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Issues, Questions, and a Research Agenda for the Role of Pricing in Residential Electrification

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December 1, 2021

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1 The Opportunity: Potential GHG Reductions from Residential Electrification

Within most developed economies, the general blueprint for reducing greenhouse gas emissions involves decarbonizing the electric sector, followed by significant transitions to electricity within the transportation, commercial, and residential sectors. Recent trends summarized in Figure 1 reveal how early in this process the United States is. Overall US greenhouse gas (GHG) emissions declined from 5,631 mmTons in 2010 to 5,298 in 2018 despite a decade of economic growth. However, this drop of 333 mmTons reflectd a nearly 500 mmTon/year decline in the electric sector partially offset by increases in all other major sectors, including the residential (958 to 1,007) and transportation (1,874 to 1,935) sectors.

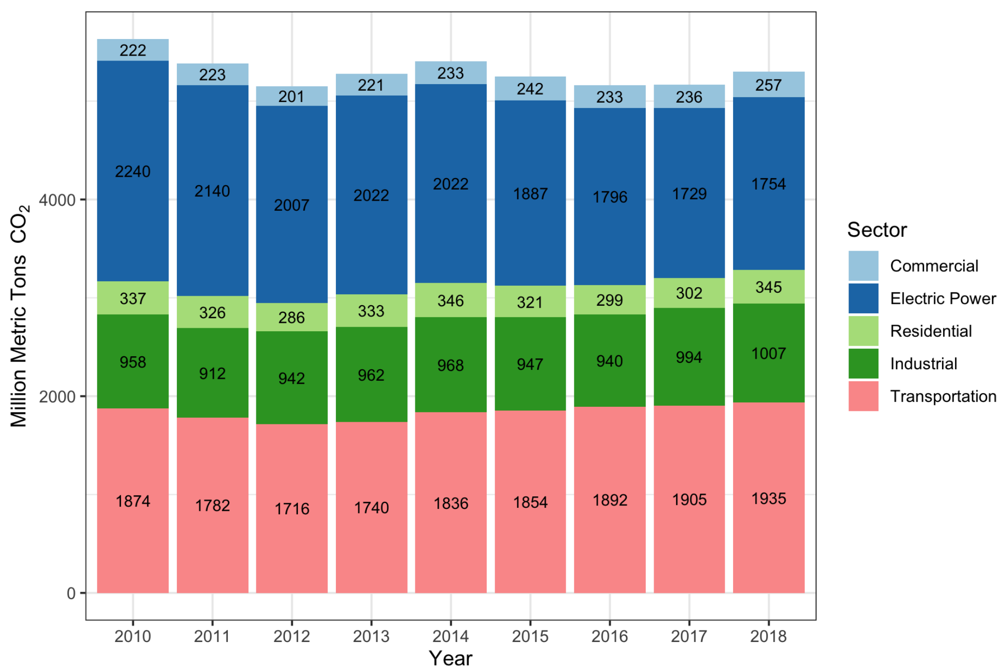
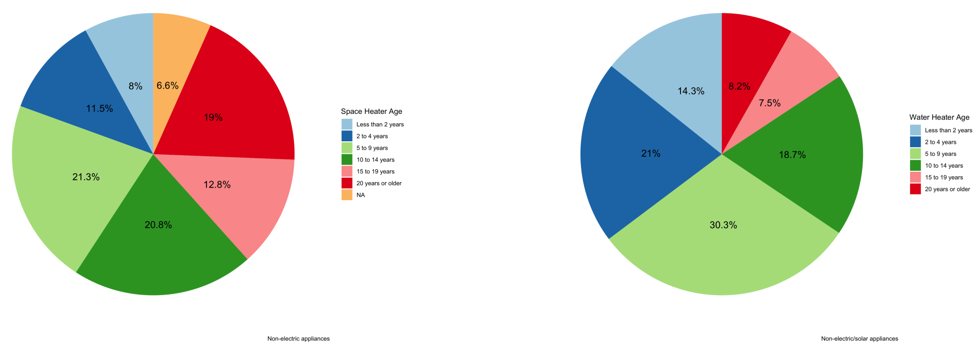


Fig. 1. US GHG Emissions by Year and Sector

Substantial progress has been made in electricity, and the combination of rapidly increasing renewable generation and looming retirements of substantial coal generation capacity suggest this will continue, if not accelerate. The GHG growth in all other sectors during the 2010s indicates just how important decarbonization in these sectors will be to accelerate declines in overall emissions. In this paper, we focus on two of these sectors: residential transportation (i.e., light-duty vehicles) and direct residential emissions. Direct residential emissions are dominated by two energy services, space heating Unlike the decarbonization of electric generation, decarbonizing these sectors will require decisions by millions of individual consumers, who will in turn need to commit to newer technologies capable of providing services powered by electricity. There are a myriad of factors driving such choices, including the relative convenience of using the new technologies, the potential need for upgrading household electrical systems, and the relative costs of the new appliances or vehicles. Another factor is the age of these durable goods. Residential furnaces and water heaters can last more than 20 years, yet according to the Residential Energy Consumption Survey, over two-thirds of these appliances are currently less than 15 years old (Figure 2)



(a) Space Heat **(b) Water Heat**

Fig. 2. Age Distribution of Residential Appliances in the United States

One other fundamental factor is the costs of powering an electric vehicle (EV) or appliance relative to their conventional counterparts. While electric vehicles and appliances have been touted as significantly less expensive to use, this is not the case in all locations or circumstances. In a survey of the current electrification landscape, Davis (2021) shows that electricity price relative to other energy sources is the key consideration in consumer choices regarding space heating. Consumer acceptance of electric appliances will be impaired if they are only modestly less expensive, let alone *more expensive*, to use than their conventional counterparts, given the other challenges confronting a transition to electrification.

This challenge is even more daunting when one considers how local environmental and utility regulatory policies affect energy prices. In the next two sections of this paper we characterize the marginal retail prices of the key fuels—electricity, gasoline, and natural gas—relative to the social marginal costs of those fuels. One key takeaway is that gasoline is underpriced relative to its social marginal cost in nearly all of the United States, while electricity is highly overpriced in some of the most populous parts of the country. In section 4 we discuss why the price of electricity, and to a lesser extent natural gas, came to be so much higher than social marginal cost, while gasoline remains underpriced. The main point here is that traditional approaches to utility rate design have created large upward biases in utility prices. While the underpricing of environmental externalities somewhat offsets this upward bias, on both coasts of the United States the externality costs are not sufficient to offset regulatory rate distortions in electricity. In Section 5 we explore options for correcting this situation. Most options involve a rethinking of both the objectives and implementation of utility rate design. In Section 6, we explore how mispricing energy is likely to affect incentives for residential electrification. Section 7 concludes with a list of topics for future research raised by the issues and analysis discussed.

