.20	2.54	2.84	3.73
P-SMC ($/gal)	-0.25	0.25	-1.27	-0.33	-0.09	0.32
(P-SMC)/P	-0.10	0.10	-0.52	-0.14	-0.04	0.11

N=3105 (counties). Statistics are population-weighted.

Note: Each observation is the average for one county over 2014-2016.

Table 3—: Gasoline Averages of Prices and Marginal Costs (2014-16)

SMC are much larger than of price greater than SMC, and occur in counties of much larger population.

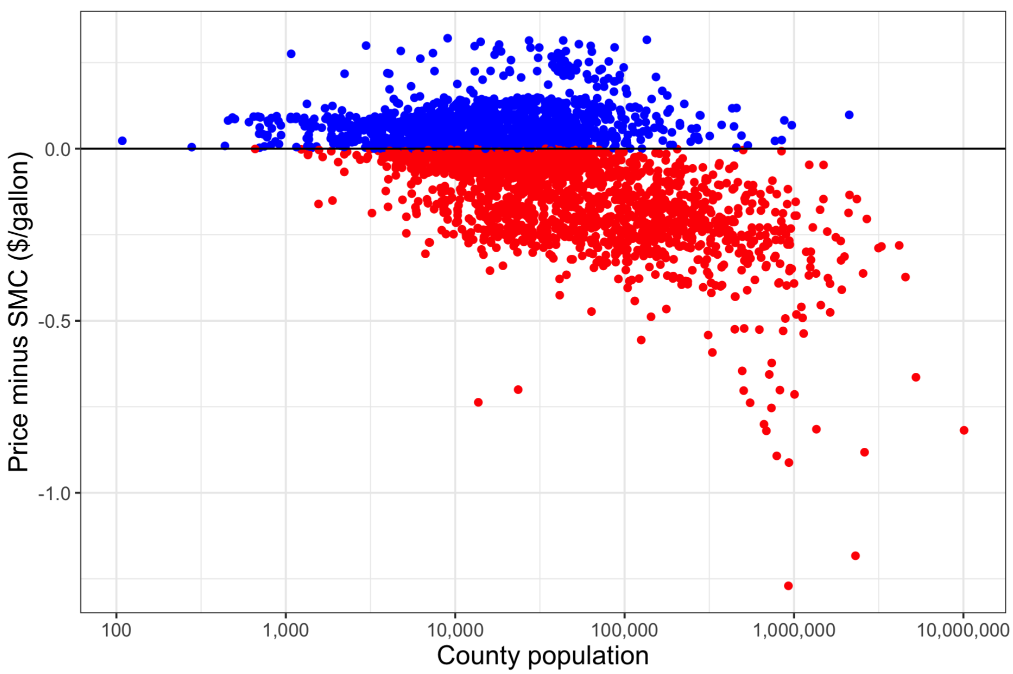


Figure 6: Gasoline Price Minus SMC versus County Population

D. Comparison of price versus social marginal cost across energy sources

Figure 7 presents the price versus social marginal cost maps for the three fuels, but for ease of comparison all are now in dollars per kWh with the same legend.[18] Besides converting the units, we make one further adjustment for gasoline, recognizing that internal combustion engines are only about 33% efficient on average,[19] which triples both the price and the social marginal cost of delivering energy to the engine. Thus, regardless of the sign, this adjustment triples the gap between price and social marginal cost in cents/kWh.

It is immediately evident that electricity is mis-priced to a much greater degree than gasoline or natural gas. Relative to social marginal cost, electricity is overpriced to a greater extent in most of the country, but where it is underpriced, that underpricing is larger on average than where natural gas or gasoline are underpriced. The explanation for overpricing electricity is fairly straightforward: the utility is recovering fixed costs associated with the natural monopoly operation of the company, and in some cases such as California, also recovering costs for a variety of public purpose programs. The areas of underpricing are associated with large amounts of unpriced externalities from coal-fired generation.

While all three energy sources are underpriced or overpriced in different parts of the country, the customer/population share column next to the legend of each map suggests that overpricing is far more prevalent on a customer-weighted basis for electricity, while underpricing is far more prevalent for gasoline. The results are less clear-cut for natural gas.

In the appendix, we also present an alternative analyses of the gap between price and SMC, using the Lerner index, $\frac{P-SMC}{P}$, rather than levels. Though in some ways proportional markups for each of the fuels are more intuitive, we don't think they are as useful as the analysis in levels (with all fuels in the same energy units) when thinking about the implications of moving prices to SMC for fuel choices. As we show in the next section, the financial incentive impact on fuel switching when fuel prices change depends on the change in the relative level of costs of using each fuel, and on the comparison of these cost differences to other costs and characteristics of the appliances or vehicles. Nonetheless, looking at the

[18]Natural gas units are converted at a ratio of 293.07 kWh per MMBTU. Gasoline, with an adjustment for 10% ethanol, is converted at a ratio of 0.0305 kWh per gallon.

