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A review of barriers in implementing dynamic electricity pricing to achieve cost-causality

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Abstract

Rapidly changing economics, customer preferences, and policy to address climate change and local environmental pollutants have driven increased deployment of a wide range of distributed energy resources in the U.S. electricity system. Distributed energy resources have enabled an expanded role for energy consumers and non-utility third parties to reshape system costs, drawing renewed attention to the potential of reforming electricity rate design based on the further application of cost-causal principals to improve overall system fairness and efficiency. One mechanism to move toward greater application of cost-causal rate design is dynamic pricing, which varies electricity prices across time and location to reflect costs of providing electricity to consumers under specific market conditions and grid operation conditions. While dynamic electricity pricing has penetrated some markets, and it has not been widely implemented, particularly for residential consumers. In this review article, we provide a brief summary of electricity rate design, including the possibility of introducing dynamic prices, and explain why dynamic prices are more reflective of the short-run marginal costs of electricity supply than volumetric rates. We then explore the barriers to the widespread adoption of residential dynamic pricing, emphasizing technical, economic, and political challenges. Our assessment reflects the ability of dynamic prices to engender more equitable and efficient outcomes by achieving the goal of cost-causality, and we argue that a move toward more dynamic pricing can constitute a welfare improvement over volumetric rates. However, dynamic pricing does not completely address the full set of challenges associated with rate design and, alone, is unlikely to enable the full recovery of fixed costs and the fair attribution of the positive and negative externalities of electricity provision. Therefore, electricity rate design requires tradeoffs, making it as much an art as a science. This analysis synthesizes literature across multiple fields and suggests avenues for further research.

1. Introduction

A number of emerging societal and technological changes are challenging the infrastructure that is required to provide electricity service to virtually every household in the United States and the utility business models developed in the 20th century to own and operate electricity systems. The declining cost of distributed energy resources (DERs), the persistence of the challenge of addressing energy affordability, and the increasing urgency of climate change mitigation, among other trends, have created challenges for the management of the electric grid. In this context, many state, regional, and federal bodies are debating new rules to govern the electric grid, while still ensuring reliable electricity service, making electricity affordable, providing grid security, reducing environmental impacts, and enabling some forms of consumer choice. These various developments have spawned renewed calls for electricity rate design that incorporates cost-causal principles (Convery *et al* 2017, Pérez-Arriaga *et al* 2017).

The cost of providing electricity services to consumers varies over time—from minute-to-minute, day-to-day, and season-to-season—as well as by location. The total cost of providing electricity includes not just the cost of generation, but includes the costs of large capital investments in the transmission and distribution system, as well as grid services that have public good characteristics such as grid security and reliability. A traditional flat ('volumetric') electricity rate bundles the costs of providing many energy services—generation, distribution, transmission, and other operational costs—into the sale prices of kilowatt-hours (kWhs). Such a pricing structure does not reflect the variation in the costs of providing electricity for a specific kWh of demand. In contrast, cost-causal principles of rate-design suggest varying the rates charged to consumers proportional to the cost of providing all energy services to that consumer at each point in time and location (Sherwood *et al* 2016). In other words, cost-causal rate-design principles[1] establish prices for energy services that reflect the underlying short-run marginal system costs—including all externalities—of providing electricity for a specific kWh of energy, as would be accomplished in idealized competitive markets that internalize externalities. Standard economic framing requires prices to equal marginal social costs for social welfare to be maximized. Cost-causal rate design seeks to align prices with the *specific* marginal social costs of delivering electricity services to a *specific* consumer at a *specific* time.

Advocates of cost-causal rate design principles argue that electricity systems would be more efficient if rates properly passed all marginal costs through to consumers and thus aligned the private incentives of energy consumers with the marginal costs incurred to meet demand. While cost-causal rate design principles primarily address economic efficiency, advocates have argued that such principles do not preclude, and may even enable, equity and environmental goals as well (Convery *et al* 2017). However, as we discuss in this review article, cost-causal principles advance a straightforward goal in abstract but are difficult to implement in practice for several technical, behavioral, political and institutional, and economic reasons specific to the electricity sector.

Real-world electricity prices deviate from marginal social costs, sometimes substantially (Borenstein 2016). Electricity rate design differs from the cost-causal ideal due to the requirement that supply and demand must always be balanced in near real time, but retail prices for the vast majority of customers do not fluctuate in real time, so some degree of simplification is required even if marginal costs are reflected in average prices. While time variant costs of generation are incorporated into retail prices, fixed costs and public good characteristics present more of a challenge. Rate design occurs in a heterogenous, balkanized governance system with rate-design decisions occurring in a polycentric regime of interacting actors with partially aligned or conflicting institutional incentives that differ substantially by utility type and by state (Borenstein and Bushnell 2015).[2] Finally, most jurisdictions do not account for the external costs of climate change in electricity rates, and where they do, incremental costs accounting for climate impacts are below the social cost of carbon.[3]

In this article, we discuss the institutional contexts of electricity rate design and review the arguments for how cost-causal principles of rate design can address many of the simultaneous, often competing objectives of electric grid management for the 21st century.[4] Our focus in this review is the U.S. electricity system and service to residential end-users, but our analysis may also apply in other contexts.[5] Following this theoretical justification, we focus on the set of practical implementation challenges for reforming electricity rates to incorporate cost-causal principles. We group these challenges into technical, behavioral, political and institutional, and economic categories, largely to reflect the nature of different fields of study, recognizing that these distinctions belie the interconnected nature of the challenges of rate design. Then, after outlining each set of challenges individually, we proceed to discuss their interactions.

[1]Throughout this article, we define 'cost-causal principles' as rationales to reform electricity rates to assign a greater fraction of the incremental costs of serving a particular kWh of load to the consumer of that load. This includes not only the attribution of costs of generation to consumption at a particular place and time, but the attribution of costs of provision of the transmission and distribution system and a wide variety of grid services to individual users based on their consumption patterns.

[2]For example, states and regions with competitive retail electricity markets differ substantially from those that preclude retail choice. Further, investor-owned utilities are often rate regulated by state regulators, whereas municipal and cooperative utility rates are largely self-regulated.

[3]For example, in the Regional Greenhouse Gas Initiative—a cap-and-trade program covering the electricity sector in some New England and Mid-Atlantic States, the clearing price for emission allowances was less than \$6 per ton in 2019. The Federal Interagency Working Group on Social Cost of Greenhouse Gases estimated the social cost of carbon under a wide variety of assumption, finding values \$10 per ton at the highest discount rate analyzed. (Interagency Working Group on Social Cost of Greenhouse Gases 2016, RGGI, 2020)

[4]Our review is focused on retail rates for residential consumers, but we note that cost-causal principles have been applied to a greater extent in other parts of the electricity system where implementation barriers differ (e.g. wholesale rates and commercial and industrial rates).

[5]Specific market rules in parts of some states have created conditions where alternative institutional designs create pricing regimes with less direct regulatory control, such as the competitive market in Texas. Customers in the competitive zones of Texas can opt to receive service from retail energy providers that offer dynamic pricing. However, even in areas with competitive generation markets and competitive and dynamic electricity rates, there are significant barriers to incorporating cost causal principles.

We find that while a move toward greater incorporation of cost-causal rate design principles generally constitutes a welfare improvement over the predominant status quo reliance on volumetric residential retail rates, other considerations require careful attention in reforming electricity rates. Questions remain about the full recovery of long-lived infrastructure and the fair attribution of the positive and negative externalities associated with the operation of the electricity system. With multiple objectives and different institutional contexts, there may not be a single optimal design, implying that rate design will always require the social negotiation of trade-offs (Faruqui *et al* 2012) and the need for rate reform to strike an appropriate balance between accuracy and practicality. Further, the methods through which rates are developed and negotiated is not purely technical. Rate reform processes are driven as much by political and institutional factors as by economic principles. As different jurisdictions—at different levels of governance—experiment with rate design and deploy new rate structures, principles of cost-causality are likely to remain an idealized notion with the gap between theoretically perfect dynamic prices and what is implemented in practice requiring continuous negotiation (Joskow and Wolfram 2012).