2 Energy Prices and Consumer Choice

A fundamental precept of an efficient economy is that a consumer purchases a product if and only if their value from consuming the product exceeds society's cost of supplying the product. If consumers are well-informed and rational—an issue we return to below—this matching of value to cost will be achieved so long as the prices of products reflect their social marginal cost. Social marginal cost (SMC) includes both the direct costs to the producer, private marginal cost (PMC), and the external marginal costs imposed on others in the economy from the production or consumption of the product. If consumers have fairly price-inelastic demand, then the deadweight loss (DWL) from mispricing in either the upward or downward direction can be fairly small. In energy, the predominant view for decades has been that demand is quite inelastic, so the DWL from any mispricing is not that large. While that may have been true in the past, changes in technology now allow consumers to more easily switch among energy sources: between electricity and refined petroleum products for powering vehicles and between electricity and natural gas for space and water heating, for instance. This increase in energy options makes customers more price-sensitive and increases the potential DWL caused by mispricing. In particular, if electrification is viewed as a central strategy in reducing greenhouse gases—at least where the SMC of providing an energy service with electricity is substantially lower than the alternative decarbonized energy sources—pricing electricity well above its SMC will discourage switching to electricity and increase the cost to society, primarily through higher GHG and other pollution externalities.[1]

Thus, sorting out the relevant prices and SMCs for alternative energy sources—which nec-

[1] The optimality of setting price equal to SMC applies for establishing the correct incentives for consumers' marginal decisions. SMC at any specific quantity is not necessarily the correct benchmark for policy changes that induce nonmarginal quantity changes, such as a policy to build a network of electric vehicle chargers. Nonetheless, once any policy that induces nonmarginal change is implemented, the efficient price for energy for that usage is still SMC. For instance, following a perhaps very substantial investment in a fleet of electric vehicle chargers, the efficient price for using them is still the SMC of charging vehicles, regardless of how much capital the vehicle chargers required. Charging a price above SMC in order to cover costs from this or other capital investments may be the least inefficient way to cover those costs, but the gap between price and SMC is still relevant to analyzing the inefficiency caused by recovering costs in this way.

essarily includes deriving costs of the pollution externalities that they create and examining the relationship between the price of incremental consumption and the SMC of supplying it—is critical to evaluating the efficiency and effectiveness of energy and climate policy. Standard economic theory of competitive markets implies that equilibrium price will be pushed towards PMC. There are at least three reasons that substantial deviations from SMC are likely to occur. The first, which is the primary focus of policy debates these days, is unpriced environmental externalities, which raise SMC above PMC while having little or no impact on price, thus pushing up SMC relative to price. The second applies to electricity and natural gas, the transmission and distribution of which continue to be natural monopolies: natural monopoly is defined by declining average cost per unit, which implies marginal cost below average cost. Thus, if costs are recovered through a volumetric price that is set equal to average cost, that price will tend to be above PMC. The third reason, closely related to the second, is an increase of price above PMC due to the exercise of market power. In energy, this is most frequently discussed in the context of production and retailing of oil and refined petroleum products. As with cost recovery through volumetric pricing under natural monopoly, this pushes up the price relative to PMC.

As discussed in Section 3, in electricity, our research suggests that environmental externalities (the first reason) approximately offset markups of price above PMC (due to the second and third reasons) in many areas of the United States, resulting in prices that are close to average SMC. However, in some large markets, including California, prices are well above SMC, and in other markets, price is well below SMC.[2] Perhaps more importantly, if or when electricity systems reduce emissions, there will be a growing tendency for price to rise relative to SMC.

Economic analyses of efficient retail pricing of energy typically focus on one energy source and the deviation between price and SMC for it. But if the primary mechanism of consumer response to price changes is substitution among alternative sources that can deliver roughly comparable energy services, then a complete analysis requires studying both pricing of the current energy source and pricing of alternatives to or from which customers might switch. In Section 3, we report on such analyses that we have done, and discuss the need for more work in this vein.

These standard economic concerns generally have failed to include distributional considerations, and in particular, the impact of prices and pollution externalities on low-income communities and communities of color. Discussions of rate design for electrification and decarbonization are now taking these distributional considerations more seriously, though exactly how much weight such concerns will carry in the final policies remains to be seen. Nonetheless, any discus-

[2]The exact gap between price and SMC will depend on the assumed damages from various environmental externalities. Our base-case analysis assumes a social cost of carbon of $50 per ton. However, the conclusion that California and some other significant regions of the country have price well above SMC is robust to assuming a social cost of carbon many times higher. Of course, a much higher social cost of carbon would increase the gap where price is already well below SMC.

sion or analysis of electricity rates, and energy pricing more generally, must include study of not just the overall economic efficiency, but also the impact on disadvantaged communities.

Finally, most economic analyses of energy policy assume that consumers are well informed and make rational decisions in response to the prices they face. It is clear that consumers are not perfectly informed—most do not know how much electricity different devices in their house use, or, in many cases, even the units in which electricity or natural gas quantities are measured—which calls into question whether setting price equal to SMC necessarily creates the consumer responses that would be economically optimal. Policies to improve consumer information and possibly discourage or eliminate sales of products that well-informed consumers would be unlikely to buy may be valuable complements to strategies to improve pricing efficiency.[3]

Related to issues of consumer information and decision-making is the fact that pricing of electricity or natural gas is typically not a simple price per unit consumed. Many customers face a monthly fixed charge regardless of their consumption level plus a price per unit of consumption. Many also face a price per unit that changes with their consumption level, either increasing for marginal units as their consumption goes up ("increasing-block pricing") or declining for marginal units as their consumption goes up ("declining-block pricing"). It's likely that such pricing complexities make it more difficult for consumers to infer their true energy cost or savings from a given decision, and for researchers to infer which price(s) consumers are likely to respond to (Ito, 2014). Again, this has important implications for analysis of the efficiency of retail price setting. For instance, if one focuses on the marginal price a customer faces, but the customer actually does not know what marginal price they face and just responds to the total bill, that might affect the efficiency of consumer choice outcomes in response to different pricing schedules. Such nonlinear pricing can also have important implications for the allocation of cost burden between more and less advantaged households if, on average, they consume substantially different quantities.

3 Regional Differences in Energy Prices and Costs

We return to the issues of distributional considerations and consumer information in Section 5, but first we address the basic question of how the marginal energy prices that consumers face compare with the social marginal cost of the energy supplied. In previous research (Borenstein and Bushnell, 2021a,b) we have documented the extent to which prices for the three main energy sources—electricity, gasoline, and natural gas—deviate from social marginal cost. We briefly summarize these calculations here, but for details please see the original papers.

To do this, we start by inferring the marginal price customers pay, which is straightforward for

[3]To the extent that consumers lack the information or cognitive skill to make privately optimal consumption decisions, overconsumption or underconsumption can result from myriad factors, such as misinformation regarding the product under consideration or substitutes and complements for it.

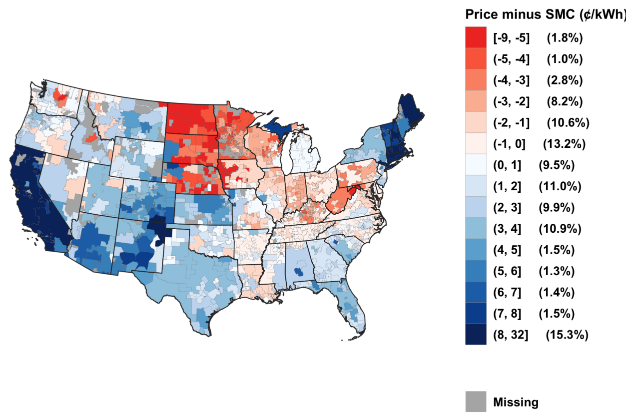
gasoline because it is sold on a linear price basis, but more complicated for electricity and natural gas, which are often sold based on nonlinear price schedules. Luckily, the primary deviation from linear pricing is due to monthly fixed charges, on which we collect data and make adjustments to the average price in order to reflect the marginal price. Increasing-block and decreasing-block pricing, while common, do not impose large price changes in most markets, so they have relatively little impact on the analysis of marginal price.