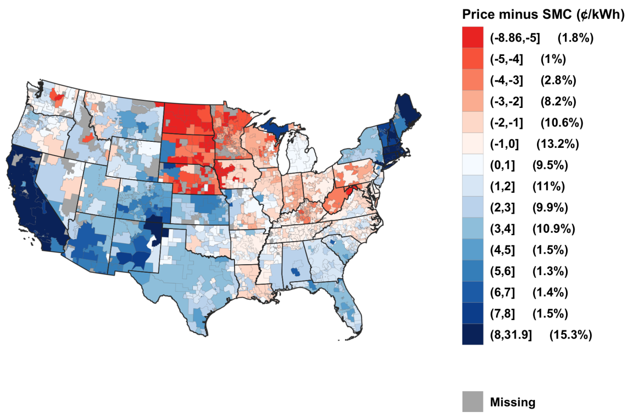
[19]See `https://www.fueleconomy.gov/feg/evtech.shtml.`

proportional distortions suggests the same conclusion, that distortions in electricity pricing are far larger than in natural gas or gasoline.

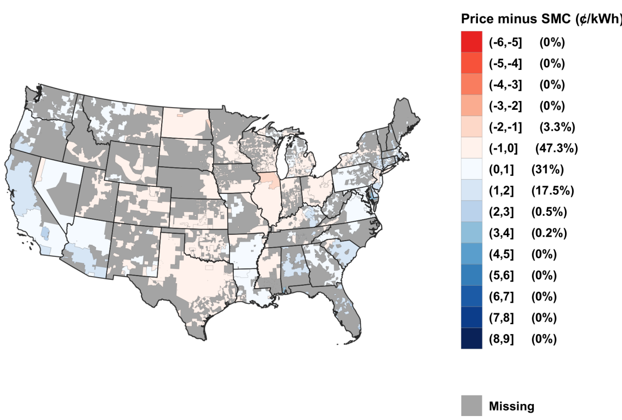
In the last year or two, there has been increasing discussion and research suggesting that the social cost of GHG emissions may be substantially higher than $50 per metric ton. In the appendix, we also present an analysis that is identical to our primary analysis except we use a $100 per metric ton cost of GHG emissions rather than $50. Of course, all of the maps turn more red with a higher cost of GHG emissions. An extra $50 per metric ton translates to an SMC increase of about $0.40/gallon of gasoline, which turns the entire gasoline map red.[20] The natural gas map becomes mostly light pink, with some light blue still present in a few locations, but mispricing in both directions is relatively small. The electricity map shows substantial change in the Midwest and Plains states, as well as parts of the South, but changes fairly little in California or New England, where the grids are already relatively low carbon.

As discussed in the introduction, as opportunities for fuel switching increase, the differences in mispricing across the energy sources become more policy relevant. In the next section, we apply the results of this analysis to appliance and transportation choices for households in California.

[20]It's important to recall that these calculations do not include congestion and accident externalities from driving. If one desired to internalize those externalities through gasoline pricing, then gasoline would be even further underpriced. Those externalities, however, are very imperfectly correlated with gasoline consumption, so other approaches to pricing them may be preferred.



(a) Electricity



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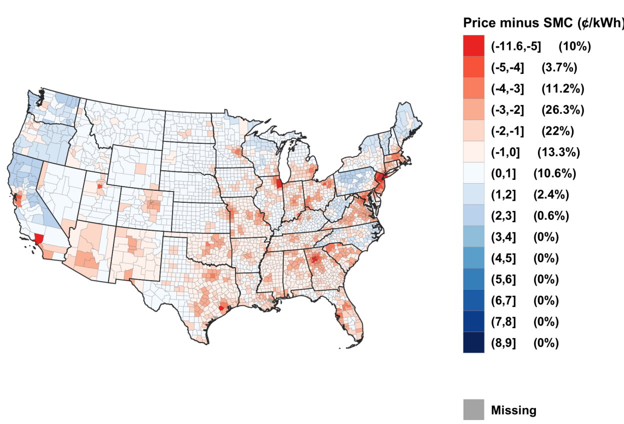
(b) Natural Gas



(c) Gasoline

Figure 7: Price Minus Social Marginal Costs Across Fuels (in Adjusted \$/kWh)

III. Implications for building and transportation electrification

In this section we explicitly consider the implications of the mispricing of alternative energy sources by examining how those prices impact the relative costs of key household services that rely on energy inputs. We first consider the two largest in-home appliance energy uses: space heating and water heating. The EIA estimates that these services account for about 62% of all home energy use,[21] and the vast majority of residential natural gas consumption. In each case, electric power alternatives, based on heat pump technology, have emerged as viable substitutes for many households. We then consider the light-duty vehicle market by comparing the operating costs of electric vehicles to somewhat comparable gasoline-powered internal-combustion engine (ICE) vehicles.