2. Reforming rate design to incorporate cost-causal principles

We begin by providing background on traditional rate design and ratemaking processes, newer market changes that elicit questions about the appropriateness of traditional rates, and the different types of rate designs that have been introduced to incorporate cost-causal principles.

2.1. Traditional rate design

Bonbright's (1961) seminal work on public utility rates advocated for rates that are simple, understandable, acceptable to the public, and feasible to apply and interpret. Additional factors that are considered in rate design include effectiveness in meeting revenue requirements for financing long-lived infrastructure, stability of rates and revenues, equity across customers, and economic efficiency. These multiple goals may align but often, at least partially, conflict with each other, leading to the politicization of rate design.

To comprehend the challenges associated with the implementation of cost-causal rate-design principles, it is helpful to understand the traditional ratemaking process. Public utility rates represent negotiations between utilities, regulatory bodies, and public stakeholders—as well as their representatives and elected officials—to balance the multiple objectives of rate design under uncertainty about the future (Bonbright *et al* 1988). The majority of jurisdictions currently employ an embedded cost (i.e. average cost) of service methodology for at least part of established rates. In this approach, a total revenue requirement is established that allows a utility to recover the costs of service—and in the case of investor-owned utilities, also earn a 'reasonable rate of return.' This amount is then assigned to rate classes based in part on historical load characteristics[6] (Lazar *et al* 2020). Some jurisdictions alternatively apply a marginal cost of service approach that bases allocated costs on marginal costs rather than average expended costs.

In practice, the assignment of costs to customer classes is not merely a mathematical exercise but instead a political process that appeals to cost-causal principles among many other norms and constraints. For instance, determining whose usage necessitated investment in a new generating facility or an upgrade of the distribution system requires strong assumptions about causality and is therefore not a strictly analytic exercise. This is reflected in the 2016 ratemaking guidance from the National Association of Regulated Utility Commissioners (NARUC), which underscores the persistent challenges of disaggregating costs by their function and allocating costs to specific consumers. NARUC's guidance describes a number of methods that have been developed, but acknowledges that a 'range of reasonableness' leaves room for considerable interpretation (National Association of Regulated Utiltity Commissioners Staff Subcommittee on Rate Design 2016).

Under a typical flat volumetric rate structure where consumers pay a fixed price for each kWh of electricity consumed within each month, rates are only adjusted periodically. Therefore, rates are unresponsive to changes in supply and demand within and across billing periods. Historically, in an environment with relatively homogeneous customer classes, steadily growing demand, monopoly retail electricity providers, and no technologically feasible way to determine individual consumer load patterns, flat volumetric rates achieved many of the societal goals of rate design. Flat rates also have the advantage of being relatively easy to calculate (simply divide the revenue requirement by the kWh sales for each customer class) and relatively easy to understand (a single price for electricity for all customers within a class at all points in time within a billing period). However, the conditions under which flat volumetric rates were first adopted no longer exist: heterogeneity in customer classes has become an important social concern (Thompson 2016); demand is flat or declining

[6] A typical rate-making process is composed of three steps: functionalization, classification, and allocation. Functionalization is the purpose of a cost, which is typically categorized as generation, transmission, distribution, or other. Once disaggregated into functions, costs are then classified into categories including demand (fixed costs based on kW), energy (costs that vary by kWh), and customer (investments to establish basic service, metering, and other customer service). Finally, costs are allocated to customer classes to determine how much each customer class should pay.

in many jurisdictions (EIA 2020); DERs and market reforms are challenging monopoly utility structures; and advanced metering infrastructure is making unprecedented levels of new data available.

Because flat rates do not necessarily incorporate principles of cost causation, they often fail to transmit price signals that reflect the varying costs of service provision to energy consumers. If utility rates do not reflect marginal social costs, consumers will be incentivized to make socially suboptimal decisions (Borenstein 2016). Relative to a socially optimal profile of consumption, flat rates can lead to over-consumption during periods of high cost and under-consumption during periods of low cost. Over-consumption during peak hours is especially costly since utilities must purchase expensive capital equipment or energy services from other parties to meet critical peak loads, even though this capacity can be used for as little as 60 to 100 h a year (Faruqui *et al* 2009). In most regulatory contexts, the capital costs of these infrequently run peaker plants and inadequately utilized transmission and distribution infrastructure are shared by all electricity consumers, creating short-run cross-subsidies from consumers who use relatively less electricity during high-cost periods to those who use relatively more during these periods (Johnson *et al* 2017).

2.2. Cost-causal rate design principles and emerging changes to rate design

Legislators, regulators, advocates, and utilities are rethinking electricity rates and have expanded efforts to study and pilot alternative rate designs to incorporate cost-causal principles. Cost-causal rate design seeks to allocate costs of providing electricity service to the actor whose consumption made the incurrence of the cost necessary. Cost causal principles center the marginal cost of electricity service delivery as the fundamental basis of prices.

Academic researchers have modeled the consequences of alternative rate structures (Azarova *et al* 2018), and proposed rates that more explicitly incorporate cost-causal principles (Burger *et al* 2019b). In fact, most jurisdictions have adopted some form cost-causal rate-design principles, incrementally moving away from a flat volumetric structure. Many other sectors within the electricity industry have also moved toward the incorporation of some cost-causal principles, such as the use of locational marginal pricing in wholesale electricity markets and the Federal Energy Regulatory Commissions' dynamic pricing of transmission.

Efforts within the retail residential electricity market to move away from flat volumetric rates have included concepts such as fixed charges and block rates. Figure 1 displays penetrations of electricity rate structures for residential consumers that vary prices over time within a day to reflect differences in marginal costs as of 2017. More recently, more complex structures are becoming increasingly prevalent. These rate options exist across a spectrum with flat volumetric rates on one end and rates that update in real-time and with location- specific marginal pricing on the other.

2.2.1. Temporal cost-causal rate design.

Ideally, a program that embodies cost-causal rate design principles could adapt to reflect cost changes for delivering energy services in near real-time in response to system conditions. A number of rate design options include elements of cost-causal design principles, specifically with respect to the timing of demand relative to coincident costs. These approaches begin to introduce temporal variation into electricity rates but do not necessarily capture the full temporal variation in system costs (Borenstein 2005). Proposals to introduce temporal variation in rates vary in complexity. In this section, we enumerate a number of utility pricing strategies that introduce at least some temporal variation in prices. Figure 2 shows a schematic representation of different time-varying electricity pricing in relation to a daily load profile.

The simplest incorporation of a cost-causal principle is to establish **seasonal differentiation of flat volumetric rates**, to address higher loads in winter and summer periods or adjustments to the fuel component of rates to reflect changes in underlying fuel costs.

Greater temporal disaggregation can vary electricity rates by predictable time-of-use schedules within a day. '**Time of Use Pricing**' sets regular rate schedules and a limited numbers of price fluctuations based on historical supply and demand information. Early experience with these programs has demonstrated the elasticity of residential consumer demand to temporally varying prices (Herter *et al* 2007, Herter and Wayland 2010). To the extent that Time of Use rate designs are more temporally dynamic, they can represent an efficiency improvement over volumetric charges.

Critical Peak Pricing, where consumers are charged a higher rate during peak hours, is close in concept to a dynamic rate in that rate changes are not known far in advance. Yet Critical Peak Pricing is typically restricted to a maximum duration and number of price-change events per period, and uses pre-set price levels, which limits this approach's ability to capture all variations in marginal costs. Variations in creating price differentiation specifically at peak periods include Variable Peak Pricing and Critical Peak Rebate programs which reward customers for reducing consumption as opposed to charging more for consuming during critical peak periods.