Each of the energy sources requires different calculations to determine PMC, but in all three cases our calculations are based on a wholesale market price with adjustment for delivery and retailing marginal costs. Externality costs are more complex, but generally are incorporated by determining the location of fuel combustion associated with consumption of an energy service, which we then mapped to the pollutants created by that combustion. Next, we used a model of damages associated with those pollutants to assign financial costs to the emitted pollution in order to determine the extern all marginal cost.[4]

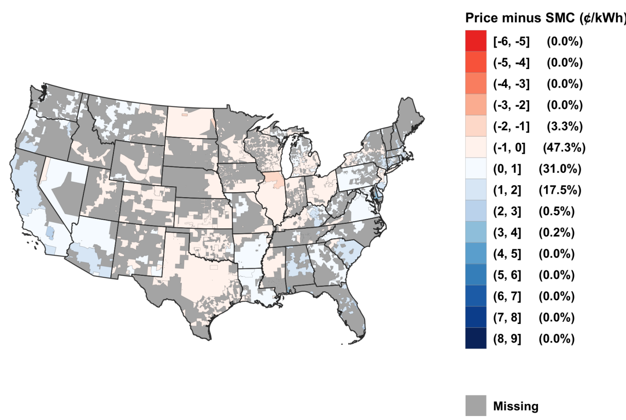
Figure 3 illustrates the differences across the United States in price minus SMC. To make the comparisons meaningful, the maps are presented in normalized kilowatt-hour (kWh) units for the three fuels.[5]. Regions in blue denote prices in excess of SMC and regions in red denote locations where prices are "too low" (i.e., below SMC). These pricing gaps can vary substantially by fuel source and by region. For example, while gasoline is largely underpriced in most of the country, electricity is priced relatively close to SMC, on average, in much of the middle part of the United States. Electricity is underpriced in the upper Great Plains regions. In parts of both coasts, however, marginal electricity prices average many multiples of the SMC of electricity (Figure 3a). Therefore, in many of the most populated regions of the United States, electricity prices are well above SMC, while gasoline is priced below SMC and natural gas prices are fairly close to SMC. This state of affairs implies that many customers in these regions might choose electricity over natural gas and gasoline if they were offered efficient prices, but they face a significant pricing disincentive to do so.

[4]The model that we use is the AP3 version of Nicholas Muller's APEEP model. See https://public.tepper.cmu.edu/nmuller/APModel.aspx. For gasoline, we do not incorporate estimate of the externalities from congestion or accident risk. These are certainly real externalities of driving, but presumably they do not change much based on whether a vehicle is powered by gasoline or electricity. So for purposes of analyzing fuel switching incentives, they can be ignored. Our analysis has compared new vehicles and home appliances using different energy sources. For such a comparison, the vast majority of environmental externalities from electricity are from CO_2 and SO_2, while the vast majority of externalities from combustion of gasoline and natural gas are from CO_2. Local pollution from natural gas combustion in new residential space and water heating or from gasoline combustion in new light-duty vehicles is estimated to have low pollution effects. (This would not be true for older vehicles or for trucks consuming diesel.)

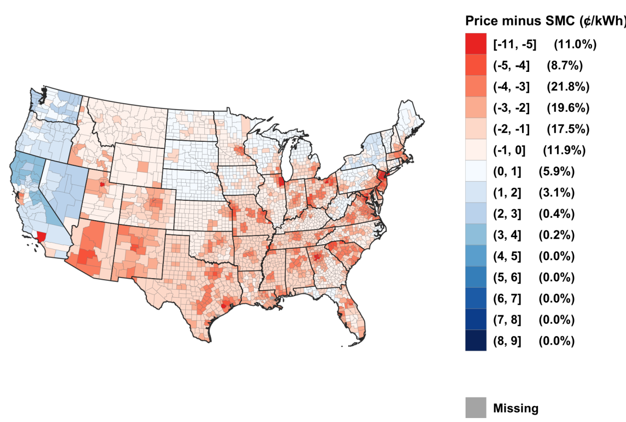
[5]Prices per gallon for gasoline are converted to cents/kWh equivalents and multiplied by 3 to account for the three times higher efficiency of electric drive trains



(a) Electricity



(b) Natural Gas



(c) Gasoline

Fig. 3. Price Minus Social Marginal Costs Across Fuels (in Adjusted cents/kWh)

4 Why Are Current Energy Prices Inefficient?

In the previous section we explained how prices of energy in many parts of the country are distorted relative to their social marginal costs in a way that discourages efficient electrification. In this section, we discuss the underlying reasons for these price distortions and how those reasons might change in the future. In the next section, we describe changes to electricity rate design that could improve the alignment between price and SMC for electricity both now and going forward.

4.1 Commodity Costs and Taxation

Each of the three energy commodities features a rather different supply environment. In general, wholesale prices of refined gasoline and natural gas are much more homogenous across the United States, and over short time horizons, than the wholesale price of electricity. While market power in the production of energy can distort prices away from efficient levels, this has not been a dominant concern in recent years, with some isolated exceptions. Therefore in our previous analyses, we assumed wholesale prices of gasoline, natural gas, and electricity accurately reflect the wholesale private marginal cost of supply of these commodities. While the production of each of these energy commodities involves significant capital costs, these costs are either recovered through mechanisms of scarcity pricing or occasionally not recovered at all, resulting in periodic bankruptcy of natural gas or oil producers.[6]

The distribution of energy commodities to end users creates additional costs, much of which are fixed infrastructure costs such as gas stations, pipelines, and distribution wires. Here gasoline differs significantly from the other two energy products in that it is distributed through market-based retail competition among gas stations, rather than through regulated distribution utilities. The fixed costs of gas stations are recovered through a combination of periodic scarcity rents and locational market power, each of which allows stations to charge prices somewhat above their direct marginal cost of supply. With the possible exception of California, retail gasoline margins have not been a large share of retail prices.[7] The fixed costs of electricity and natural gas distribution, which are much more substantial as a share of the total retail cost, are recovered through regulated utility rates and constitute a significant portion of the difference between price and private marginal costs. These considerations are discussed in more detail in Section 4.3.

Finally, excise, sales, and other taxes influence the separation of retail prices from the costs of supply when they are passed on through retail prices. Given the relatively low elasticity of de-

[6]Significant amounts of the fixed cost of electricity generation are captured in scarcity components of electricity prices, which we use for the basis of our private marginal cost calculation. There is ongoing debate over whether nontrivial amounts of electricity fixed costs are "missing" from wholesale electricity prices, and this debates underpins various efforts to provide capacity payments to electricity generators.

[7]After subtracting wholesale prices, taxes, delivery costs and credit card fees, the remaining retail margin is typically less than $0.20 per gallon in the United States.

mand for each of these energy commodities, it is widely assumed that taxes are almost completely passed through to retail prices. The variation in taxes is most significant for gasoline, where the combination of federal, state, and local taxes can range from \$0.33 in Alaska to over \$1.00 per gallon in California, inclusive of emissions prices. Unlike natural gas and electricity, where recovery of distribution costs plays a significant role, taxes account for the bulk of the gap between prices and private marginal cost for gasoline.

4.2 Externality Costs

While market power, distribution costs, and taxes can all drive prices to levels above private marginal cost, the cost of unpriced externalities can significantly bias prices downward relative to social marginal cost. Our work and that of others (Graff Zivin, Kotchen and Mansur, 2014; Holland et al., 2016; Burger et al., 2020; Davis and Sallee, 2020) has focused on the external costs of air pollutants and draws largely on the work of Nick Muller and the AP3 version of his APEEP model (Muller n.d.). Our externality estimates do not include the cost of toxic chemical or water pollution, or the life cycle impacts of energy production, although we do account for methane leakage and line losses in distribution.