Extending these calculations to estimates of the welfare losses created by pricing inefficiencies would require estimates of consumer preferences over the attributes offered by appliances with different fuel sources, which is beyond the scope of this paper. However, we show that for these large residential energy uses, pricing inefficiencies can tip the economics of fuel costs from one source of energy to another, and can have a significant impact on the overall economics of appliance choice.

For each of the in-home appliances, we evaluate the energy requirements for providing specific services – furnace heat output or increase in tank water temperature – using electricity or natural gas as the energy source. We carry out this study for California, both because electrification is a major policy goal in the state and because the state's 2019 Residential Appliance Saturation Survey (RASS) allows us to infer estimated distributions of space heating and water heating service demand quantities across households. These quantity distributions imply distributions of the fuel cost difference from providing these services using electricity versus natural gas.

To evaluate the range of impacts that electricity and natural gas pricing in California could have on energy costs for each appliance, we focus on the 27,583 single-family detached dwellings and townhouses in the RASS.[22] We exclude apartments, mobile homes and other

[21] `https://www.eia.gov/todayinenergy/detail.php?id=37433`

[22] The RASS dataset includes sampling weights, which we use in constructing the summary statistics and fuel cost distributions.

dwellings. For each household, the RASS reports every appliance in the home and an estimate of the appliance energy usage, based on a simulation that incorporates total household usage, appliance specifications, household demographics and other survey responses. From these simulated energy usage quantities, we apply specific efficiency measures to infer the energy services produced.

The RASS surveys customers in the service territories of the five largest electricity distribution utilities in California: Pacific Gas & Electric, Southern California Edison, San Diego Gas & Electric, Los Angeles Department of Water and Power, and Sacramento Municipal Utility District. Together, these utilities serve about 92% of all residential customers in California. The survey covers virtually all residential natural gas customers. The survey includes the name of the utility that provides electricity and natural gas to the household. We use those identifiers to match each household to a marginal energy rate for each fuel from the analysis in section II.

We then use the RASS to infer the household's quantity demanded from the appliance. Unfortunately, the data made available do not include direct estimates of the quantity of appliance usage, so we infer quantity from the estimated energy input combined with an assumed efficiency of the appliance. The RASS does not include the efficiency of the appliance, but it does include the age of the appliance, in multi-year categorical variables. For each age category, we take the efficiency to be a weighted average of the federal minimum efficiency standard and the federal Energy Star efficiency standard over the years of manufacture within that age category.[23] The efficiency standards are weighted by data on national sales proportion of Energy Star appliances over the manufacture years within the age category.

Once we have the quantity of services demanded from a particular appliance, we can convert to energy use for any particular energy source for that appliance using another efficiency assumption. We do this by assuming new appliances using electricity or natural gas and meeting the 2019 Energy Star standard for either. Thus, information from the RASS is used to establish a distribution of energy service quantity demanded from each appliance

[23]For details on the standards, see `https://www.energy.gov/eere/buildings/appliance-and-equipment-standards-program`.

across the households in the survey, and then we compare the energy cost of providing that quantity of service from new appliances powered by, alternatively, electricity or natural gas. Implicitly, we are assuming no change in energy service quantity demanded with the change in energy price. Given marginal retail prices for electricity and natural gas, this yields a distribution of dollar savings or additional costs from using electricity rather than natural gas. We create these distributions if each fuel were sold at its actual marginal retail price and if each fuel were instead sold at its social marginal cost.

For light duty vehicles, we follow a similar logic, but have a direct measure of services provided, vehicle-miles traveled, from a survey carried out by the Federal Highway Administration. We discuss the light duty vehicle analysis in more detail below.

Our analysis compares the cost of energy sources using total-demand-weighted average prices, not accounting for the ability of consumers to reallocate their consumption towards lower cost periods. It is worth noting that this omission almost certainly biases our analysis against electricity, because short-term price variation in electricity is much greater than in the other two (far more storable) energy sources. Thus, the option to shift demand to lower price time intervals would likely reduce the cost of using electricity by more than it would reduce the cost of using natural gas or gasoline.

A. Space heating

The 2019 RASS survey suggests that 79% of California residences used on-site natural gas combustion as their primary heat source, while 12% used electricity, with the remainder coming primarily from propane and wood. Electricity has long been considered an inefficient and expensive energy source for heating, but attractive to some households (and landlords) because of the low upfront capital investment required.[24] This view is based on the electric resistance heating technology that is in nearly all portable electric space heaters and electric baseboard heating.

In the last decade, however, heat pump space heating has made significant technological progress.[25] A heat pump uses expansion and compression of a gas to move heat from one location to another. Refrigerators are heat pumps that use the principal to move heat out

[24] See Davis (2021).
[25] See Energy+Environmental Economics (2019).

of the enclosure to the surrounding air. The same technology can be used to move heat from outside a home to inside, even when the outside temperature is substantially below the inside temperature. If it gets too cold outside, however, the heat pump is able to extract very little heat from the outside air and becomes much less efficient. With recent technological improvements, heat pumps can now operate more effectively even at low temperatures.

