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PERSPECTIVE

Retail rate design for decarbonized and resilient electricity systems

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Abstract

This perspective examines trade-offs in designing residential electricity rates that improve economic efficiency while ensuring feasible and distributionally favorable outcomes. We analyze rate structures across three key dimensions: improving economic efficiency by reflecting social marginal costs; ensuring affordability, technology access, and residual cost recovery; and simplicity in customer understanding and implementation. While real-time pricing based on social marginal costs is the most economically efficient choice, intermediate approaches like time-of-use rates or critical peak rates may better balance competing objectives. We recommend that decision-makers (1) move towards pricing environmental externalities in time-varying electricity rates, (2) introduce time-varying rates with predictable price periods gradually, (3) expand access to flexibility enabling technologies for low-income customers, and (4) carefully design fixed charges for residual cost recovery to avoid distributionally regressive impacts. These findings are particularly relevant as utilities nationwide consider rate reforms to support electrification while maintaining ratepayer affordability.

1. Introduction

The U.S. electricity industry is undergoing important changes that will have non-trivial impacts on residential consumers. First, electricity generation from low-carbon variable renewable energy resources such as wind, solar, and storage technologies has increased owing to declining costs [1]. Second, transmission and distribution expenses as a proportion of overall utility costs have increased due to the expansion and maintenance of the grid infrastructure [2]. Third, customers with distributed energy resources (DER) and flexible loads, enabled by the proliferation of advanced metering infrastructure or smart meters, can generate their own electricity and actively interact with the grid. Fourth, electrification with low-carbon power has emerged as the predominant strategy for reducing air emissions from transportation, heating, and residential energy use [3]. Lastly, after years of stagnant load growth, demand has increased due to the electrification of end uses and the expansion of data centers [4, 5]. These separate but interconnected developments provide new opportunities and challenges for the electricity industry and its customers.

In this rapidly evolving electricity landscape, rate design—the regulatory practice of designing electricity prices faced by retail customers—has emerged as a tool to achieve multiple objectives. Utilities and regulators want to design electricity rates that improve overall grid efficiency, encourage electrification, ensure reliability during high-stress events, and maintain affordability. Electricity rates that reflect underlying time-varying marginal costs while recouping residual costs with fixed charges can potentially improve economic efficiency and reduce infrastructure needs by encouraging customers to change their consumption patterns in response to prices.