Even higher temporal disaggregation can vary rates by actual time-of-use service costs, sometimes referred to as '**Real Time Pricing**.' These

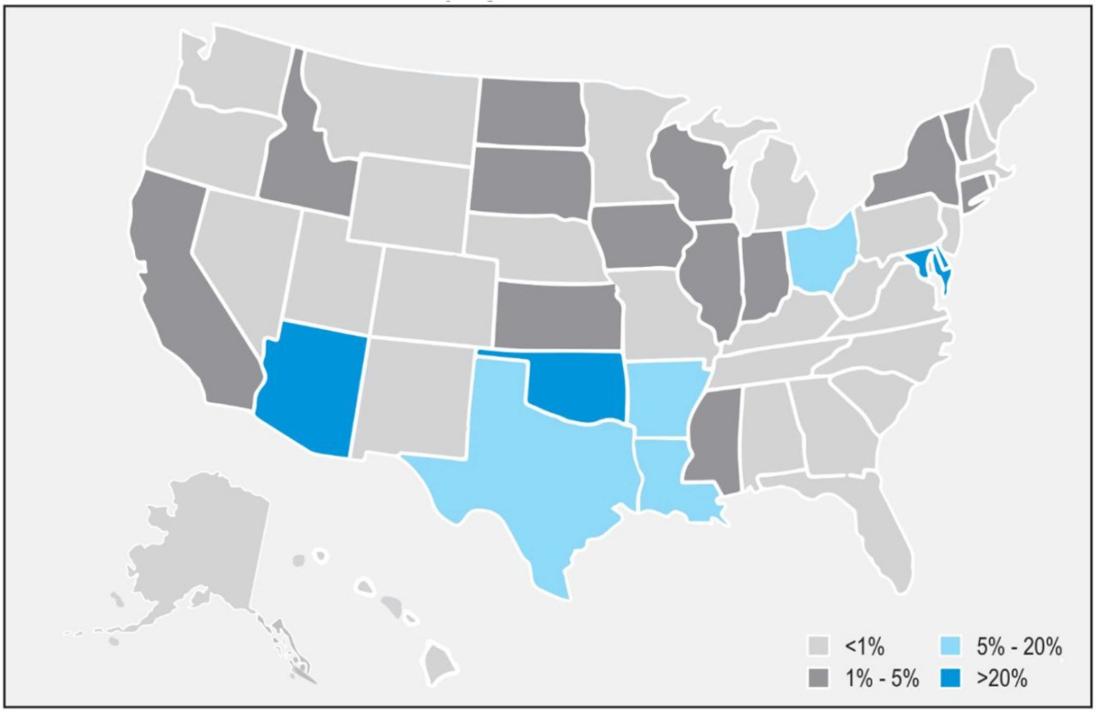

Figure 1. Percent of Residential Consumers on Time-Varying Rates, as of 2017. Compiled from EIA Form 861. The figure only includes programs that vary residential retail rates within a day and does not include related schemes such as rate reductions or rebates for load-control adoption. Additional programs are scheduled for adoption in the next few years, notably a large program in California. For further information about specific pilots and case studies, see Faruqui et al.(2012) and Environmental Defense Fund (2015).

dynamic pricing structures provide residential electricity consumers prices that are directly pegged to the time-varying marginal costs of providing electricity service (Joskow and Wolfram 2012). Real Time Pricing programs are currently rare for residential consumers. Where they exist, they typically are only used for large customers in the commercial and industrial classes.[7] One notable exception is Illinois, where Ameren Illinois and ComEd offer variations of real-time pricing to their residential customers.[8] Further, while Real Time Pricing is able to pass through temporally variant generation costs, it does not avoid controversy in deriving marginal rates for network costs. And while dynamic pricing comes closest to the ideal of cost-causal rate design, even the most precise approach to temporal disaggregation does not necessarily incorporate spatial variation in pricing, as discussed in section 2.2.2.

2.2.2. Spatial cost-causal rate design.

The costs of delivering electricity services vary not only with time but also by the location within a network. Cost-causal principles can also capture this variation. In wholesale markets, such variation is captured in nodal, or locational marginal pricing, which is widely used across the U.S. However, at the distribution level, to implement spatially disaggregated rates, utilities may require greater information about the distribution of net load on the networks to estimate specific locational marginal prices. As DERs and other 'grid-edge technology' penetration has increased, distribution networks have become more flexible, accommodating two-way flows of power and taking on many of the same characteristics of transmission systems (Sotkiewicz and Vignolo 2006). This has led to some calls for locational marginal pricing principles used at the transmission level to also be applied at the distribution level (Burger *et al* 2019a). A wider use of distribution-level locational marginal pricing would compensate DERs for their role in reducing line losses (Shaloudegi *et al* 2012) and for their flexible dispatchability in a distribution network with congestion (Huang *et al* 2015). Locationally-variant pricing could also properly incent DER placement in a distribution network to minimize the costs of distribution-system upgrades (Sotkiewicz and Vignolo 2007). Research suggests that a distribution-level locational marginal pricing method would be especially important in systems with significant electric vehicle loads (Li *et al* 2014). To our knowledge there are no existing residential rate programs that incorporate distributional locational marginal pricing for the entire class of residential customers.

[7]For example, Georgia Power implemented one of the first and most widely used real time power programs which offers customers a number of implementation options: https://www.georgiapower.com/business/prices-rates/business-rates/marginally-priced.cshtml

[8]https://www.pluginillinois.org/realtime.aspx

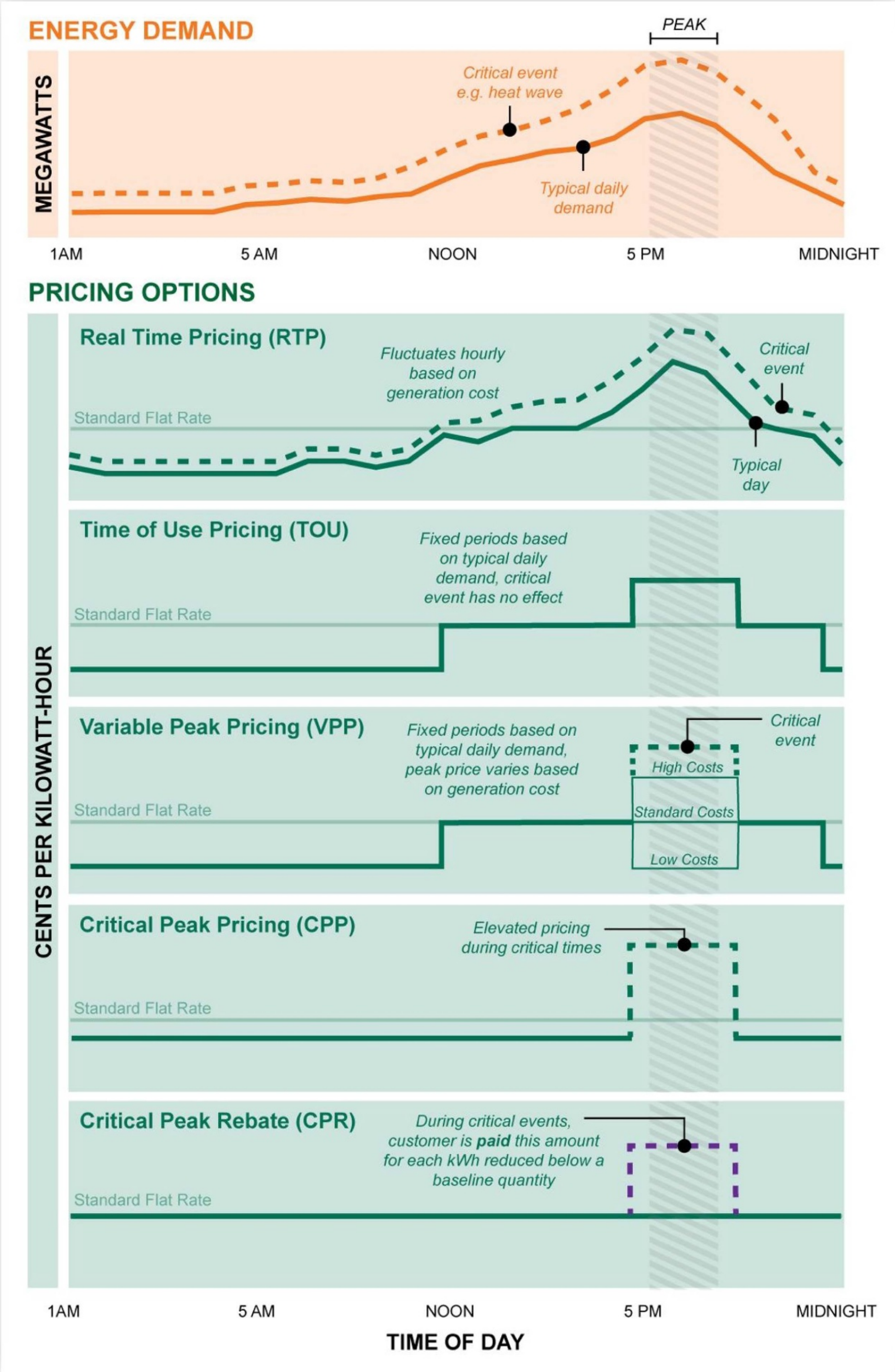

Figure 2. Schematic representation of summer energy demand load profiles and time-varying rate design options. The load profile (top subplot) shows load for a typical day (solid line) and a day with a critical event (dashed line). Critical peak pricing and real time pricing are responsive to critical events (dashed lines).[9]