Appliance	Efficiency Index	Efficiency	Units in	Price ($/..)	SMC ($/..)	Energy service out	Units in/out	$/Service P	Cost SMC
Space Heating									
Gas	AFUE	0.90	therm	1.057	0.682	kWh	0.038	0.046	0.028
Heat Pump	HSPF	8.50	kWh	0.180	0.059	kWh	0.401	0.084	0.027
Water Heating									
Gas	EF	0.67	therm	1.057	0.682	kWh	0.051	0.054	0.035
Heat Pump	EF	2.00	kWh	0.180	0.059	kWh	0.500	0.090	0.029

Table 4—: Average Energy Price and Cost Assumptions for Appliances

Note: EF=Energy Factor; AFUE=Annual Fuel Utilization Efficiency; HSPF=Heating Seasonal Performance Factor

To maximize comparability, we ignore portable and room heaters, and focus on whole house forced-air natural gas furnaces versus whole house forced-air air-source heat pump furnaces, both of which use a fan to push the air through ducts to the rooms of a house. In both cases, calculations include the electricity used to run the fan. The top panel of Table 4 presents the underlying assumptions used to evaluate the two appliances that we compare for space heating. Note that the 0.401 in the "Units in/out" column for heat pump space heating suggests that only 0.401 kWh of electricity in is required to create 1 kWh of heat out, due to the absorption of heat from outdoor air. This is considerably more efficient than an electric resistance heater, which has a ratio of about 1.0. The last two columns of the table suggest that at current retail prices heat pumps cost about twice as much as natural gas furnaces on average, but if prices were set to SMC, the cost would be about equal. Figure 8 shows the distribution of annual energy savings from using a heat pump furnace rather than a gas furnace, given our assumptions about efficiency and the distribution of usage. At current prices, in the areas of California covered by the RASS (which does not include most of the Sierra-Nevada mountain areas), the fuel cost of heat pump furnaces is greater than natural gas almost everywhere, implying negative fuel cost savings. On average, heating with natural gas is $157 less expensive per year. If both fuels were priced at SMC, however, there would be virtually no difference in the fuel costs of each.[26] For a rough comparison, homeadvisor.com estimates the total purchase and installation cost for an Energy Star gas furnace to be $3400 and the total purchase and installation cost for an Energy Star heat pump central furnace to be $6400. We found, however, that these estimates vary quite a bit across sources, and depend very much on the need to upgrade electrical service or gas service. In addition, as discussed earlier, the two appliances deliver different service characteristics. Importantly, heat pumps are built to also run in the opposite direction as air conditioners, which potentially greatly increases their value. So, a complete choice analysis would need to include many other factors. Still, given that furnaces typically last 20 or more years, the difference in annual energy costs for heating is likely to be a major factor in appliance choice.

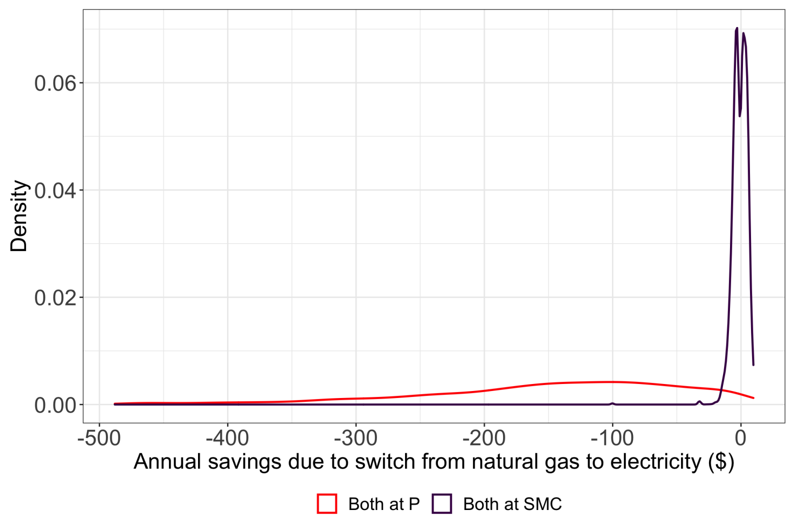


Figure 8: Distribution of Annual Energy Cost Savings for Space Heat

B. Hot water heating energy sources

Our analysis of water heaters follows along the same lines as space heating. We consider only tank water heaters. We compare an efficient (Energy Star) gas-fired water heater with a heat pump electric water heater. As of 2019, natural gas tank water heaters were present

[26]Some studies, such as Energy+Environmental Economics (2019), suggest that the heat pump efficiency level that we are using, matching the qualification level for the Energy Star program, is lower than some models that are now available. We are not aware, however, of data showing that such models have significant market share, perhaps due to their novelty, high price, or other attributes. To the extent that heat pumps are more efficient than we assume, this would shift both distributions to the right. Results using the assumptions for heat pump efficiency that are assumed in Energy+Environmental Economics (2019) are in the appendix.

in 74% of surveyed California homes and electric tank water heaters were in 7%. Most of the remainder were tankless or were on propane. Heat pump electric tank water heaters were about 0.5%, but advocates of electrification generally argue they are the preferred technology to replace water heaters that use natural gas or propane. As with space heating, we derive the energy service units as the quantity of heat output (measured in kWh), in this case in the form of higher temperature water.