Air quality externality costs vary considerably by energy source and location. Externalities from the distribution and combustion of natural gas are relatively uniform across the country. By contrast the externality costs of gasoline consumption are highly concentrated in urban areas where smog and particulate pollution can affect large local populations. Therefore, there is a large urban-rural difference in gasoline externalities. The method for estimating externalities associated with electricity consumption requires mapping consumption in a given region to the output of specific power plants, combined with estimates from AP3 of the externality cost of emissions from those specific plants. Since power plants "serve" consumption drawn from large regional grids, these estimates are aggregated to relatively large regional blocks based on electricity reliability planning regions. Despite this aggregation, the variation in electricity externalities is much larger than for natural gas. Our estimates of externality costs range from \$0.03 per kWh in California to over \$0.10 in the coal-heavy upper Great Plains. Notably, average externality costs of electricity are estimated to be about twice as large as the private cost of power, meaning that social marginal cost can be more than three times private marginal cost in the high externality regions.[8]

[8] Our estimates of the damage from emissions do not vary by time of day or year. For a long-lived, uniformly mixed pollutant like CO_2, this has very little impact, but it could potentially alter the estimated impact of some local pollutants depending on the time pattern of emissions.

4.3 Considerations of Utility Rate Design

In the utility sector, particularly in the electric sector, economic regulation plays a substantial role in setting prices and therefore contributes to the gap between prices and social marginal cost. The pricing problem takes two forms. One problem, discussed in Section 3, is that the average price paid by customers of a utility for an incremental kWh of electricity can differ from the average social marginal cost of the electricity that utility supplies. In some parts of the country average price can be less than half of average SMC, while in other places it can be more than double. Such significant gaps between average price and average SMC can greatly influence customers' decisions on whether to purchase electricity consuming appliances and vehicles. The second pricing problem, more prevalent in electricity, is that energy utility prices are fairly static, changing only once every few months or longer, while the social marginal cost of producing electricity is quite volatile from hour to hour. This phenomenon, which is attributable to the very high cost of technologies to store electricity, is especially true in renewables-intensive electricity systems such as California, where the wholesale cost of electricity can frequently be zero or even negative during periods of surplus solar or wind generation, and on occasion may rise to over $1 per kWh during periods of relatively scarcity.

Therefore, even in regions of the United States where the average electricity price is reasonably close to the average SMC, prices and costs can differ dramatically during a given day or hour. The failure to reflect the social cost of electricity in a *timely* manner can greatly influence the usage of appliances, and represents a lost opportunity for shifting consumption from high to low cost periods, effectively using electrified loads as a form of storage.

The main reason average consumer electricity prices can diverge from the average private marginal cost of producing electricity is that electricity rates generate revenue that covers not just the production of energy, but also a wide variety of physical infrastructure, billing, and programmatic costs. Almost all of these infrastructure and programatic costs are fixed, or vary little with the quantity of electricity that is distributed across electricity networks. Figure 4 summarizes the composition of costs for a representative customer of Pacific Gas & Electric (PG&E) in California from 2013 to 2018. Over half of the 24 cents/kWh this customer paid in 2018 was collected to pay for transmission, distribution, taxes, and other costs.[9] As we discuss in Section 5, much or all of the revenue needed to cover the cost of transmission, distribution, and other programmatic costs is collected in the form of volumetric (e.g., cents/kWh) prices. While PG&E is an extreme example, this is a common feature of utility pricing everywhere.

[9] Even this breakdown overstates the marginal cost of electricity supply. The height of the blue bars reflects PG&E's average cost of "procured energy," which captures per-kWh costs of long-term contracts paid for renewable energy and other generation sources. These costs are well in excess of the average 2018 wholesale price of electricity in the California ISO's market.

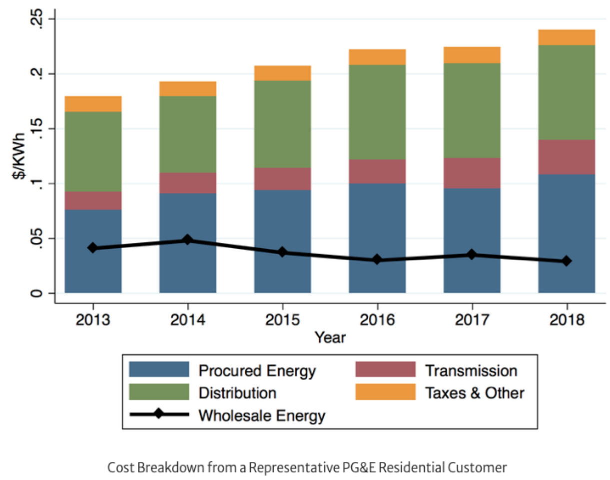


Fig. 4. Composition of PG&E Revenue Requirement

4.4 Combined Effects of Pricing Distortions

We combined the various sources of potential distortions to arrive at the maps presented in Figure 3. Natural gas is modestly overpriced relative to SMC in coastal parts of the country and modestly underpriced in the Midwest. This is largely because utility infrastructure costs priced into variable rates are relatively close to the externality costs of distribution leakage and household combustion. Both the utility distortion and the externality costs are fairly uniform across the United States but the former outweighs the latter in coastal areas and vice-versa in the Midwest. Gasoline is modestly underpriced in much of the United States, but underpriced to a much greater extent in urban areas where externality costs are large and more than overwhelm taxes. In the most rural and highly taxed parts of the country, the much more modest externality costs contribute to a modest overpricing of gasoline.[10]

In electricity, utility pricing regulation, along with more common distortions such as sales taxes, tends to increase the retail prices paid by customers to levels well above the *private* marginal cost of supplying them energy. In "cleaner," higher cost areas, the utility pricing (upward) bias dominates and in some coal-heavy low cost states the environmental externality (downward) bias dominates. However, in many parts of the country the two sources of opposite bias are close enough to roughly cancel each other out, leaving current average prices relatively close to current estimates of SMC.

[10]These estimates apply an assumed social cost of carbon of $50/ton. When we apply a $100/ton assumption, closer to the views of many leading climate economists today, gasoline becomes underpriced in all parts of the country. Note that fluctuations in the commodity prices of natural gas and oil do not change these conclusions so long as they reflect fluctuations in PMC and are fully passed through to customers.

4.5 The Future of Energy Costs and Prices

Our summary of retail prices and estimates of social marginal cost presented in Section 3 and applied in later sections are based on recent history, drawing on data from 2014-2016. Given this relatively narrow temporal snapshot of prices, it is important to note the short-term and potential long-term trends in the pricing relationships of these energy commodities.

Gasoline prices are greatly influenced by global oil prices, which are relatively volatile, having peaked at over $140 per barrel in 2008 and dropping to levels under $30 per barrel in both 2009 and 2020. The relative appeal of electric vehicles can therefore fluctuate significantly along with gasoline prices. While we will not even begin to speculate on future oil price levels in the medium term, decarbonization of the transport sector would be expected to place downward pressure on prices over the long-term.

Retail energy prices in the utility sector (for natural gas and electricity) are heavily influenced by the cost structures associated with procuring and distributing energy to households. As highlighted by the earlier example from PG&E, providing retail gas and electricity service requires substantial investment in fixed infrastructure such as pipelines and distribution wires. When energy consumption declines, whether due to increased efficiency, substitution to other fuels, or self-production via rooftop solar, these fixed infrastructure costs are spread over declining volumes of energy sold, increasing average costs and prices. In the case of electricity distribution, this dynamic has raised fears of a "utility death spiral" given the prospect of higher retail prices leading to ever larger amounts of rooftop solar penetration. The specter of a natural gas distribution death spiral has only recently emerged as efforts to shift large amounts of residential gas consumption to electricity gain momentum (Davis and Hausman, 2021).