2.3. Cost-causal principles and distributed energy resources

Distributed Energy Resources (DERs) are energy resources deployed at the distribution level, either for supply—including rooftop solar and other forms of distributed generation (DG), or for decreased or controllable demand—including demand response, energy storage, and energy efficiency. While DERs predate centralized generation and waves of DER deployment have occurred in multiple periods, the current period of DER deployment has raised critical questions at the core of the utility business model and the role of regulation. There are a number of outstanding issues related to the compensation and pricing of DERs that are inseparable from larger questions about the cost-causality of electricity tariffs. In fact, increasing penetrations of DERs are a key driver of the renewed interest in cost-causal rate design. A central question is how to set fair compensation for DERs owned by individuals, aggregators, and other non-utility actors. Some forms of DER incentives, such as energy efficiency rebates, may be justified on cost-causal principles—greater efficiency can reduce the system peak and therefore avoid capacity expansion. However, state net metering policies typically do not appeal to cost-causal principles under current rate designs, which has led some to suggest that net metering for DG acts as a cross-subsidy whereby other ratepayers partially subsidize the grid services utilized by owners of DG (Johnson *et al* 2017). However, it is also possible that DG owners are under-compensated for the social value they create if reimbursement is below the social value. Studies calculating the value of distributed solar have found social values both significantly greater than and significantly lower than retail prices.[10]

Many U.S. states have studied design options for compensating DER owners and incorporated the same logic of cost-causation described above for rate design. For example, the federal Public Utilities Regulatory Policy Act (PURPA) of the late 1970s established a requirement for utilities to purchase qualifying generation from independent power producers at avoided cost, which is fundamentally premised on cost-causal principles; however, the implementation of PURPA by states has varied substantially. Recently, at least 25 states have conducted benefit-cost analysis on distributed solar resources in response to concerns that the value of the resource may differ from the compensation received by the owners of solar systems (Carley and Davies 2016). One example of an alternative approach to DER compensation is to establish a Value of Solar (VOS) or Value of Distributed Energy Resource (VDER) that reflects the full social value of solar or DERs (Pitt and Michaud 2015). VOS and VDER calculations, now established in tariffs in Austin. Texas, Minnesota, and New York, estimate solar or DER's avoided generation, transmission, distribution, and environmental costs on a per-kWh basis over the life of a project.[11] Barring other market imperfections, DERs that receive reimbursement under a VOS or VDER will be deployed at a socially optimal level, reflecting all of the resource's private and social costs and benefits. However, this approach faces many of the same obstacles of standard rate design in that the value of solar differs depending on the input assumptions and these assumptions are value laden (Hansen *et al* 2013).

One type of DER that has important implications for electricity pricing is battery storage, both stationary and mobile. Batteries can be charged during low-cost and off-peak time periods and then deployed during on-peak times, with the benefit of displacing other sources of peak generation and flattening load curves. The literature argues that it is possible to optimally design end-user batteries to minimize system costs and that battery integration can lead to cost reductions under dynamic pricing schemes (see, e.g. Van de Ven *et al* 2013, Kamyab and Bahrami 2016). Battery storage also has the potential to reduce price fluctuations under dynamic pricing models due to a flatter load curve. Mobile storage, as a vehicle-to-grid source of electricity, has often been touted as a viable means of load management but persistent barriers still prohibit vehicle batteries from serving such a role (Noel *et al* 2019). The most critical barriers include battery degradation from repeated charging and discharging, consumer acceptance, and technological maturity (Van de Ven *et al* 2013, Sovacool *et al* 2017).

3. Barriers to implementation of cost-causal rate design principles

Cost-causal principles suggest that varying rates (and DER compensation) over space and time in accordance with short-run marginal costs—or avoided costs—can lead to many system improvements. These improvements arise by sending price signals that convey system-wide benefits, rather than only individual benefits, for electricity consumption and DER investment. However, proliferation of cost-causal rate design principles in the residential sector will require addressing a host of technical, economic, behavioral, political and institutional barriers that may impede the realized benefits of cost-causal rate design.

In table 1, we present a distribution of all dynamic pricing articles according to the barriers discussed or evaluated in each. The articles counted in this table are those that we were able to locate through a systematic literature search in the Web of Science,

[10]See Weissman and Fanshaw (2016) for a review: https://environmentamerica.org/sites/environment/files/reports/AME%20ShiningRewards%20Rpt%20Oct16%201.1.pdf

[11]As implemented and proposed, VOS and VDER rates are not dynamic. Instead, they calculate monthly or annual schedules for reimbursement based on approximations of how solar generation or DERs will avoid other system costs over time (accounting for temporal and spatial heterogeneity of avoided costs through approximations and averages). VOS and VDER rates also are limited in their incorporation of locational differentiation (Baker *et al* 2013, Vaishnav *et al* 2017).

Table 1. Summary of articles from the literature and this paper that discuss barriers to dynamic pricing.

	Total No. Relevant Articles	Technical Barriers	Behavioral Barriers	Political and Institutional Barriers		Economic barriers		
				Inequality/ Political	Institutional Capacity	Fixed Costs	Enviro. Externalities	Public Goods/CPR
Web of Science Articles	70	13	49	16	8	23	6	3
Additional Manually Identified Articles	46	17	26	14	18	12	3	7
Total	116	30	75	30	26	35	9	10

supplemented by the authors' knowledge on the subject and then coded by research assistants for relevance. Appendix 1 summarizes the Web of Science methodology for assembling a complete list of articles and the coding scheme and protocol developed for this review. Although our search uncovered 701 articles, many of these articles did not specifically discuss barriers to dynamic pricing,[12] and additional coding was needed in order to limit the sample to articles that were specifically relevant to barriers to dynamic pricing. In addition, numerous articles that the authors knew to be relevant were not captured, and thus we supplemented the sample with an additional 77 articles. After coding each article for specific relevance to the review subject, a close inspection of each article led us to a final sample of 116 articles that discussed technical, economic, behavioral, or political and institutional barriers in some detail (as well as an additional 41 articles that were otherwise relevant for the review). Of these 116 articles, 75 covered behavioral barriers, 30 covered political barriers, 26 covered institutional barriers, 35 covered economic barriers relating to fixed costs, 9 covered economic barriers related to environmental externalities, and 10 articles covered economic barriers related to public good arguments. Thirty articles covered technical barriers. In our discussion of the literature below, we pull selectively from these studies and synthesize their main arguments.

3.1. Technical barriers

The implementation of cost-causal rate design principles requires more sophisticated metering technology than what was traditionally deployed. In particular, rate design that varies temporally requires advanced metering infrastructure (AMI), or 'smart-meters,' (Convery *et al* 2017). In this section, we focus on AMI, reflecting the focus in the literature and in practice on AMI requirements as a prerequisite for time-varying rates.