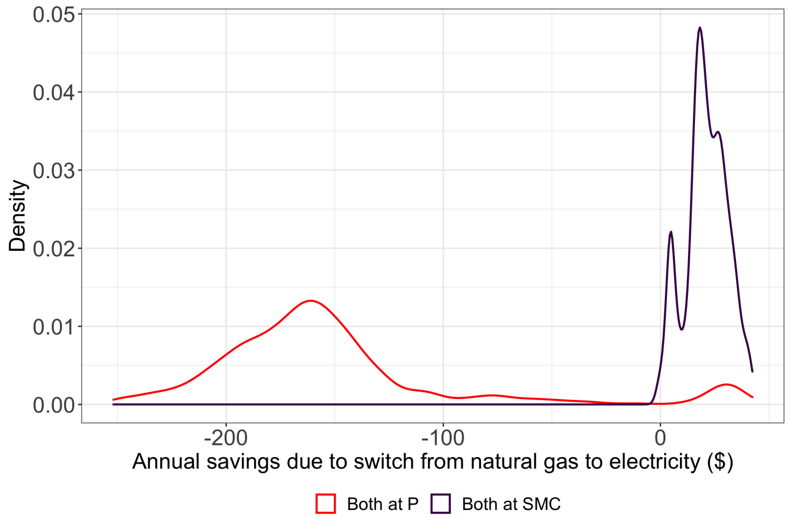


Figure 9: Distribution of Annual Energy Cost Savings for Water Heating

The energy technology of a heat pump water heater is quite similar to a heat pump space heater, so it's not surprising that the energy cost differentials are also quite similar. Table 4 suggests the average cost differential again goes from nearly a 2:1 ratio at current prices to about parity, actually a slight cost advantage for heat pumps, if energy prices were sent to equal SMC. Figure 9 incorporates the distribution of usage, showing once again that at current retail prices for electricity and natural gas, the operating cost of gas is much lower than for an electric appliance, an average savings with gas of $155 per year. But if both prices were reset to SMC, at current efficiency levels of heat pump water heaters, they would be slightly less expensive to operate than natural gas water heaters, an average savings with the heat pump of $22 per year. According to homeadvisor.com, full purchase and installation cost of a medium size gas water heater would be $1300 compared to $2300 for the heat pump water heater. The same caveats apply in this case as with the space heating comparison, but it is even more clear with water heating that the difference in annual energy costs, and how that would change if prices reflected social marginal cost, would be very material to the appliance choice.

C. Implications for electric vehicles

Light-duty vehicles (LDV), to a much greater extent than home appliances, feature a wide range of amenities and dis-amenties that can be closely linked with the choice of an electric vs. ICE vehicle. The most obvious is the trade-off of slower charging and potentially less driving range with the convenience of refueling at home. Others, for example Muehlegger and Rapson (2021), consider the full range of costs and conveniences associated with the choice of electric vs. gasoline powered transportation. In this paper we limit ourselves to consideration of the impact of energy pricing on the operating costs of relatively comparable vehicles.

Table 5 summarizes the efficiencies and unit costs of a selection of Battery Electric (BEV), ICE, and Plug-in Hybrid Electric (PHEV) vehicles. The two most directly comparable options are the Nissan Leaf and its ICE analog, the Nissan Versa, and the Prius Prime PHEV. The Prius Prime presents the most direct opportunity for energy price arbitrage given its ability to run on either electricity (for 25 miles) or gasoline. Note that at recent average marginal prices in California the costs per mile are almost equivalent for the Prius Prime. This result, based upon California average marginal electricity price, masks the substantial number of households that pay electricity prices above this average for whom powering a PHEV with gasoline would be less expensive than with electricity. At social marginal cost, the comparison is not close: powering vehicles with electricity is clearly substantially less expensive.