Large-scale electrification of vehicles and appliances could reverse the trend of declining average residential consumption and at least reduce concerns of distribution utility death spirals, while perhaps accelerating the financial exposure of gas distributors. However, the aging of distribution infrastructure, combined with increased stresses posed by climate change-induced extreme weather, is also driving needs for increased infrastructure investment. Further, while electrification may reverse recent trends and lead to growth in average household electricity consumption, the changing *load shape* of energy consumption will have cost implications as well, both because SMC varies over the day and year, and because the changes may spur the need for higher capacity distribution, and therefore increased investment. Consider the canonical example of a California city where residential rooftop solar places increasing backflow stress on the distribution system during the day and high EV loads create new distribution consumption peaks during the evening or night.

There are also challenging questions about how deep decarbonization of electricity generation could and should affect future electricity prices at both the wholesale and retail levels. Zero-carbon generation sources tend to be highly capital intensive (renewable, nuclear) with high capital and extremely low marginal costs. High levels of renewable energy production have already had pronounced effects on wholesale energy prices (Bushnell and Novan, 2021; Fell and Kaffine, 2018), and have raised concerns about the ability of market prices to support further investment. The design of electricity markets that feature large amounts of renewable generation and storage resources continues to be an active area of research. In general, two options present themselves: an increasing reliance on compensating generators for making capacity available—regardless of how much energy that capacity produces— to fill any gaps between energy sales revenue and average generation costs or an increased emphasis on more accurate and more extreme scarcity pricing. Under either scenario, wholesale electricity prices are likely to grow more volatile and less predictable than they have been historically.

Therefore, while our analysis of recent data indicates that in many parts of the United States, average electricity prices do not greatly diverge from social marginal cost, there is good reason to anticipate that even the current modest gaps between retail prices and average social marginal costs will grow in these regions as electricity providers continue to accelerate decarbonization efforts.

5 Residential Rate Designs and Options for Improvement

In the previous two sections, we have described how energy prices in general can deviate from social marginal costs. Our own research has found that among the major household fuel choices, the two most serious cases of mispricing are the underpricing of gasoline in urban areas, due to high damages from local air pollution, and the over-pricing of electricity, largely on the East and West Coasts. Much of this electricity mispricing is created by regulatory rate designs that use volumetric pricing to cover large aggregate fixed costs. In this section we discuss several options for improving electricity rate design to better align pricing with social costs.

5.1 Current Rate Structures

Most residential consumers face utility price schedules that fairly closely follow a two-part tariff pricing approach: a fixed charge per month (or other billing period) and a marginal price for each additional kWh, regardless of when it is consumed. The primary deviation from the standard two-part tariff is that some utilities increase the marginal price as a household consumes more over the month, while others decrease the marginal price as the household consumes more. For most households on such increasing-block or decreasing-block pricing schedules, however, the change in the incremental price is fairly small. Importantly, such changes to the marginal price are unrelated to the time when the electricity is consumed, and therefore to changes in the marginal cost of supplying that electricity.

The monthly fixed charge, sometimes referred to as a connection charge, is generally uniform across residential customers and in most cases is relatively modest. Monthly connection charges for electricity average about $10.50 per month, and customers in much of California pay zero monthly fixed charges. Monthly fixed charges are more common and somewhat larger for natural gas customers, averaging $12.50 per month and ranging from approximately $2 to $23 (Table 1). Fixed charges constitute 20 percent of average gas bills and only about 10 percent of average electric bills. Thus, current levels of fixed charges have a fairly small impact on the relationship between volumetric electricity price and SMC.

Table 1: Monthly Fixed Utility Charges

	Mean	P5	P95
Electric Fixed Charge ($/month)	10.73	0.00	24.21
Electric Fixed Charge proportion of monthly bill	0.09	0.00	0.19
Natural Gas Fixed Charge ($/month)	12.55	1.80	22.61
Natural Gas Fixed Charge proportion of monthly bill	0.20	0.03	0.35

2014-2016. 1756 electric utility-states; 189 NG utility-states. Statistics are sales-weighted.

5.2 Reforming Rates to Better Reflect SMC

To frame a discussion for improving electricity pricing, it is helpful to first characterize the optimal or first-best pricing from an efficiency standpoint, even if implementation of such a standard is not feasible, or possibly not even desirable due to equity concerns. The most efficient pricing would feature a marginal price that varies at least hourly in a way that reflects variation in the SMC at that time and location of consumption. These marginal prices would not be linked to the amount of energy consumed but would vary by location, to the extent that transmission constraints and losses can be accurately captured in the energy price. When these marginal energy prices at times exceed the private average generation costs of electricity producers (including any environmental fees generators must pay), these prices would allow for some recovery of fixed costs as well. However, for most electric utilities in the United States, some fixed costs would remain unrecovered by efficient marginal prices and would need to be recovered in some way in order to maintain the utilties' financial viability.

This is not true for all utilities, particularly ones that create large externalities while generating power from low-cost coal-fired plants. Those utilities tend to charge prices that are below SMC. For those utilities, a fairly simple solution is to reduce their fixed charges and increase volumetric prices. Reducing fixed charges below zero, however, would be quite controversial in many locations.[11] Nonetheless, this problem of pricing below SMC is likely to decrease considerably as utilities phaseout coal and increase reliance on generation that produces far fewer externalities.

Beyond the simple principle of having marginal prices reflect social marginal cost, economic theory provides little additional insight as to the best ways to recover remaining costs (See Borenstein (2016)). There are two primary options for mitigating the distortion currently caused by the common practice of recovering fixed costs from the marginal component of electricity prices: shifting cost recovery to other sources and increasing utilization of fixed charges.

5.2.1 Moving Costs out of Utility Bills

Our discussion thus far has focused on direct utility costs such as transmission and distribution infrastructure investments. However, utility bills often include charges that fund programs that are only indirectly related to the cost of electricity supply. These include subsidies for low-income energy consumers and for households with behind-the-meter solar generation, support for energy efficiency incentives, and the cost of compliance with various mandates such as renewables portfolio standards. Economic efficiency, at least in the electricity sector, would be improved by shifting those costs unrecovered by efficient marginal prices to taxes or fees not directly linked to the quantity of electricity consumed.[12]

Economic efficiency considerations often imply that fixed utility costs could be funded at least partially from other sources such as general tax revenue. However, political realities have often produced the opposite effect and shifted general social programs into electricity rates. Rates tend to be much less transparent and are usually not subject to process restrictions, such as supermajority vote thresholds, that are frequently imposed on tax legislation. The political convenience of packing social spending into utility rates may have been tolerable at low levels in the past. Still, the technology trends that are the focus of this paper—namely the rise of distributed solar energy generation and increasing private and social attractiveness of electrification—have greatly increased the consequences of such practices.

The practice of funding programs through utility rates can also exacerbate inequality. Taxing the consumption of electricity—as volumetric price increases could be viewed—is far more regres-

[11] California, however, does a form of this with its climate rebate, a semiannual payment that is the same for all residential customers.

[12] While efficiency in the electricity sector would no doubt be improved by paying for fixed utility costs with general tax revenue, the efficiency effect for the economy as a whole would depend on the sources of tax revenue and the economic impacts of those taxes. The comparison depends crucially on the elasticities of demand for the various products being taxed (Browning, 1976). Still, if the ability to substitute between fossil fuels and clean energy increases, the inefficiency of allowing those prices to deviate from SMC will also increase. The Build Back Better proposal from the Biden administration does shift some of these costs to the federal budget, so it accomplishes some of what we are suggesting. In addition, where the price is well above SMC, moving it to more closely reflect SMC would likely reduce the need for low-income programs. Federal (or state) pricing of GHGs would help align price with SMC in areas where prices are below SMC, but could exacerbate the pricing and efficiency where $P > SMC$.

sive than taxing income, consumption, or even gasoline (Borenstein, Fowlie and Sallee, 2021).