AMI is required to be able to determine a customer's usage in fine temporal intervals and to send and receive data in near real time between the point of load and the utility. Definitions of what constitutes an 'advanced' meter vary and some electricity meters have more functionality than others. AMI installations range from real-time meters with built-in two-way communication, capable of recording and transmitting instantaneous data, to basic hourly interval meters. As the time interval of measurement shrinks, requirements for communications and data management increase. Despite some definitional ambiguity, the penetration of some forms of AMI has increased significantly in the last decade. As of the end of 2018, 86.8 million smart meters had been installed in the U.S., the majority of which was in the residential sector (U.S. EIA, 2017).

The cost of deploying AMI, however, may be prohibitive for some utilities, and in general, the implementation of cost-causal rate design principles faces the challenge of justifying the lifetime cost of AMI with the prospective system benefits of varying rates. Despite recent declines in cost, smart meters retain a non-trivial price, and in some regions, the scale of AMI upgrades needed requires hundreds of billions of dollars in capital investment (Gellings 2011). The recovery of these capital costs provides a political dilemma similar to fixed-cost recovery for other energy services. Opponents of smart meters have pushed back against investment costs (Smith 2009). Proponents of smart meters and cost-causal rate design insist that the benefits exceed costs, but significant uncertainty still exists in measuring incremental costs and benefits associated with AMI investments (Joskow 2012). One difficulty in calculating benefits of smart grid investment is that benefits are largely dependent on consumer behavioral response, which varies substantially across studies (Faruqui and Sergici 2010), as discussed in section 3.2.

[12] A search that limits results to a specific discussion of barriers to dynamic pricing produced few results.

Most smart meters are composed of several sensors and control devices that must be supported by dedicated communication infrastructure[13] (Zheng *et al* 2013). Additional data and communications networks produce increased data security concerns (Mcdaniel and Mclaughlin 2009). Smart grids have risks from a number of deliberate threats including industrial espionage, terrorist attacks, and cyber warfare, as well as more inadvertent failures such as user-error or equipment failure. While there are a number of protocols, cryptographic algorithms, and encryption schemes and controls proposed by industry and academia to secure smart devices (Metke and Ekl 2010), the security is ultimately dependent on device manufacturers and users (Knapp and Samani 2013). Consumers may also fear breaches in personal privacy.[14] These consumer anxieties contribute to the political resistance towards the implementation of smart meters (Zhou *et al* 2016).

Even with the promise of smart meter data, the fundamental challenge of establishing consistent and transparent methodologies for valuation of disparate services and marginal pricing remains. Data analysis can reveal patterns of customer use, but the use and interpretation of results is likely to be stakeholder dependent. This dynamic presents an opportunity for aggregation of smart meters by utilities or third parties that can provide demand-side management and other services to more effectively align social benefits with distributed decision making (Siano 2014).

3.2. Behavioral barriers

The net benefits of smart meter investments and of implementing cost-causal rate design reforms depend on whether consumers are able and willing to respond to more frequent fluctuations in prices. The responsiveness of demand to new forms of price signals remains a critical uncertainty and a key area of inquiry for cost-causal rate design. Home energy management systems and devices that can be remotely controlled allow many energy uses to be automated or even subject to direct utility intervention. While these programs demonstrate that many consumers may be willing to give up some autonomy in order to receive savings, consumers will likely want to maintain some level of control. Understanding consumer behavior to changing rate structures is crucial to accurately forecasting the costs and benefits of implementing cost-causal rate design.

While time-varying rates might better reflect cost-causal principles, it is not clear whether consumers—particularly at the residential and small commercial level—have the information, understanding, capability, or sufficient incentive to respond to rapidly fluctuating price signals (Ito 2014). Evidence has shown that the demand for electricity is particularly inelastic over the short-term (Reiss and White 2005). In the presence of uncertainty about consumption and supply, rational consumers may respond to an expected price rather than actual time-specific prices (Borenstein 2009).[15] When the costs of understanding time-varying prices are substantial, consumers may use average prices as a heuristic (Liebman and Zeckhauser 2004). At present, many consumers, even those with AMI, may only become aware of their usage when they receive their bill at the end of the month (more may not be aware at all, particularly if they are on automated billing systems), raising concerns about the salience of time-varying prices and the attentiveness of consumers to energy price information.

Accounting for consumer behavior patterns that diverge from strict economic rationality, the success of cost-causal rate design principles partly depends on information provision that makes consumers more responsive to prices (Jessoe and Rapson 2014). The literature provides little information about the effectiveness of information when moving from time-of-use or critical-peak pricing to fully dynamic rates. In a randomized control trial, Ito *et al* (2018) found that economic incentives produced large and persistent behavioral changes that reduced peak demand, while Asensio and Delmas (2015) found the effects of real-time pricing to diminish over time. In a real-time pricing system, however, information signals for critical peaks might be muddled by frequent smaller fluctuations in price. Consumers may find the pricing information overwhelming and resort to rational inattention (Sallee 2014).

As a result of the limitations to the responsiveness of consumer demand to time-varying price signals, scholars have begun to examine non-price incentives, such as information about energy's health and environmental impacts (Asensio and Delmas 2015), and behavioral interventions (Allcott and Rogers 2014). If ordinary consumers have struggled to respond to

[13]To manage the data flow from smart meters to data centers will require an integrated, flexible, interoperable, reliable, and scalable two-way communication platform (Gungor *et al* 2011, 2013). Meeting the needs of smart grid components requires optimized latency, frequency range, date rate, and throughput specifications (Ancillotti *et al* 2013). A primary goal of the industry must be standard setting. To date, a number of communication platforms have emerged (e.g. power line or radio frequency communications, or internet based networks) that have various advantages and obstacles (Colak *et al* 2016). Regardless of which technology eventually 'wins', significant investment is needed in the distribution grid, where limited information technologies have been deployed.

[14]Smart metering data could reveal occupancy and activity within the home (Krishnamurti *et al* 2012). Consumers may worry about the use of such data for targeted nefarious activities (e.g. thieves finding unoccupied homes), commercial uses (e.g. targeted advertising), law enforcement use (e.g. detection of illicit activities), or for legal purposes in disputes (Mckenna *et al* 2012).

[15]In this case, dynamic pricing may have a similar overall effect as time-of-use pricing, with consumers relying on heuristics to anticipate what real-time marginal prices will be, which under rational expectations would align with time-of-use price schedules.

existing price signals, it seems unlikely that consumers would respond more rationally when facing even more price information. Rather, evidence suggests that most people are not eager to dedicate resources to thinking about energy and fuel and perceive that the costs of altering their consumption behavior outweigh the benefits (Parag and Sovacool 2016).

To fully capture benefits of real-time pricing, it might be necessary to avoid the need for repeated human response and to instead rely on automation and utility-controlled demand response (Harding and Lamarche 2016). Of course, automation technologies such as home energy management systems, smart appliances or thermostats, and other technology solutions may be capital-intensive and could increase consumer costs and generate further equity concerns. However, some inexpensive demand response technologies also have been deployed, such as controllable switches on thermal loads (Mathieu *et al* 2012).

3.3. Political and institutional barriers

Even if cost-causal rate design is feasible from a technical standpoint, there remain substantial institutional and political barriers to implementation. In particular, while cost-causal rate reform may be beneficial in aggregate, benefits may not accrue to all consumers (Borenstein 2007) and approaches vary in the extent to which they may impose costs or benefits to utilities. The prospect of winners and losers can create political and institutional barriers. As mentioned above and discussed further below, fundamental aspects of rate design are an inherently political exercise due to the necessity of large capital expenditures that can be considered 'fixed costs' and the public goods nature of grid reliability and other ancillary services and security.

While utilities typically propose electric rate designs, approvals occur at state public utility/service commissions (PUCs or PSCs). Although we reviewed the general process above, legislative acts and judicial precedent typically do not specify particular methodologies for calculating rate structures. As a New Mexico commissioner commented, '[there is] a zone between confiscation [of utility assets] and extortion [of customers] in which the Commission has great discretion in setting just and reasonable rates' (Fremeth *et al* 2014).