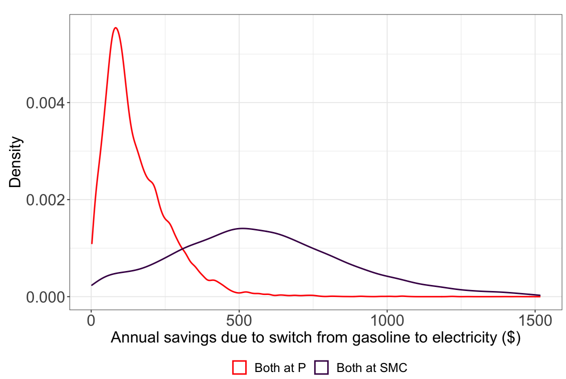
Make	Model	Units	Units per 100mi	P ($/unit)	SMC ($/unit)	MPGe	$/Mile P	$/Mile SMC
Nissan	Leaf S Plus	kWh	30.0	0.176	0.059	108	0.053	0.018
Nissan	Versa	gallons	2.9	2.463	2.779	34	0.071	0.081
BMW	740i	gallons	4.2	2.463	2.779	24	0.103	0.117
Tesla	Model S std.	kWh	30.0	0.176	0.059	111	0.053	0.018
Tesla	Model 3 std.	kWh	24.0	0.176	0.059	135	0.042	0.014
Prius	Prime	kWh	25.0	0.176	0.059	133	0.044	0.015
Prius	Prime	gallons	1.9	2.463	2.779	54	0.047	0.053

Table 5—: Average Fuel Price and Cost Per Mile

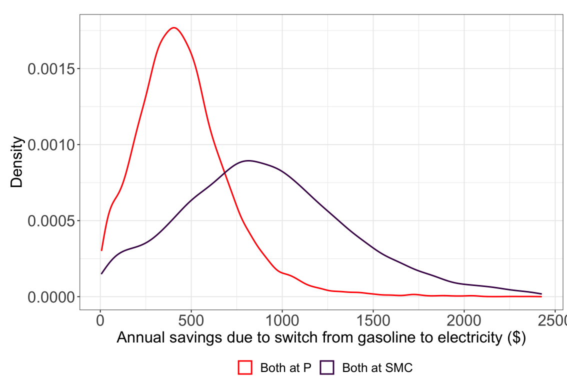
In order to gauge the magnitudes of the operating costs differential in terms of annual costs for typical consumers we apply data from the 2017 National Household Travel Survey (NHTS). The NHTS is a periodically held comprehensive survey of household travel behavior collected by the Federal Highway Administration. There were roughly 47,000 California vehicles participating in the 2017 survey. Following Davis (2019), we divide the vehicle's odometer reading by the age of the vehicle to construct an annual average VMT. The distribution is then re-weighted by the sample weights provided in the NHTS.

The survey results allow us to identify the usage and location of each household, and apply the energy price and marginal cost associated with that location. For example, we match the marginal electricity price based upon the utility service territory in which the household is located and apply the externality damages from combusting fuel within that household's county. We then multiply the per-mile cost of operating a specific vehicle by the number of miles driven for each household in the survey. The thought exercise is basically looking at the annual operating cost implications of choosing a gasoline or electric powered vehicle - setting aside any differences in convenience, ammenities, and purchase costs. We then summarize the annual operating cost "savings" (or premium) of the electricity choice for all households in the survey.

Figure 10: Distribution of Annual Fuel Savings for California Drivers



(a) Versa vs. Leaf



(b) Tesla S vs. BMW 740i

We apply the operating cost differences from Table 5 to the resulting distribution of 2017 California VMT to generate estimates of the distribution of annual operating savings under two choice options. The first compares the Nissan Leaf to the Nissan Versa, and the second compares the Tesla Model S to the BMW 740i. This calculation is summarized in figures 10. Again, the red line illustrates the savings for the electricity choice at current retail prices and the black line summarizes the distribution of savings if the both energy sources were priced at social marginal cost. In both cases, drivers save on operating costs even at current prices, but the savings are relatively modest (about $100 annually on average) for the Leaf comparison at current prices. That savings would be about 5 times larger on average if both fuels were priced at social marginal costs. The Tesla, which is much more efficient than a BMW 740i, produces large savings under either scenario, but again those savings are substantially larger when both fuels are priced at social marginal cost.

IV. Conclusion

Achieving real change in emissions of greenhouse gases and other local pollutants will require both achieving enormous technological progress in "green" energy and removing incentive and institutional barriers to the adoption of those new technologies. In California and some other parts of the United States, distorted electricity prices are likely to be among the most significant incentive barriers to reducing fossil-fuel emissions through electrification, particularly as costs of electric appliances and vehicles decline.

We have shown that prices for all three major energy sources for homes and light-duty vehicles differ from their social marginal cost, in some cases substantially, and there is quite a bit of geographical variation in these differences. Even the sign of the deviation varies regionally. In general, electricity in the continental US is priced above its SMC, though there are regions, covering about 38% of customers, where we estimate it is priced below. Importantly, the largest deviations in electricity are due to over-pricing and cover substantial shares of the entire US residential customer base. About 32% of US households face electricity prices at least three cents per kilowatt-hour above SMC – a larger gap than we estimate over 99% of households face when buying gasoline or natural gas – and for 15% of households prices are at least eight cents above SMC.