5.2.2 Two-Part Tariffs

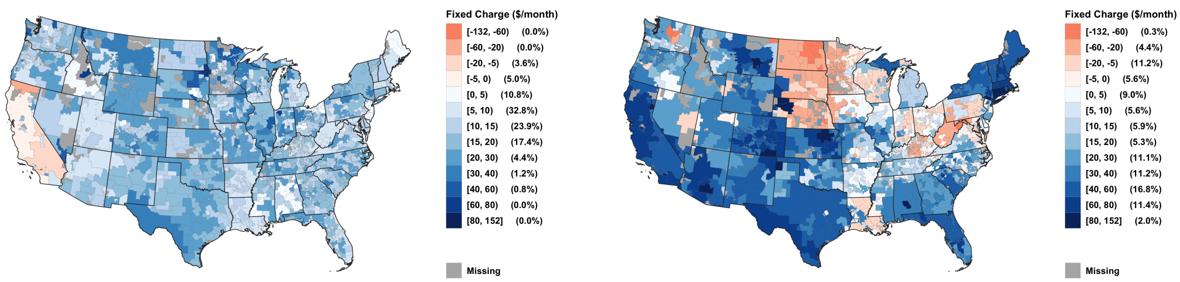
Another standard approach to recovering residual costs is through the monthly fixed charge component of a two-part tariff.[13] Although such charges are common, in many states they are too small to allow for marginal prices to be set at social marginal cost. In other states where externality costs constitute a substantial portion of the total SMC, setting marginal prices to SMC would result in substantial revenues above private marginal cost, assuming the utilities were not in turn taxed for their external damages. In some parts of the country, the windfall to utilities of rolling these externality costs into marginal prices would more than offset total fixed costs. In order to gain a rough sense of what fixed charges would be necessary to exactly cover utility revenues while also charging marginal prices equal to SMC, we perform the following calculation. Using data on total monthly utility revenues, we calculate the revenue that would be generated by charging a price equal to SMC, instead of the actual marginal price, on the same volume of sales. Thus, we assume no increase in consumption in response to lower marginal prices. We then divide the gap between total utility residential revenues and revenues generated from $P = SMC$ by the total number of residential customers to calculate the fixed charge that would support efficient volumetric pricing while still allowing the utility to cover costs.[14]

The results of this calculation are presented in Figure 5. In some cases, the revenue collected from optimal marginal prices more than eliminates the need for a fixed charge, instead requiring a fixed rebate to maintain revenue neutrality. The average optimal fixed charge is around $13 per month, which is not that far off from the average actual fixed charge. However, the distribution of these optimal fixed charges is quite different. Utilities in the Great Plains area tend to utilize higher fixed charges, partly due to a need to recover fixed costs from a smaller number of more geographically dispersed customers. However, electricity in these regions is currently underpriced, and raising marginal prices to SMC would produce a windfall that would more than offset the fixed charges, resulting in rebates. At the opposite extreme, California's low SMC would result in cutting marginal prices by two-thirds and necessitate monthly fixed charges averaging over $50 per household.[15]

[13]There is an active debate, inspired partly by Ito (2014), about whether customers actually respond to the marginal price of consumption of energy, rather than average price or total bill. Ito (2014), however, studies consumer response to a fairly complex increasing-block pricing schedule, not a comparatively simple two-part tariff. Ito and Zhang (2020) directly study consumer response to fixed versus marginal price and find that consumers are able to distinguish fixed charges from marginal price of consumption.

[14]This calculation is only for residential customers, so we are implicitly assuming that revenues from commercial and industrial customers are unaffected.

[15]The huge gap between price and SMC in California is driven in part by normal transmission and distribution fixed costs of providing electricity, but the bulk of it is due to social and environmental programs—subsidies for energy



(a) Actual Fixed Charges **(b) Fixed Charges at P = SMC**

Fig. 5. Actual Fixed Charges and Fixed Charges Under Efficient Volumetric Pricing

It is important to note that these values reflect the uniform residential fixed charge for each utility that would be necessary to reset the volumetric price to equal SMC and maintain profit neutrality.[16] Utilities, however, do not have to charge all of their customers the same fixed charge. The only real constraint on fixed charges would be to stay below the threshold at which a significant number of consumers may choose to disconnect or "defect" from the grid. While the combination of distributed solar, batteries, and backup generation make such defection technically feasible, it still remains a very expensive option. Economic efficiency does not require that all households pay the same charge, however. Consumer advocates in California and elsewhere have raised objections to increasing fixed charges on the grounds that such a policy would be regressive. Such concerns can be mitigated by aligning monthly fixed charges to income, either through blunt programs such as a single separate low-income fixed charge, or through a more precisely aligned sliding scale that would be linked to a consumer's income (Borenstein, Fowlie and Sallee, 2021).

5.2.3 Ramsey Pricing for Electrified Households

The fixed charges discussed in the previous subsection would be sufficient to allow for efficient marginal electricity prices for *all* households. However, to the extent that political, regulatory, or other constraints limit the ability to keep all unrecovered fixed costs out of marginal prices, the

efficiency, rooftop solar, or low-income customers—as well as climate mitigation and, most recently, climate adaptation. In other states, large gaps have resulted from past investments in nuclear power or other expensive technologies that are still on the books.

[16]We carry out these calculations assuming that there is no demand elasticity. With nonzero demand elasticity, the calculation would change to the extent that SMC exceeds PMC, because setting price equal to SMC would still mean that quantity changes alter profits because $P > PMC$.

consequences of mispricing can be mitigated in theory by limiting the mispricing to less price-responsive households or uses. This concept of efficient price discrimination is known as Ramsey pricing. The general principle of Ramsey pricing implies that in order to minimize the dead-weight loss created by charging prices above marginal cost the more price-elastic customers or uses should receive prices closer to marginal cost, while less price-elastic customers or uses should bear the brunt of the price markup.

If the view is that certain energy services, such as water heating or vehicle fueling, would be especially responsive to electricity prices in the decision to switch from fossil fuels to electricity, then the households that commit to such a switch could be offered lower-priced electricity for those services, or for the household's entire usage. Ideally, under Ramsey pricing, the electricity price would be differentiated by usage as well as household, with prices closer to SMC for the energy services most likely to switch, such as electric hot water heating or vehicle fueling, rather than for air-conditioning or lighting.

While special electrification rates are fairly common, and offer benefits relative to overcharging for all electricity, this approach has a few potential limitations. The first is the disparities it can create across different households. While providing lower-priced electricity for energy services especially amenable to fuel switching, such a policy would raise equity concerns to the extent that lower-income households, and renters, would be less likely to use electricity for those services. A second concern is the technical issue of whether to provide a reduced price for the household's entire consumption, or only for specific energy services. The latter policy is more in line with the efficiency of Ramsey pricing, but it requires more capital investment in metering, which is potentially expensive. Electric Vehicle (EV) rates, for instance, are a common option in California, but fewer than 1 percent of EV owners are on the usage-specific rate that requires a separate electricity meter capable of measuring only the power going into a vehicle. Over time, one would expect the cost of such granular metering to decline.

A last critique of this approach returns again to the basic point that pricing above social marginal cost is inefficient for every household and usage. When prices exceed SMC by significant amounts, as in California, it can lead to inefficiently depressed consumption as well as substantial wasteful capital investment in distributed generation and storage that is economic only because of distorted marginal prices. As the debate over net-energy metering policy in the last decade has demonstrated, once the focused benefits of inefficient pricing to a substantial minority of customers take hold, they are very difficult to change.