Current regulatory policy in the utility sector is determined by periodic rate reviews conducted by the PUCs. In most jurisdictions, commissioners are required to provide an evidentiary basis for their decisions. Incremental changes can be more easily justified; but obtaining supportive evidence to overcome 'burden of proof' requirements can be costly for stakeholders wishing to initiate new policies, such as dynamic rates. Information asymmetries further raise costs and tend to insulate current practice against regulator induced change. Trade secret laws limit public accountability. The evidentiary requirement for change creates a bias toward the status quo as the benefits of new policy can be outweighed by the costs of affecting the change. These factors have contributed to the documented elements of path dependency of regulated electric utilities and their rate setting procedures (Parag and Sovacool 2016).

Changing rates will undoubtedly face resistance as any new rate proposals will result in a set of winners and losers. Utilities have responded to disruptive innovation in their markets by using campaign contributions to influence PUC races and other state-level elections (Rule 2017). Groups representing the solar industry and solar adopters (Warrick 2015), environmental organizations (Doblinger and Soppe 2013), and vulnerable populations have demonstrated recent interest in rate proceedings due to the implications for DERs and equity. The residential consumers who will ultimately be impacted by a move toward greater application of cost-causal rate design principles are a relatively dispersed group facing collective action obstacles.

In the case of cost-causal rate design principles, changing existing rate structures is likely to draw the interest of coalitions with divergent interests. Although consumers typically give little thought to electricity rates and markets, these elements draw attention when prices rise to cover new investment (Staff 2017). Without sufficient protections, cost-causal principles could lead to more volatile and unpredictable bills. Some consumers tend to value certainty of regular bills, as evidenced by the popularity of budget billing programs in which consumers pay a premium for a consistent bill each month, essentially acting as insurance for electricity bill volatility. In order to support proposals for rate reform, consumers expect and are promised lower prices; however, these expectations frequently conflict with economic realities (Spence 2005). Dynamic pricing shifts risk to consumers (Faruqui 2012), which may engender concern from consumer advocates.

Moving towards cost-causal rate design principles for residential consumers will also have to compete for policy salience with other proposals in utility regulation. For example, Woo and Zarnikau (2017) have suggested increasing the number of rate classes as consumers become increasingly heterogeneous. Other competing proposals include decoupling, performance-based regulation, and specific fees for types of utility services (Tian *et al* 2016). More comprehensive reform that addresses alternatives to utility business models provides another approach to reforming the electricity sector (Augustine and Mcgavisk 2016, Barbose *et al* 2016, Rai *et al* 2016). Finally, within the realm of cost-causal rate design options, there remain numerous alternatives. An improved understanding of these approaches and their distributional effects is warranted, as these effects impact the political feasibility of all potential options, and proposals are not mutually exclusive.

3.4. Economic barriers

Economic barriers capture both theoretical and practical concerns of implementing cost-causal rate design principles in a manner consistent with existing incentives, market rules, and business models. For our purposes, we delineate economic barriers as those related to the traditional market failures of natural monopolies, externalities, and common pool resources.

3.4.1. Allocating fixed costs.

An inherent challenge in applying cost-causal rate design principles is moving to a pricing basis that does not guarantee the financing of long-lived infrastructure that serves many consumers, some of which can be considered 'fixed costs.' Traditional rate design based on average costs virtually guarantees the ability to finance shared infrastructure (see section 2.1), but cost-causal principles imply prices based on short-run marginal costs that may fall below average costs.

Central to the regulation of utilities is the conceptual delineation of fixed costs. Fixed costs are generally understood as the shared infrastructure costs required to support electricity service, but actual delineations of fixed versus variable costs vary across states and utilities. In principle, over the long-run, all costs are variable (Wood *et al* 2016), and the lack of a strict definition of the timeframe and scope over which a variable cost becomes a fixed cost creates ambiguity. In practice, definitions of utility fixed costs generally include transmission and distribution costs as well as a utility's recurring operations costs. However, in some contexts, fixed costs can also include generation capacity, and in other contexts, transmission and distribution costs are attributed to specific deployment of either supply or demand and are not considered fixed costs.[16] The impact of incremental demand on incremental costs—or the marginal avoided cost of avoided demand or of new generation—has led to contentious debates in many states due to the conceptual ambiguity of fixed costs (Hirsh 1999, Baskette *et al* 2006).

While definitions of fixed costs vary, cost-causal principles are derived from short-run marginal costs and do not necessarily guarantee the recovery of a utility's costs, fixed or otherwise, that are necessary to provide electricity service (Wood *et al* 2016). Rate design that incorporates calculated short-run marginal transmission costs may not raise enough revenue to recoup the fixed costs of building and maintaining transmission infrastructure over the long-run. Instead, financing transmission infrastructure may be better accomplished through regulation of a 'natural monopoly.'

The distribution and transmission functions of utilities—and to a lesser extent, generation functions—have many characteristics of natural monopolies, where one firm can provide a good or service at lower cost than many competing firms due to high capital costs and economies of scale that drive marginal costs below average costs with increasing quantity (Weimer and Vining 2015). In order to prevent distribution utilities from exercising market power, these utilities have been regulated by state PUCs (in the case of most investor-owned utilities), locally-elected boards (in the case of most electric cooperatives), municipal governments or elected/appointed bodies (in the case of most municipal utilities), and other organizations (e.g. federal oversight of federal power marketers). In firms with substantial capital costs, such as utilities with transmission or distribution functions, setting price equal to short-run marginal cost typically fails to cover total costs, and firms would fail to make necessary investments. To enable such investments, regulators allow utilities to charge prices in excess of marginal costs, at a rate based on average costs plus a 'reasonable' rate of return.

The under-recovery of fixed costs is not solved by designing and implementing rates that are intended to send dynamic price signals to consumers to align their private decisions with socially efficient choices. Conversely, the 'fixed' infrastructure upgrades needed to achieve dynamic rates (see section 3.1) exacerbate the fixed cost problem further. A cost-causal rate design must also consider the additional objective of utility fixed cost recovery. Frameworks that treat all costs as if they were variable costs that can be attributed to specific units of demand violate the ideals of cost-causal rate design that only attributes short-run marginal costs (Borenstein and Holland 2003). Because rate design must achieve both objectives, it is likely that the rate must incorporate more than a marginal component (i.e. a fixed charge plus dynamic price), further contributing to the analytical challenge of determining each component.

3.4.2. Negative externalities of electricity production.

Another key economic challenge in electricity pricing is that the generation and distribution of electricity

[16]For example, avoided distribution and transmission costs associated with reducing demand through specific residential energy efficiency technologies are a key component in state evaluations of utility efficiency programs (Goldberg; 2018). As another example, residential demand charges could be thought of as an approach to attributing specific transmission and distribution costs to specific consumers. Demand charges, employed in several states—particularly for large consumers, include charges based on a consumer's individual peak usage (Hledik 2014). However, empirical evidence suggests demand charges do not accurately reflect consumers' contribution to network peaks (Passey *et al* 2017). and may be too inaccurate to be used in ratemaking to attribute distribution and transmission costs to specific consumers (Borenstein 2016).

produces negative externalities that fall under heterogeneous regulatory regimes that do not fully internalize the harm caused by delivering electricity service. To account for the environmental impact of electricity delivery under cost-causal principles, electricity prices should include environmental externalities. Regulation of criteria air pollutants under the Clean Air Act sets individual pollution standards based on protecting public safety, not equalizing marginal benefits of pollution reduction. Further, implementation of the Clean Air Act is delegated to states, which creates further heterogeneity in the marginal environmental impacts of delivering electricity service. With the exception of California and New England, electricity is not regulated for its climate impacts. Even still, current carbon prices in those systems are below the social cost of carbon, and therefore do not fully internalize climate impacts. Other external environmental impacts of electricity service fall into an even wider patchwork of federal, state, and local regulation (e.g. coal ash containment, strip mining for coal, the management of nuclear waste, methane leakage from natural gas distribution, water impacts of hydraulic fracturing, landscape value degradation from transmission siting, and some solar siting's impact on endangered species). The power sector's patchwork of regulations result in shadow prices for environmental impacts that likely vary significantly from social damages, and therefore, current electricity prices fail to provide an accurate price signal of total environmental impacts.