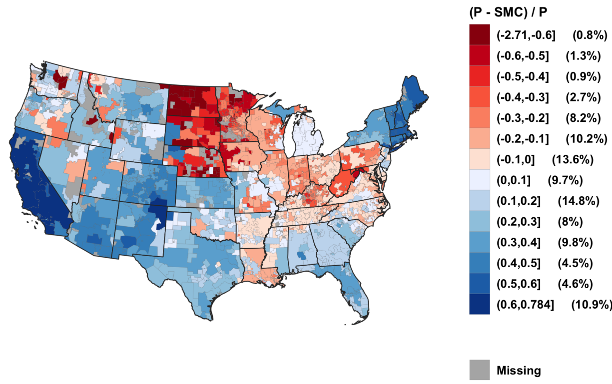
If shifts towards electricity for home appliances and vehicles are expected to happen through customer choices, then distortions in energy prices could substantially deter choices to switch to lower-carbon energy sources. If these shifts are mandated, then the high electricity prices create both potential hardship for low and middle income households, and the potential for serious political resistance.

To date, the preferred policy intervention to promote electrification has been to subsidize the purchases of electric appliances and vehicles through tax credits, rebates, or share mandates. Our results demonstrates that the size of such implicit or explicit subsidies necessary to induce switching may be substantially increased by the inefficient pricing of the underlying fuels, particularly electricity. Beyond the direct burden on public funds of direct subsidies, there are other reasons why addressing retail fuel pricing distortions would be a preferable solution, or at least complement, to subsidizing appliance and auto purchases. First, programs focused on the purchase of new appliances suffer from a variety of inefficiencies in the use and life-extensions of the existing installed base, which in this case rely on fossil fuels.[27] Second, while purchase subsidies may correct for the extensive margin purchase of the new devices, reform of fuel prices is still necessary to address the intensive margin of their use.

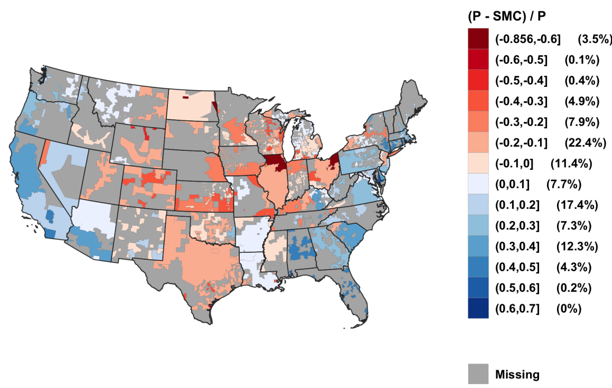
This study also shows the importance of accounting for pre-existing distortions in discussions of pricing GHG emissions. Even without California's low carbon price, its retail electricity prices greatly exceed social marginal cost, so adding the impact of a carbon price won't necessarily increase efficiency. Luckily, policymakers do have alternatives to raising revenue through volumetric prices that are multiples of SMC, including fixed monthly connection charges, that can be income-based to improve equity, or shifting many of the programs paid for through electricity prices to date budgets.[28]

[27]See Stavins (2006).
[28]See Borenstein, Fowlie and Sallee (2021) for more discussion of these options.