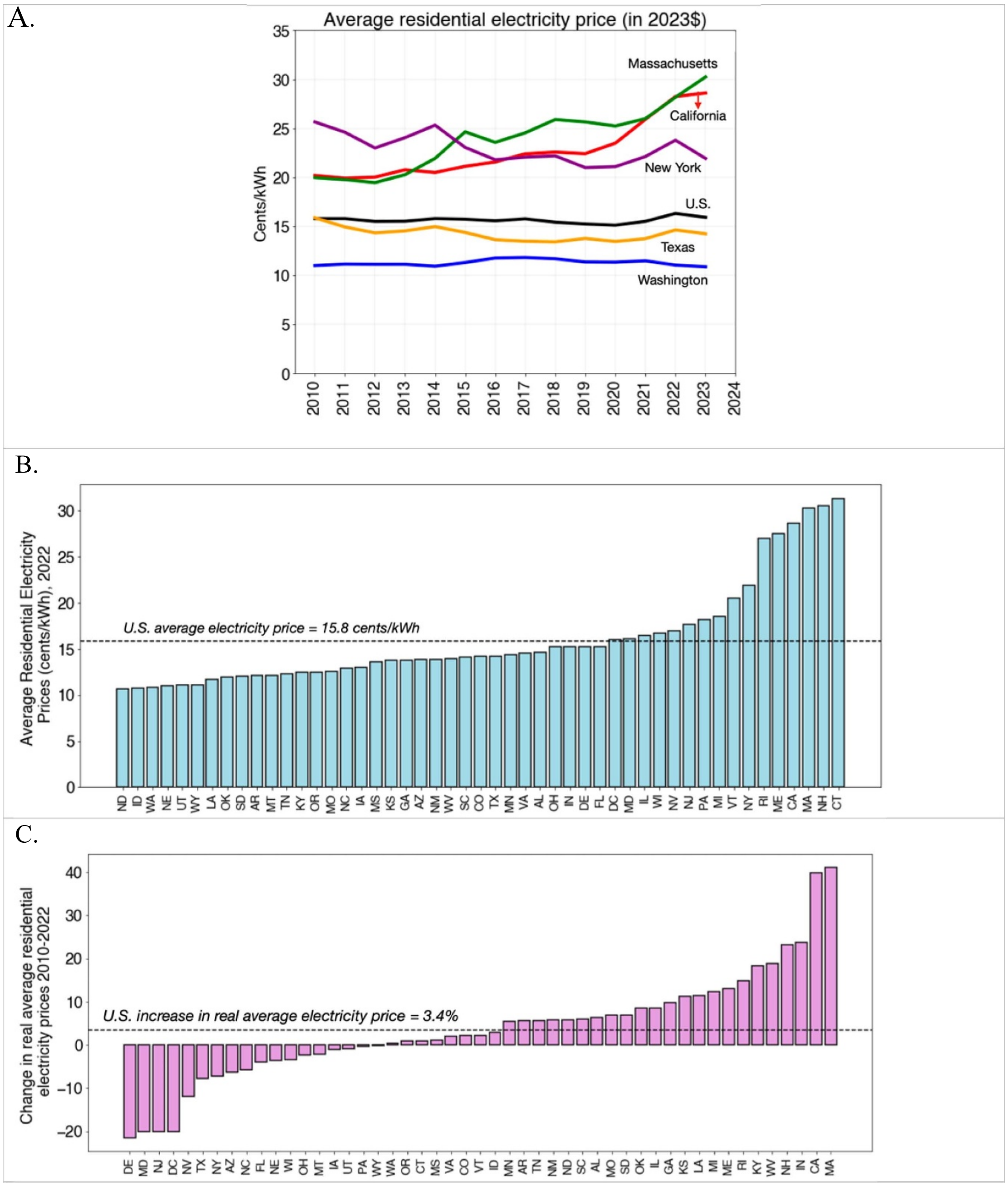

Figure 1. (A) Average residential electricity price in the US. and selected states from 2010–2023, in real 2023 dollars. (B) Average residential electricity prices in 2022. (C) Change in real average residential prices between 2010–2022. The average residential electricity price is calculated as the total revenue from the residential customers divided by the total electricity sold to them. *Source*: EIA-861 [7].

Currently, most U.S residential customers face relatively simple rate structures. Electricity bills are computed using a flat volumetric rate ($ kWh^{-1}) multiplied by consumption (kWh) and a monthly fixed charge ($/month) [6]. The mean fixed charge is around $11/month, and the mean volumetric rate is roughly 0.l6 $ kWh^{-1}, though there is significant variation across the U.S., as shown in figure 1 [6–8]. California and New England have the highest average electricity prices (22–26 cents per kWh) and have seen 30%–40% increases between 2010 and 2023 (in real terms), while the Southern US. and parts of the Midwest have seen a milder increase, and Texas, Nevada, Maryland, and Delaware have seen a decline in real electricity prices [7]. Simple volumetric rates have the benefit of being easy to communicate and use, but they do not reflect the underlying time and space-varying costs of producing and delivering electricity. Such rate designs also lump residual costs unrelated to electricity production and delivery, such as costs related to long-term infrastructure, public purpose programs, energy policy, wildfire mitigation, etc., onto prices [9, 10].

Initial steps towards more sophisticated rate designs have focused on time-of-use (TOU) rates where the per-kilowatt-hour charge increases during pre-determined hours of the day [11]. About 9.4% of US