In short, to truly achieve cost-causal pricing, the externalities associated with electricity must be internalized. An important nuance to including external environmental costs is that the environmental impact of electricity consumption—and of DER generation—changes substantially over the course of a day, across seasons, and at specific locations (Li *et al* 2017). Marginal emissions factors in wholesale markets can help approximate the marginal environmental impact of consumption decisions. For example, the environmental impact of electric vehicle charging has shown significant regional heterogeneity in the United States (Holland *et al* 2016). Just as cost-causal rate design principles suggest varying rates based on the marginal costs of delivering electricity service, incorporating environmental externalities should also vary by the specific impact associated with meeting load.

3.4.3. Public good characteristics of the grid.

A third economic barrier to implementing cost-causal rate design follows from the need to meet specific physical criteria to maintain proper network frequency, reliability, and security standards. While electricity itself—the actual electrons consumed—is a private good, when consumers use electricity, they are actually making use of a bundle of that which include reliability, voltage, and frequency. Components are interdependent, which makes it difficult to disaggregate and, as a result, electric power networks create a system where consumers share frequency and voltage services (Pless and Fell 2017). Thus, grid voltage and frequency have common pool resource attributes, and grid security and reliability are often thought of as public goods. Joskow and Tirole (2007) note that the possibility of network collapse makes operating reserves a public good and without regulatory mandates on operating reserves, there would be underinvestment in such reserves and lower overall levels of reliability. As in the canonical literature on the provision of public goods, it is economically challenging to design marginal incentives for individuals to prevent free riding when resources are non-excludable.

While some aspects of electricity are readily translated into marginal costs, many others are not. Addressing these economic barriers introduce interactions presented in other challenges. This illustrates why a single field or perspective is insufficient to address the challenge of cost causal rates. In the following section we delve further into the interplay between barriers and illustrate how entwined they are.

4. Discussion—interaction of barriers

The modern U.S. electricity sector requires rate designs that are more sophisticated and efficient than the flat, volumetric rates that have historically dominated. As the sector evolves—and confronts new challenges and opportunities such as the integration of utility- and residential-scale distributed energy resources, the expansion of smart technologies, and regional wholesale market competition—so too have rate designs. Over the past decade, we have witnessed a proliferation of new rate structures. Many states are making incremental changes to rate design and are still far from dynamic rates that would improve overall system efficiency. Further, our discussion highlights the technology, economic, behavioral, and political challenges associated with allocating the large fixed costs and other costs and benefits associated with the provision of energy resources on the electric grid.

In this review article, we set out to collect and summarize a disparate literature on rate design drawing from the engineering, economics, and policy literatures, to better understand the barriers to dynamic pricing, and to examine whether these barriers can be overcome to achieve a more optimal rate design. After a brief overview of historical developments and the growth of rate designs that incorporate some elements of cost-causal principles, though rarely in a complete fashion, we explored various technological, economic, behavioral, and political challenges associated with moving toward dynamic pricing. The content of these sections collectively suggests that, although cost-causal rates are potentially optimal in theory, in practice there are a number of technological, market, and political challenges to implementation that are especially prevalent in traditionally regulated markets. These challenges include large technological investments needed to enable dynamic pricing and the political difficulties involved in allocating these costs. In particular, utilities frequently have goals to keep rates and bills low for low-income customers. The allocation of large fixed costs poses significant challenges for equity goals, as well as for efficient energy use and the use of rooftop solar. Requiring massive investment and allocating large fixed costs and public goods associated with a move to cost-causal pricing may be incompatible with equity goals. Further, dynamic pricing is subject to persistent barriers. For example, dynamic pricing is imperfectly aligned with the large fixed costs and public good attributes of the electric grid; people may not respond to dynamic price signals in electricity markets; and rate setting—in particular for the fixed costs and public good attributes of the grid—is inherently a political process in which the costs cannot be converted into dynamic marginal costs. Advocating for a move to more dynamic prices is, at best, an incomplete way of conceptualizing the challenge of providing cost-causal rates.

To begin to address these barriers, we suggest a number of research areas that can inform policy approaches to address nascent challenges with dynamic pricing and related technological challenges. An increased deployment of smart meters needs to be coupled with standards that harmonize communication and security protocols. Improved understanding of the benefits and costs of smart meters can help policymakers to design cost-causal cost-recovery measures that can lead to increased customer support for these measures.

Network costs, including the security and reliability of the electric grid will require a different approach than energy rates. An improved understanding of the role of DERs in changing distribution network costs and their allocation is required. The impact of DERs on network costs depends on DER penetration, location, concentration, size and technology. These additional costs or benefits can be allocated to the DER owners through network tariffs (Picciariello *et al* 2015). How these network costs can be allocated to DER owners requires an improved understanding of electricity consumer behavior, and the barriers associated with consumer understanding of complex pricing schemes. The behavioral patterns of individuals interact with the penetration of DERs, various pricing approaches, and other smart grid technologies (such as automated smart appliances) are important research areas that can help policy-makers understand the consequences of technological and policy changes of smart grid deployment.

Finally, an updated understanding of rate-making politics and policies is warranted, given the rapid technological changes taking place and pressure on current rate structures. The work on the politics and policy of ratemaking suggests that utilities, interest groups, and the public influence decision making by affecting personnel and controlling information streams. That said, there remain a number of competing theories attempting to explain the operation of public utility commissioners. An economic theory of regulation suggests that public service commissioners are captured by organized interests (Stigler 1971, Peltzman 1976). In contrast, Berry's study of commissions found that commissioners operate with two objectives: a 'nonpecuniary' principle of rates and a goal of survival (Berry 1984). Gormley's study on public utility commissions focuses on the role of grass roots advocates and finds that they can be effective in PUC decision-making processes when issues are low in technical complexity (Gormley Jr 1983). More recently, Ka and Teske (2002) found that legislative ideology is a central driver of redistributive decisions such as rate making. Understanding the policy process in this domain is critical to promoting progress, but remains unclear. Further, the primary work on these issues pre-date the disruption of distributed energy technologies and the opportunities of the smart grid. Additional study of the politics of regulatory rate-making is warranted in light of the significant impacts these decisions have.

5. Conclusion

Technological change and societal preferences have interacted with the constraints of electric grids and goals of regulators to create challenges for grid operation and utility business models. As a result, the industry is currently undergoing a period of change at the nexus of engineering, economics, and policy. Electricity rate design has received a great deal of scrutiny with the emergence of distributed resources. Some have proposed that 'cost-causal' rate design can address current issues and promote efficiency, equity, and environmental goals (Convery *et al* 2017). However, the cost-causal goal is difficult to achieve in the face of energy services that have disparate economic characteristics, technological requirements, behavioral barriers, and political obstacles. Nearly all rate proposals derived to address the industry disruptions have sought to efficiently attribute fixed and variable costs (Blank and Gegax 2014, Whited *et al* 2016, Wood *et al* 2016).

One specific proposal to promote cost-causality is to introduce dynamic rates that vary by time and location. These rate structures have historically been offered only to larger commercial and industrial customers, but are starting to make inroads into markets in the U.S. Still, these rate reforms primarily deal with the time-variant generation of electricity, and have yet to address broader cost-of-service considerations. We have identified some of the complexities associated with achieving such a goal. These challenges explain, in part, why regulators have pursued more incremental changes. Going forward, we need to recognize these challenges and understand how they constrain policy solutions. Not all proposed rates move towards cost-causality and the interaction of multiple market failures, large fixed costs, and equity considerations can highlight the inherent tradeoffs in simultaneously pursuing multiple policy goals. Rather than reacting to the challenges as they arise, we encourage regulators and policy makers to design tariff structures that reflect market conditions, to develop pilot programs, to experiment with opt-out as opposed to opt-in rates, and to employ robust experimental designs to accurately measure impacts. Partnerships with researchers can help facilitate improved learning in this space. Many U.S. distribution systems are aging, and utilities are embarking on large distribution network replacement programs. Because these investments are long-lived, utilities should be forward-looking in their investment strategy. Deploying automation and communication technologies is prudent even if the deployment of distributed generation, electric vehicles, and alternative rate structures is expected to be slow (Joskow 2012). Convincing consumers to bear the costs of such technology upgrades will not be easy, and the academic community can play a role in providing evidence and disseminating information.