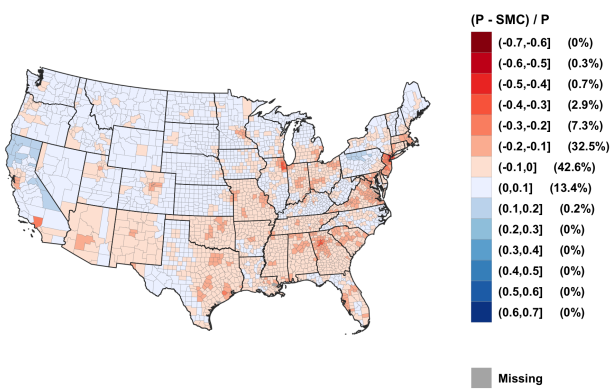
Appendix



(a) Electricity

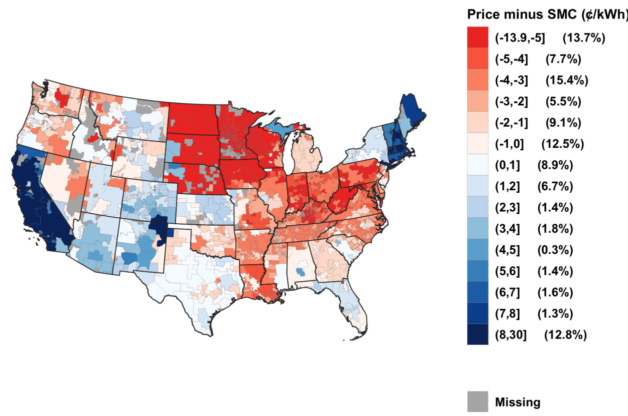


(b) Natural Gas

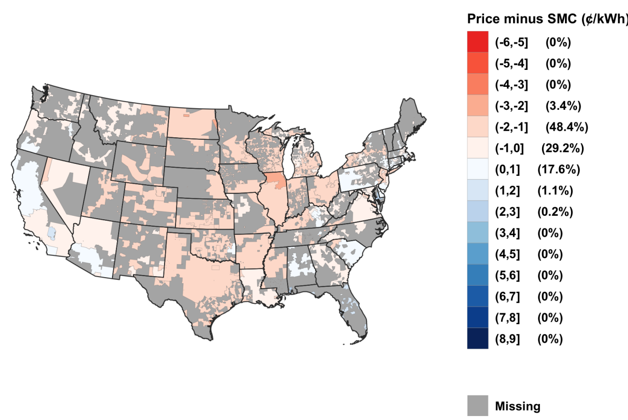


(c) Gasoline

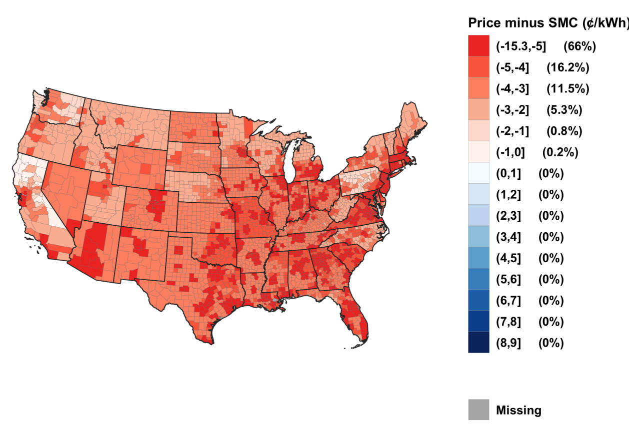
Figure 11: $\frac{P-SMC}{P}$ Comparison Across Fuels



(a) Electricity



(b) Natural Gas



(c) Gasoline

Figure 12: Price Minus SMC Across Fuels (in Adjusted $/kWh) with SCC =$100/ton

Analysis of in-home appliance savings that includes efficiency assumptions from E3 study

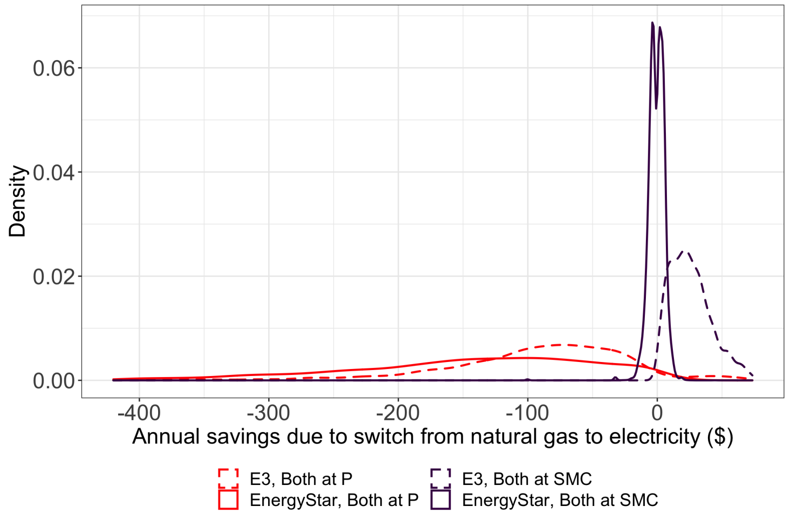


Figure 13: Distribution of Annual Energy Cost Savings for Space Heat

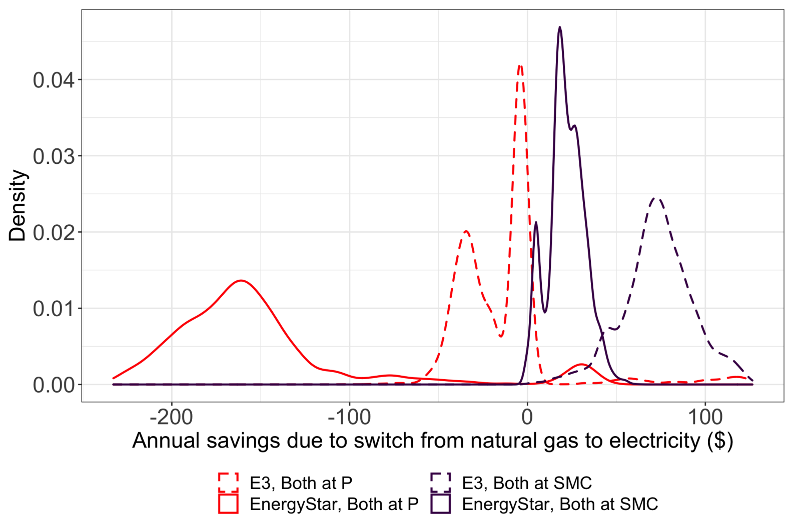


Figure 14: Distribution of Annual Energy Cost Savings for Water Heat

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