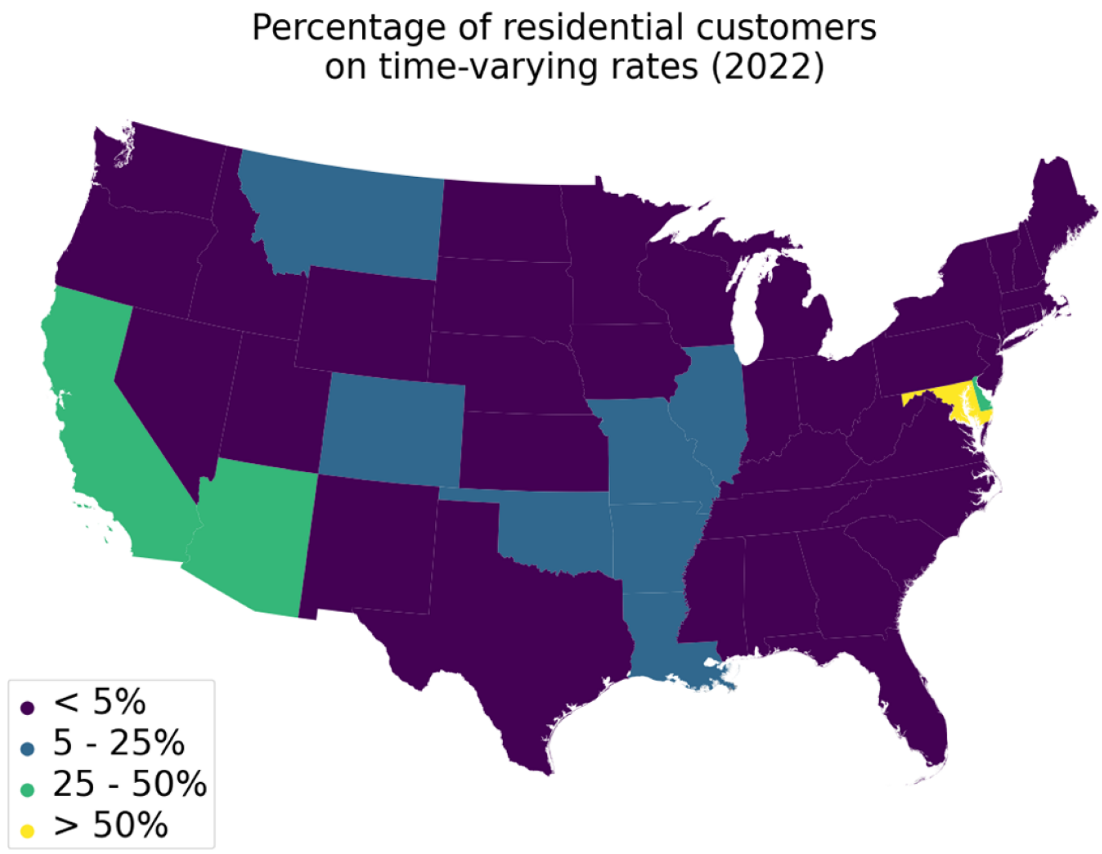

Figure 2. Percentage of residential customers on time-varying rates in 2022. *Source*: EIA 861 [6].

residential households are on TOU rates, with more than 25% of residential customers in California, Arizona, Maryland, and Delaware on such rates (figure 2) [7]. The proliferation of smart meters, DER, demand flexibility, and automation enables utilities to move consumers beyond TOU rates to highly time-varying dynamic rates that reflect real-time marginal electricity production and delivery costs. While real-time pricing (RTP) can improve economic efficiency and grid reliability by exposing customers to underlying marginal costs, it is a big departure from how electricity is currently used. Electricity is an essential product, and rate design must carefully balance various considerations that balance efficiency and equity. As outlined by the Bonbright principles, rates should be 'simple, understandable, acceptable, free from controversy in interpretation, stable, and non-discriminatory' [12, 13]. While these tenets still apply, changes in the utility structure and technologies have led to alternative electricity rate designs.

In this perspective, we evaluate how different electricity rate structures perform on efficiency and social dimensions while highlighting the importance of improving customer awareness and access to technologies as we transition to more time-varying rate designs. Fundamental economic principles of electricity pricing discussed in this piece remain consistent across jurisdictions, but each region faces unique challenges and opportunities in its rate design. For example, while European utilities are far advanced in moving customers to more complex rate structures, state-owned utilities in India often lack sophisticated system cost estimates. To maintain geographic focus, this perspective addresses U.S. residential customers, though comparative analysis across different national contexts warrants future research.

2. Common types of rate designs

Historically, most residential customers in the United States have faced a flat volumetric rate and a monthly fixed charge. These rates bundle the revenues a utility aims to recover from customers, including a guaranteed rate of return on its capital, onto the total electricity sold [14]. Traditional flat volumetric rates are giving way to rates that reflect the costs of electricity production and delivery [15]. The rates could be designed as (i) the currently used flat volumetric rates where consumers pay a fixed price per kWh for their electricity consumption; (ii) increasing or decreasing block rates (also called tiered rates), where rates move to higher or lower price tiers for higher levels of energy consumption; (iii) seasonal rates that address