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Data Availability Statement

The data that support the findings of this study are available upon request from the authors.

Appendix: Systematic Review of Literature

I. Scoping

The scope of this literature review is to survey all peer-reviewed publications that focus on the barriers to the adoption of dynamic (or more generally, time-varying) electricity pricing. In our review article, we create a taxonomy of four types of barriers organized by the following key questions (see paper for more detail):

1. **Technical barriers**: can the required deployment of enabling technology (particularly advanced metering infrastructure) act as a barrier to time-varying electricity pricing?
2. **Behavioral barriers**: can the limitations of human behavior to respond to price signals act as a barrier to fully realizing the benefits of time-varying electricity pricing?
3. **Political and institutional barriers**:
    1. Is the reality or perception that time-varying electricity can exacerbate **inequality** (by disproportionately impacting low-income households) likely to create a political barrier to the implementation of time-varying electricity pricing?
    2. Does the limited **institutional capacity** of electricity regulatory bodies (i.e. utility commissions) pose a barrier to the implementation of time-varying electricity pricing?
4. **Economic barriers**:
    1. Could the implementation of time-varying electricity pricing erode the ability of a utility to recover its '**fixed costs**,' thus posing a barrier to time-varying electricity pricing?
    2. Could concerns regarding **environmental externalities** and the ability of time-varying electricity pricing to incorporate appropriate charges for environmental externalities pose a barrier to time-varying electricity pricing?
    3. Because electricity systems rely on shared infrastructure with **public-good/common-pool-resource attributes**, could the difficulty of disaggregating specific costs of service pose a barrier to time-varying electricity pricing?

II. Process

We used Web of Science to conduct a comprehensive search of the literature. To search for articles, the challenge is to find the most complete set of past studies without having to sift through an unmanageable quantity of material. Carefully selected search terms make this possible. To this end, we used the 'Topic' search, which searches title, abstract, author keywords, and Keywords Plus.

We employed the following search criteria:

1. electric* Topic
2. price* OR pricing OR rate Topic
3. 'time-varying' OR dynamic OR 'real-time' Topic
4. policy OR econ* OR psych* OR cost Topic

In search results, we limited results to 'ARTICLE' under 'Document Types'

Figure A1. Web of Science Results for Topic Search for Dynamic Pricing Relevant Articles.

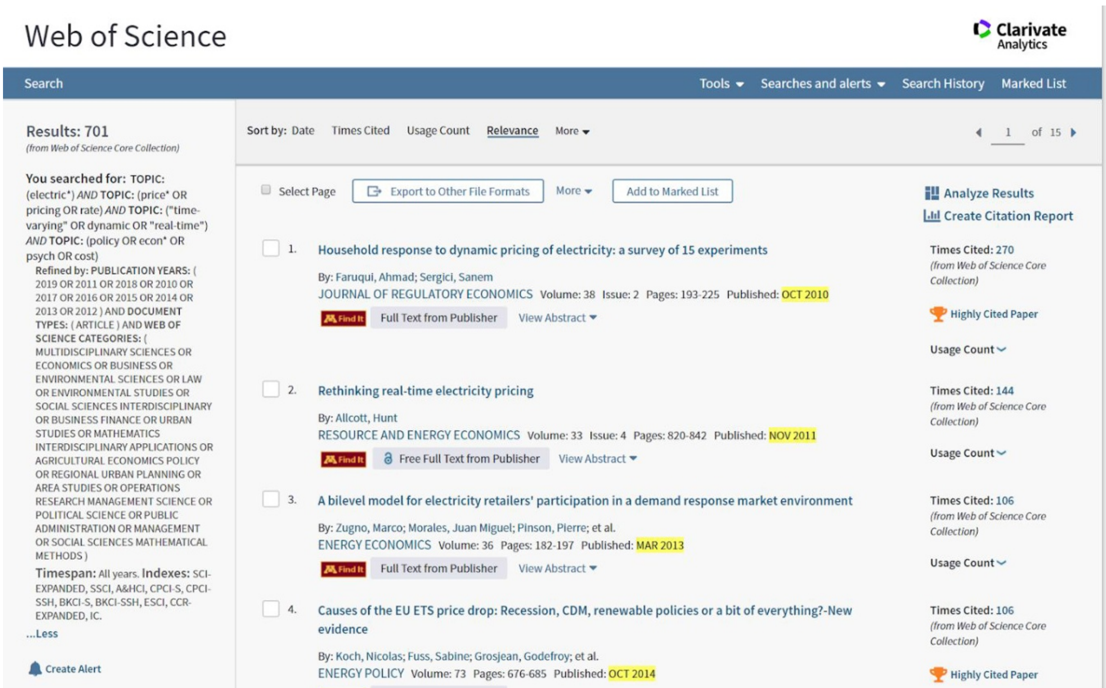

Figure A2. Screenshot of results for dynamic pricing related articles, limited by date and discipline.

These search criteria yielded **2507 articles** with the following breakdown by Web of Science Categories:

We then narrowed the search results to the following Web of Science Categories: ECONOMICS OR ENVIRONMENTAL STUDIES OR ENVIRONMENTAL SCIENCES OR OPERATIONS RESEARCH MANAGEMENT SCIENCE OR MANAGEMENT OR ENGINEERING MULTIDISCIPLINARY OR BUSINESS OR BUSINESS FINANCE OR REGIONAL URBAN PLANNING OR SOCIAL SCIENCES MATHEMATICAL METHODS OR STATISTICS PROBABILITY OR PUBLIC ADMINISTRATION OR GEOGRAPHY OR LAW OR URBAN STUDIES OR AREA STUDIES OR AGRICULTURAL ECONOMICS POLICY OR HISTORY OR HISTORY OF SOCIAL SCIENCES OR INTERNATIONAL RELATIONS OR POLITICAL SCIENCE OR SOCIAL SCIENCES INTERDISCIPLINARY OR SOCIOLOGY.

You searched for:

TOPIC: (electric*) *AND* TOPIC: (price* OR pricing OR rate) *AND* TOPIC: ('time-varying' OR dynamic OR 'real-time') *AND* TOPIC: (policy OR econ* OR psych OR cost)

Refined by: PUBLICATION YEARS: (2019 OR 2011 OR 2018 OR 2010 OR 2017 OR 2016 OR 2015 OR 2014 OR 2013 OR 2012) AND DOCUMENT TYPES: (ARTICLE) AND WEB OF SCIENCE CATEGORIES: (MULTIDISCIPLINARY SCIENCES OR ECONOMICS OR BUSINESS OR ENVIRONMENTAL SCIENCES OR LAW OR ENVIRONMENTAL STUDIES OR SOCIAL SCIENCES INTERDISCIPLINARY OR BUSINESS FINANCE OR URBAN STUDIES OR MATHEMATICS INTERDISCIPLINARY APPLICATIONS OR AGRICULTURAL ECONOMICS POLICY OR REGIONAL URBAN PLANNING OR AREA STUDIES OR OPERATIONS RESEARCH MANAGEMENT SCIENCE OR POLITICAL SCIENCE OR PUBLIC ADMINISTRATION OR MANAGEMENT OR SOCIAL SCIENCES MATHEMATICAL METHODS)

Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC.

Limiting the search results to articles from 2010–2019 yielded **701 articles** (see figure A2). Had we attempted to limit the search to just articles that contained explicit discussion of barriers to dynamic pricing—we would not have produced any results; expanding the search to more years produced an unmanageable amount of results to individually code. Because the Web of Science was unable to produce articles that specifically discuss the barriers to dynamic pricing (emphasizing the innovative and unique nature of our research discussion) it was necessary supplement this initial list of 701 articles with articles that the authors knew to be relevant. The authors added 77 articles to create a list of 778 articles that were potentially relevant. Then, with the assistance of three graduate students, the authors coded papers that explored the role of barriers in the implementation of dynamic prices. Graduate students read each abstract and determine which (if any) barriers are discussed in each article. The summary results of this coding are incorporated in table 1 in the main paper. Complete results of the coding exercise are available from the authors upon request.

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