5.2.4 Time-Varying Pricing

Time-varying prices have an important role to play in decarbonization. Marginal cost of supply has always been more volatile in electricity than practically any other industry due to the extremely high cost of storage and very inelastic demand at every point in time. Moving to much greater supply shares from intermittent resources is likely to make marginal cost even more volatile, though advances in storage and in demand response and direct load control are likely to have the opposite effect. Nonetheless, on net the volatility of energy supply marginal cost seems likely to remain at least as high as it had been in the past, maintaining the strong policy arguments for retail prices that change within a day to reflect marginal cost variation.

Because a much larger share of supply in the future is likely to be intermittent as a function of weather, time-varying rates could play an important role in shifting demand to times when supply is available. The three largest residential energy uses typically noted to have high potential for substitution of electricity for higher GHG energy sources—space heating, hot water heating, and vehicle fueling—all have the significant potential to time shift over short durations (e.g., less than one hour) and the last two have significant potential to timeshift over multiple hours. With improving technology for communicating electrical appliances and automated response, the prospects for supply-following load seem bright.

Capturing the value of these time shifts through time-varying pricing, however, will require sending price signals that accurately reflect the significant variation in SMC of supply. The most common time-varying rate schedule, time of use (TOU) pricing, typically designates three pricing periods—peak, shoulder, and off-peak—with a fixed price in each of these periods for many months at a time. Unfortunately, in ongoing research, we find that such a price structure does a poor job of reflecting SMC variation. We use the hourly SMC from Borenstein and Bushnell (2021a) to design a best-fit residential TOU tariff for each utility in our sample (nearly all utilities in the continental United States) and then analyze the share of volatility such TOU tariffs capture. A straightforward metric for this question is the *R-squared* from an ordinary least squares regression of hourly SMC on dummy variables for each of the TOU pricing periods. For over 95 percent of US utilities, the *R-squared* from such a regression is less than 0.05, implying that TOU pricing captures less than 5 percent of the variation in hourly SMC.[17] We are currently doing a similar analysis for more dynamic alternatives such as critical peak pricing, which typically raises the price for a small number of hours on 10 to 15 days per year with only day-ahead or same-day notification.

While it is tempting to think that adoption of TOU or dynamic pricing could also address the overall gap between price and SMC, that is generally not the case. The SMC calculations that we and others have reported are typically the quantity-weighted average SMC under the existing

[17]On the one hand, this analysis overstates the effectiveness of TOU pricing in that it assumes that the regulator has perfect foresight about the average energy cost in each of the TOU periods, and it ignores intrahour SMC variation. On the other hand, if TOU variation is all that consumers have the capability to respond to, then it might be the best one can do in time variation of prices. In practice, virtually all utilities offer, or require, TOU rates for commercial and industrial customers. Few residential customers are on such a rate, though the proportion is growing rapidly.

static pricing. In other words, the average SMC reported already accounts for periods of very high and very low hourly SMCs. To a first order, moving to even dynamic pricing that reflects the hourly variation in SMC would have no impact on the average SMC.[18] Thus, setting $P_h = SMC_h$ in every hour would leave the same revenue shortfall problem that would occur if a static price were set such that $\bar{P} = \overline{SMC}$. Dynamic pricing has very attractive properties and would almost surely improve efficiency, but it would not address the revenue shortfall created by covering many costs that are truly fixed, including government policies, through a volumetric electricity rates.

6 Impact of More Efficient Energy Prices on Electrification

In previous sections, we discussed how distortions in energy prices can lead to inefficient customer choices in the purchase and use of durable goods. We also described options for improving pricing in the electricity sector. The magnitude of the inefficiencies of current rate structures, however, depends entirely on consumer responsiveness to prices, both own-price elasticities and cross-price elasticities. There is an immense body of literature estimating demand elasticities for residential energy sources, but unfortunately it offers an immense range of estimates (See Zhu et al. (2018)). Furthermore, most of the literature does not explore cross-price elasticities across energy sources, which are almost certainly the most important factor in determining the magnitude of the inefficiencies from distorted energy prices. An equally important factor is that nearly all of the studies utilize data from more than a decade ago, when the electric alternatives for space heating, water heating, and personal vehicles were much less advanced, and were generally viewed as much poorer substitutes for natural gas and refined petroleum products.

Therefore, the existing literature is probably of limited value in assessing the potential efficiency gains from redesigning electricity tariffs to more accurately reflect SMC. New elasticity estimates based on recent settings with more current technologies would be extremely valuable for the policy discussion of energy pricing. Still, if technologies continue to improve rapidly, empirical elasticity estimates will always be years behind the numbers that would be most useful for a policy analysis.

Rather than relying on a single "best" empirical estimate of the relevant elasticities, one alternative approach to such a policy analysis would be to consider a range of cross elasticities and use the analysis to gain insight about the level of elasticity and price differentials that would trigger significant switching of energy sources. The weakness of this approach is that it could be difficult to interpret an analysis that relies on multiple elasticities, creating a plethora of cases to consider.

[18] In a more detailed analysis, one would want to account for the fact that dynamic pricing would almost surely lower the peak-time energy costs and therefore lower the average SMC. That would also allow a lower average retail price. These changes, however, would not necessarily increase or decrease the average gap between price and SMC. Dynamic pricing could also raise or lower quantity, which would then reduce or increase the margin above SMC on each kWh that would be needed to cover fixed costs.

Another possiblity is a more techno-economic approach, in which the alternative technologies are studied to classify appliances into types that use different energy sources but deliver comparable energy services. Based on assumptions of comparability, one can then derive energy and device prices that make one device more or less cost-effective than another for delivering the same energy services (See Energy+Environmental Economics (2019)). This approach is fairly popular in some circles, in part because it can produce fairly concrete comparisons, but it is built on the critical assumption that simple comparisons of energy services from different devices is feasible. It is unclear how credible such comparisons would be for heat pump versus natural gas powered space and water heating, or for electric versus gasoline vehicles. The characteristics of the energy services delivered by these alternatives are generally recognized to be quite different. The values that consumers place on these characteristics are almost certainly very heterogeneous, so the switching price thresholds that many of these studies attempt to infer are more likely to be broad distributions of prices.

Still, given the priority of electrification and the recognition that consumers will make these choices based in part on energy prices, it is important to derive some estimates of the impact of pricing that can be used in the policymaking process. All these approaches can contribute some value to that process.

6.1 Impact of Efficient Average Marginal Prices on Key Goods

One of our previous papers (Borenstein and Bushnell (2021b)) made a modest contribution to this area of study by calculating the energy costs of alternative devices under current prices of electricity, natural gas, and gasoline, and then recalculating what energy costs would be if prices for all three sources were set to equal SMC. In this section, we examine these impacts of pricing on space heating, water heating and light duty vehicles. In each of these contexts, there are several important dimensions beyond energy prices to consider, particularly the capital cost difference between fuel-type choices and the quality differences between, for example, an electric heat pump and a natural gas furnace or an EV and a conventional vehicle.

Unfortunately, the quality differences between technologies are not always fully separable from the costs of using those technologies. Climate, for example, can affect the performance of both heat pumps and EVs relative to their fossil-fueled alternatives. Battery performance degrades in extremely cold or how temperatures, and heat pumps for space heating may require supplemental natural gas combustion heat in extremely cold weather. Such performance issues would also increase the costs of using the electric alternative in each case. There is a need for research to better document the degree to which regional climate can affect both the performance and cost of using such technologies. In the absence of quality information on these differences we compared these devices in regions that share reasonably warm climate conditions but have significant variation in energy prices.