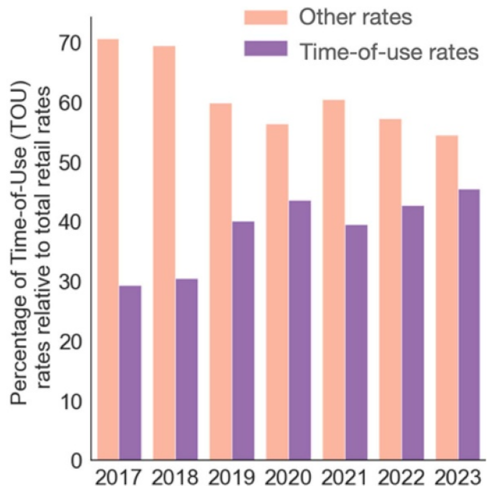

Figure 3. Proportion of time-varying rates since 2017. *Source*: the utility rate database [8].

variations in load and costs across seasons; (iv) TOU rates, in which prices are higher during certain pre-determined time periods. TOU rates have become quite popular, with nearly half of the electricity rates introduced in 2023 having time-varying components (figure 3) [8]; (v) critical peak pricing (CPP), where rates are increased a fixed number of times when system-wide peak demand events occur; (vi) critical peak rebate (CPR), where customers are paid for reducing electricity consumption relative to the amount they usually consume during hours of grid stress; (vii) RTP, where hourly electricity rates paid by consumers reflect or are equal to the wholesale market energy prices.

The rate designs discussed above show common variations of the volumetric component ($ kWh^{-1}) of electricity rates. In addition, residual costs—expenses incurred independent of energy consumption—can be decoupled from energy costs and recouped through different formulations of fixed charges ($/month). Fixed charges may be structured in various ways: as a uniform monthly fee for all customers, a variable charge that depends on the customer's income, energy consumption, or peak demand, or a charge based on the size of a customer's distributed energy resource (kW-dc) [16]. California is implementing its first iteration of fixed charges that depend on income, while Arizona has a monthly charge that varies with the size of the rooftop solar installed [17–19]. Texas has been a pioneer in enabling utilities to offer different rates to consumers since the deregulation of its electricity market in the early 2000s, resulting in more than 120 electricity rate providers and a large diversity of rate plans, including indexed market rates. The 'Power to Choose' website was created by the Public Utility Commission of Texas and provides a comprehensive resource for consumers on available plans [20].

3. Efficiency of electricity rate design

According to microeconomic theory, an efficient electricity price would correspond to the short-run *social* marginal cost of producing and delivering an additional kWh of electricity [21]. Short-run *private* marginal costs include marginal generation costs, marginal distribution and capacity costs, and system-related costs related to ancillary services and losses. Adding the costs of pollution and other disamenities from electricity production and delivery to the private marginal costs gives us the *social* marginal costs [6]. Marginal costs vary with time and space and are often categorized into generation, transmission, distribution, and other purposes and sorted by demand (kW), energy (kWh), or customer-related marginal costs [22]. However, there's considerable judgment involved in this exercise. Determining short-run social marginal costs requires a judgment of what cost is incremental, over what time frame, whether costs are forward-looking projections or backward-looking incurred costs, and how to accurately price environmental and other externalities from electricity production and supply [23]. Currently, most approaches for evaluating utility costs do not include negative externalities associated with electricity production, such as air emissions that cause climate change and air pollution [24]. There is some forward momentum in this direction. For example, California's Avoided Cost Calculator, which will be used to compensate DER owners for their electricity exports, incorporates damages for methane, air pollution, and greenhouse gas emissions in its calculation [25, 26].

However, efficient prices based on short-run marginal costs do not recover all utility costs as they fail to account for long-lasting infrastructure and regulatory expenses. In recent decades, residual costs, defined as

Table 1. Short-run marginal and residual costs.