Here, we follow the approach of Borenstein and Bushnell (2021b) to carry out similar comparisons of the cost of different energy sources in three states: California, Louisiana, and South Carolina. Energy costs per unit of energy service (i.e., kWh equivalent of space heat or water heat) of a conventional natural gas appliance compared to an electric heat pump based appliance are summarized in the last two columns of Table 2.[19] As discussed in Section 3, California has extremely high electricity prices and also high natural gas prices. In Louisiana, by contrast natural gas prices are close to SMC and electricity prices somewhat *below* SMC. South Carolina electricity and natural gas prices are overpriced at nearly 50 percent above SMC. Although heat pumps are the lower-cost energy source for Californians according to SMC, at current retail prices they are roughly twice as expensive to use as their natural gas equivalents. At the opposite extreme, natural gas appliances are actually slightly lower cost at true SMC in South Carolina and also slightly cheaper to use at current retail prices.

Table 2: Costs of Appliance Use at Price and SMC

State	Appliance	Units in	Price ($/..)	SMC ($/..)	Cost /Unit at P	Cost /Unit at SMC
Space Heating						
CA	Gas	therm	1.057	0.682	0.045	0.028
CA	Heat Pump	kWh	0.176	0.059	0.083	0.027
LA	Gas	therm	0.693	0.681	0.029	0.029
LA	Heat Pump	kWh	0.087	0.093	0.041	0.043
SC	Gas	therm	0.894	0.641	0.037	0.027
SC	Heat Pump	kWh	0.115	0.095	0.054	0.044
Water Heating						
CA	Gas	therm	1.057	0.682	0.054	0.035
CA	Heat Pump	kWh	0.176	0.059	0.088	0.029
LA	Gas	therm	0.693	0.681	0.035	0.035
LA	Heat Pump	kWh	0.087	0.093	0.044	0.046
SC	Gas	therm	0.894	0.641	0.046	0.033
SC	Heat Pump	kWh	0.115	0.095	0.058	0.047

Gas furnace assumed to have a 0.90 AFUE rating. Heat pump space heaters assumed to have a Heating Seasonal Performance Factor (HSPF) of 8.50. Gas water heaters assumed to have an Energy Factor (EF) of 0.67, and Electric heat-pump water heaters assumed to have an EF of 2.00. Furnace efficiency is also adjusted for energy consumption of fans. Units of output adjusted to KWh for all appliances. See (Borenstein and Bushnell, 2021b) for more details.

The comparison for light-duty vehicles is more difficult, given the many ways (both positive and negative) in which the EV experience can differ from that of driving an internal combustion engine (ICE) vehicle. To minimize the quality differences we limit our comparison to groups of

[19] For details of the calculations, see Borenstein and Bushnell (2021b).

closely matched vehicles. We first compare a Nissan Leaf with its ICE counterpart, the Versa. We next compare the costs of driving the *same* vehicle, a plug-in electric Toyota Prius Prime, on the alternative fuel sources it can utilize. In all three states, EVs are lower cost per mile than their ICE counterparts at SMC, but this SMC advantage is greatly diluted by prevailing energy prices (Table 3). In the case of California the problem is excessively high electricity prices. A Prius Prime is only slightly cheaper for a consumer to drive on electricity even though its SMC per mile is more than three times greater on gasoline. In the case of Louisiana and, to a lesser extent, South Carolina, the main culprit diluting the EV advantage is the *underpricing* of gasoline due to unpriced externalities.

Table 3: Costs per Mile of LDVs at Price and SMC

State	Make	Model	Units	Units per 100mi	P ($/unit)	SMC ($/unit)	MPGe	$/Mile P	$/Mile SMC
CA									
	Nissan	Leaf S Plus	kWh	30.0	0.176	0.059	108	0.053	0.018
	Nissan	Versa	gallons	2.9	2.677	2.861	34	0.078	0.083
	Prius	Prime	kWh	25.0	0.176	0.059	133	0.044	0.015
	Prius	Prime	gallons	1.9	2.677	2.861	54	0.051	0.054
LA									
	Nissan	Leaf S Plus	kWh	30.0	0.087	0.093	108	0.026	0.028
	Nissan	Versa	gallons	2.9	1.932	2.211	34	0.056	0.064
	Prius	Prime	kWh	25.0	0.087	0.093	133	0.022	0.023
	Prius	Prime	gallons	1.9	1.932	2.211	54	0.037	0.042
SC									
	Nissan	Leaf S Plus	kWh	30.0	0.115	0.095	108	0.035	0.028
	Nissan	Versa	gallons	2.9	1.896	2.272	34	0.055	0.066
	Prius	Prime	kWh	25.0	0.115	0.095	133	0.029	0.024
	Prius	Prime	gallons	1.9	1.896	2.272	54	0.036	0.043

This analysis makes a useful contribution to one piece of the puzzle that connects pricing with electrification, but mostly it highlights how complex that puzzle is. This sort of energy cost comparison could feed into an econometric study of device switching or a techno-economic study of the cost-effectiveness of alternative technologies. In either case, however, one would need to confront many other issues before reaching conclusions about the impact of price distortions on electrification.

7 Conclusion: Agenda for Future Research

In this paper, we have attempted to present an overview of the economic considerations that need to be addressed in policy discussions of energy pricing and residential electrification. While existing research has contributed some useful insights, there is need/opportunity for a great deal more work to support the policy decisions that we face today. We close with a list of questions that remain unanswered or only partially answered, but that we believe offer rich opportunities for further research.

1. Technical and economic considerations of appliance electrification

   - What is the CO_2 reduction potential from shifting new and replacement appliances from gas to electricity?
   - What is the CO_2 reduction potential from the early replacement of existing functioning appliances from gas to electricity?
   - What kinds of programmatic costs would be incurred to spur large scale appliance replacement in existing homes, factoring in adverse selection, free rider, and rebound impacts?
   - How does electric heat pump space heat efficiency vary with ambient climate? How does this affect the value proposition of heat pumps in cold climates?
   - How does expected energy usage cost influence consumer choice of appliance type? Does consumer internalization of energy cost differ by energy source?

2. Technical and economic considerations of light-duty vehicle electrification

   - What is the relative importance of the various factors influencing EV adoption, including energy costs, vehicle costs, and infrastructure considerations such as access to charging?
   - How large a role does the relative energy cost of electricity versus gasoline play in EV purchase decisions?
   - How do relative energy costs influence the usage (e.g., miles traveled) of EVs relative to ICE vehicles?
   - How do the factors influencing EV adoption vary across income and demographic groups, such as residents of single family versus multiunit dwellings?
   - How do consumers internalize regional and weather-based differences in EV efficiency and range?

- How would expansion of autonomous vehicle operation change the answers to these EV questions?

3. Considerations of electricity system costs

   - How will deep decarbonization shape the total revenue requirements and marginal costs of electricity providers?
   - How will deep decarbonization shape the average levels and volatility of wholesale energy prices?
   - What are the strengths and weaknesses of current externality cost estimates, and where is further refinement needed?
   - How much potential for reducing costs and volatility is provided by expanded electrification, including time-shifting of usage by electric space and water heating and electric vehicle charging, as well as tapping the batteries of EVs to send power back into the grid at high-value times (vehicle-to-grid integration)?

4. Considerations of utility pricing and rate design

   - How do consumers internalize the difference between marginal and average electricity prices, particularly the differences between monthly fixed and marginal charges? (See Ito (2014); Ito and Zhang (2020); Shaffer (2020)
   - What are the equity implications of different two-part tariff designs? Can all non-marginal costs be recovered through monthly fixed charges?
   - What are the equity and efficiency implications of offering lower marginal electricity prices only to electrified homes?

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