Electricity cost sources	Marginal costs	Residual costs
Generation	• Fuel costs • Generation related variable O&M (water for cooling systems and steam generation, labor costs when running at higher capacity, etc.) • Ancillary services • System losses • Short-term generation capacity costs	• Long-term power plant capital costs • Generation related fixed O&M (scheduled maintenance and inspections, staffing costs, etc). • Long-term capacity contracts • Generation-related regulatory compliance
Distribution	• Incremental transformer/equipment loading • Local congestion costs • Marginal distribution capacity costs	• Distribution infrastructure capital costs • Equipment maintenance and replacement • Vegetation management • Grid hardening and wildfire mitigation
Transmission	• Marginal transmission capacity costs • Transmission losses • Short-term congestion costs	• Network infrastructure capital costs • Right-of-way maintenance costs • Grid modernization • Grid hardening and resilience
Environmental costs	• Real-time emissions costs (CO_2, NOX, SO_2, etc.)	• Environmental compliance costs • Long term climate mitigation and adaptation
Customer and policy costs	• Real time demand response payments	• Customer service and billing related costs • Public purpose programs • Low-income assistance • Energy efficiency programs • Other regulatory costs

'the difference between incurred utility costs and the revenue collected through the marginal cost framework', represent a growing portion of overall utility costs [22, 27]. These include transmission and distribution network costs, expenses related to renewable integration and adoption, subsidies for vulnerable populations, institutional and regulatory costs, and investments in wildfire mitigation and grid hardening [9]. In the U.S., the share of utility costs for distribution, transmission, and other expenses has increased from 31% of total utility expenses in 2010 to roughly 50% by 2021 [2]. Table 1 delineates short-term marginal vs. residual costs by generation, distribution, transmission, and customer/policy costs, along with a few key examples [9, 24, 27–29]. While a real-time rate will provide efficient market signals, design challenges remain. For example, the demarcation of marginal vs. residual costs is laden with subjectivity and uncertainties, and most jurisdictions do not price environmental externalities. Furthermore, rates based purely on marginal costs cannot recover utilities' full costs, necessitating a need for fixed charges in addition to volumetric rates in customer bills.

4. Implications of alternative rate designs

Given its essential nature, electricity pricing should be guided by distributional considerations along with efficiency. Any rate design we pursue should ensure that electricity prices remain affordable and relatively simple to understand, long-run infrastructure costs (residual costs) are recovered in a way that recognizes differences in energy affordability, and a move to highly time-varying prices is complemented with demand response and energy technology access.

Electricity bills continue to be a source of economic stress for many U.S. households [30]. Twenty million households are behind on their utility bills and owe $16 billion to their utilities (electricity being one of the utilities considered) as of 2023 [31]. This amounts to $800 per family, double that of $400 per family before the COVID-19 pandemic [31]. Current volumetric rates are also regressive—i.e low-income households spend a higher proportion of their income on electricity compared to middle and high-income households, with sixty percent of low-income families (15.4 million) paying more than 10% of their monthly income on energy bills [32, 33]. Expensive electricity also discourages electrification and prompts consumers to forgo essential heating and cooling to reduce their bills [10, 34]. State governments and utilities have implemented initiatives to improve electricity affordability through rate subsidies and assistance programs, such as the federal Low-Income Home Energy Assistance Program (LIHEAP), which earmarked $4 billion in 2022 to help low-income consumers with bills [35]. Utilities and public commissions complement LIHEAP through discounted rates and payment programs to improve bill assistance, debt forgiveness, and arrearage management [36, 37]. Future electricity rate designs should prioritize affordability for vulnerable households while reducing the regressivity of how utility costs are recouped among customers.

Another dimension relates to access to energy technologies, such as DER and electric appliances that provide flexibility under time-varying rates. Residential consumers are price-inelastic in the short term, but consumers respond to prices over a longer time frame, especially if variations are large [38]. The proliferation of flexible electricity load combined with control of resources by the utility or third-party entities is changing the paradigm of a passive residential consumer. More residential customers can have backup power and respond to price signals to maximize their bill savings and respond to grid stress. However, this progress comes with a 'flexibility premium': only households with access to flexible energy technologies will benefit from highly time-varying rates, and those without could face bill increases. The relationship works in both directions. Introduction of time-varying rates increases the likelihood of demand response and DERs, as evidenced in studies showing increased rooftop solar, battery adoption, and heating electrification adoption under such rates [39–42]. However, much of the adoption of these technologies has been skewed towards high-income households rather than low-income households, with heat pumps being an exception showing more even adoption across income levels [43–47]. This means that a move to highly time-varying rates should also ensure expanded access to energy technologies for low-income customers.

In addition to traditional incentives such as tax credits and rebates, many utilities are exploring new financing and operational models to expand energy technology access. For example, Duke Energy has implemented 'tariffed-on-bill' financing where the upfront costs of energy technologies, such as smart thermostats, heat pumps, and energy efficiency upgrades, are paid by the utility and recovered through a monthly charge on the customer's electricity bill. This approach eliminates credit checks or loans as the charge is tied to the meter rather than the customers, and allows renters to use these appliances [48, 49]. Green Mountain Power, an electric utility servicing parts of Vermont, provides residential battery storage systems to its customers for backup power during outages and allows customers to avoid high-price periods by using stored energy. The utility controls the stored electricity in the battery systems to provide system-wide benefits that can help reduce overall costs for all customers [50, 51].

In some regions, under net energy metering, rooftop solar and storage adopters are compensated at retail rates for the electricity they feed back to the grid. DER adopters forgo their share of residual costs baked into volumetric retail rates, which in turn increases prices for non-adopters, particularly low-income consumers [52]. For example, in California, a state with expensive power and one of the highest adoption of rooftop solar, net energy metering has increased annual bills for low-income customers by approximately $100–$130 [53]. The challenge here lies in devising new pricing mechanisms that balance DER incentivization for low-income households while leveraging these resources to reduce overall system costs. Utilities nationwide are revamping their net energy metering with tariffs where the exported electricity from DERs aligns with the value of the electricity that residential solar or battery systems provide to the grid [54]. In addition, rates and programs are being rolled out to promote demand flexibility, wherein DERs can respond to price changes and direct signals [55].

5. Comparing rate designs across different dimensions

An ideal electricity rate should be economically efficient, affordable, and easy to understand. Economic efficiency dictates that prices vary with underlying social marginal costs, and residual costs are recovered through a combination of fixed charges. These rates should not burden low-income customers and those without flexible devices and should be simple to communicate. However, these implications are predicated on customers' behavior and whether they respond to price signals and have the resources, time, and technology to adapt to these rates.

In the real world, the behavior of electricity consumers significantly diverges from expectations. Most consumers do not grasp complex pricing schedules, often change behaviors in response to monthly bills rather than hourly prices, and cannot differentiate between the fixed and variable proportions of the bills [56–58]. Surveying published studies that examine the impacts of different rate designs, we compare the relative performance of rates on whether (i) they reflect underlying marginal costs, (ii) if the pricing schedule is easy to understand, (iii) if monthly bills could have high volatility, and (iv) if they do not result in an affordability burden. In the table 2, we provide below an example of a framework that could be used by utilities and regulators as they consider how different designs could fare across these dimensions. This table

Table 2. Strengths (↑) and weaknesses (↓) of different electricity rate designs across different dimensions.

	Reflects marginal costs	Pricing simplicity	Bill certainty	Affordability
1. Flat rate	↓↓↓	↑↑↑	↑↑↑	↓
2a. Increasing block rate	↓↓	↑↑	↑↑	↑
2b. Decreasing block rate	↓	↑↑	↑↑	↓↓
4. Seasonal rate	↓	↑	↑	↓↓
5. Time-of-use	↑	↓↓	↓	*
6. Critical peak pricing	↑↑	↓↓↓	↓↓↓	*
7. Real-time pricing	↑↑↑	↓↓↓	↓↓↓	↓↓↓

Note: * = These consequences depend on the utility service area's system load, household characteristics, climate, demand elasticity, and the peak-off-peak ratio of time-varying rates.

provides a potential structure and taxonomy that regulators and utilities could use to compare and convey the differences in outcomes across potential rate designs in their jurisdiction. Upward and downward arrows rank the relative strengths and weaknesses of different rate designs on dimensions of interest. Reflectiveness of marginal costs is assessed based on how much a rate can potentially correlate with system costs; pricing simplicity ranks the cognitive burden for customers and depends on how complex rate designs are; and bill certainty ranks potential changes in monthly bills. Affordability implications of rates are judged based on distributional impacts across income groups, as examined in the literature. While current flat volumetric rates are regressive, real-time prices are also not equitable [33, 59, 60], and the distributional implications of TOU and critical peak pricing depend on the utility service area's system load, household characteristics, climate, demand elasticity, and the peak-off-peak ratio in rates. Studies we surveyed have evaluated bill changes in low-income households and households with elderly occupants or children in various geographies and found mixed results (TOU studies: [61–65]; CPP studies: [33, 62, 63]). Thus, each utility region needs to identify and address potential concerns for customers who could be negatively impacted when moving to highly time-varying rates. While the overall performance across these dimensions will vary under specific contexts, some of the strengths and weaknesses outlined in table 2 are likely to remain consistent. Flat-rate pricing will inherently not reflect marginal costs as it remains constant, while RTP, in practice, reflects the short-run marginal costs of the marginal generator. Similarly, while a flat rate presents bill certainty provided consumers have reasonably consistent consumption patterns, RTP will introduce more uncertainty in consumer bills since the pricing would be unknown ahead of time.

In the rates discussed above, residual costs (non-energy costs) can be further decoupled from energy costs and recouped through a fixed charge ($/month) levied on customers. Such a design would reduce the overall volumetric component of rates but would require careful design of fixed charges to ensure they are equitable and not regressive. A uniform fixed charge across all customers is more regressive and inequitable than current volumetric-only rates [9, 24, 33]. Alternative designs may include fixed charges that are tied to a customer's income or other characteristics that can serve as a proxy of a customer's income, such as total consumption (kWh), peak power demand (kW), or self-generation availability (kW-dc of solar rooftop) [9, 33]. While income-graduated fixed charges may reduce the share of affordability burden compared to current rates, there are considerable implementation challenges, including privacy concerns, income verification requirements, as well as an appropriate gradient of charges across income [66].

6. Discussion and conclusions

We conclude this perspective by highlighting three key messages: i) near-real-time data and models allow us to approximate electricity rates to their social marginal costs; ii) having a retail rate design that captures marginal social costs does not necessarily equate with more equitable outcomes; and iii) increased complexity in rate design warrants additional outreach and access to technology so that consumers can make better decisions.

Near-real-time data and models allow us to approximate rates to their real social costs. The advent of smart meters, sophisticated grid modeling, and publicly available datasets on emissions and externalities enables the estimation of the social marginal costs of electricity that should be included in electricity pricing. For example, several research groups, including our own, have developed several detailed models that can estimate hourly marginal damages from climate change and air pollution (see, for example [67–69]) at the balancing area, Independent System Operators Region, State, or other geographical boundaries (see the marginal emissions and damages tool at [70]) Utilities could use these time specific estimate and incorporate them in monthly bills by multiplying the hourly damages per kWh of electricity consumption of the household by their respective hourly consumption.

Having a retail rate design that captures marginal social costs does not necessarily equate with more affordable rates for all: rates that better capture marginal social costs will improve efficiency but may not improve distributional outcomes. Abrupt price changes can increase bills for low-income customers with less flexibility to shift consumption and reduce overall customer support for the more ambitious reforms needed for large-scale electrification. The 2021 Texas winter storm highlighted this challenge. Even with opt-in structures, some customers on RTP faced bills in the thousands of dollars during the crisis [71, 72].

Increased complexity in rate design may warrant additional outreach and access to technology to provide customer benefits. Increased complexity in rate design requires more awareness and technology access for customers to realize the benefits. Time-varying rates should be introduced gradually through opt-in programs, giving consumers adequate time to adapt. To enable low-income customers to effectively respond to price signals, access to smart energy technologies such as smart thermostats, home energy management systems, and DERs should be expanded along with new rate designs.

Electrification has emerged as the lynchpin for reducing emissions from our overall energy systems. As we move toward greater decarbonization and distributed resources, rate design must balance multiple objectives: reflecting time-varying system costs, ensuring affordability, and maintaining simplicity. While no single rate structure achieves all objectives perfectly, intermediate approaches can help achieve a more balanced outcome. The transition to highly time-varying rates, such as RTP, can improve grid efficiency, but we caution against their implications across different dimensions, particularly for low-income customers who often lack the flexibility to shift their electricity consumption. A balanced approach would gradually introduce TOU rates with pre-determined high-price periods that are communicated well in advance, with stable time periods. In tandem, utilities must expand access to enabling technologies and implement customer protections to create an electricity pricing system that advances climate goals, enhances affordability and access to new technologies and services.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Author contributions

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Conceptualization (equal), Data curation (equal), Formal analysis (equal), Visualization (equal), Writing – original draft (equal), Writing – review & editing (equal)

Bruce Cain
Conceptualization (equal), Supervision (equal), Writing – original draft (equal), Writing – review & editing (equal)

Inês M L Azevedo 0000-0002-4755-8656
Conceptualization (equal), Methodology (equal), Project administration (equal), Supervision (equal), Writing – original draft (equal), Writing – review & editing (equal)

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