The economic consequences of electricity tariff design in a renewable energy era[☆]

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HIGHLIGHTS

- Traditional tariffs are less fair than newer TOU and demand charge tariffs.
- As D-RES grows, unfair cost transfers also grow for traditional tariffs.
- With traditional tariffs, social welfare decreases as D-RES increases.
- For newer tariff designs, social welfare is independent of D-RES amount.

ARTICLE INFO

ABSTRACT

Renewable generation is rapidly expanding across many electricity grids, often as distributed renewable energy sources (D-RES). D-RES, such as rooftop solar panels, change a household's electric relationship with the external grid, demanding a likewise change in its economic relationship with the retailer. In particular, D-RES can impact fairness and economic efficiency considerations for electricity tariffs. We evaluate this impact on 5 tariffs, using per-minute data for 144 households in Austin, TX, USA. Our results show that traditional tariff designs allow for large wealth transfers, often to D-RES owners from non-owners, who may be paying on the median 22% more than their fair share. For economic efficiency, traditional tariffs again perform poorly. Newer time-based (time-of-use, or TOU, and real-time dynamic pricing) tariffs show few signs of cross-subsidization and better economic efficiency. Potential demand elasticity does not significantly alter conclusions for fairness, but significantly impacts those for economic efficiency. Our results clarify how different novel tariff designs in the renewable energy era achieve differing kinds and levels of fairness and efficiency; some acceptable, while others less so.

1. Introduction

Climate change is a global coordination problem. While most of the world population experiences the consequences of climate change, they are not equally responsible for its cause, i.e. greenhouse gas emissions. Thus, the burden of negative externalities from extracting and consuming fossil fuels has fallen on some who do not partake (or partake less) in its benefits and subsidize other energy consumers.

This "cross-subsidization" of some consumers by others can also be seen in local parts of the energy system, such as electricity distribution grids. Most households subscribe to a constant "flat-rate" tariff based on measured consumption volume over a long time period (e.g. monthly,

seasonal, yearly). However, the costs of electricity delivery depend on multiple factors that may not align with this constant price. For example, electricity generation prices, particularly in liberalized wholesale markets, often change dramatically from hour to hour [1]. Due to this mismatch between costs and prices, some subscribers may pay less than their fair share for electricity while others pay more. As retailers are often regulated to meet specific financial criteria, such cost transfers are imposed as cross-subsidies on the consumer population. This fairness issue is a common theme of debate in distribution grid pricing.

Some amount of cross-subsidies, a form of inequity (or fairness), has been typical in distribution grids for over a century. It was lightly considered in design decisions due to its possibly socially progressive

nature (i.e. transferring welfare from the wealthy to the poor) [2,3], despite its economic inefficiencies [4]. However, the advent of D-RES can create socially regressive cost transfers, as seen in the US State of California [5]. Hence, equity concerns play a more prominent role in tariff design as D-RES units increase.

Economic efficiency is also a significant consideration for distribution grid pricing. This matter, namely ensuring that each product is purchased by the consumer who values it most, was previously less important in electricity tariff design compared to other more pressing matters. However, D-RES growth can influence who observes economic inefficiencies, and by how much; thus, economic efficiency's importance is now higher [4]. Consequently, research now also focuses on the economic efficiencies of electricity tariffs.

Many studies have focused on the fairness and economic efficiency considerations of electricity tariffs (detailed in Section 2). More specifically, many studies focus on the impact of D-RES on these matters. However, we are not aware of a study that uses a comprehensive set of tariffs based on all components of electricity costs. We analyze this matter using per-minute generation and consumption and pricing data from a residential population in Austin, TX, USA. Our contributions include:

- Absent D-RES, traditional electricity tariffs (namely increasing-block pricing and flat rates) create very large cross-subsidies. As D-RES grows, these cross-subsidies peak when roughly half to two-thirds of households own D-RES. More importantly, these cross-subsidies are mainly to the benefit of D-RES owners, reaching a peak of over one-fifth of their overall electricity costs. These cost transfers are likely to be socially regressive, i.e. taxing the poor more than the wealthy [5].
- Some residential tariffs are proposed to change to time-dependent and/or demand charge pricing (i.e. pricing household peak demand). For these tariffs, we find lower cross-subsidies by two to three orders of magnitude at the median compared to traditional tariffs. These cross-subsidies are not as strongly dependent on D-RES amount.
- Social welfare is worse for the traditional tariffs and better for time-dependent and demand charge pricing. As D-RES grows, social welfare worsens, but at a faster pace for the traditional tariffs, reaching values of over 20% of total household bills.
- Cross-subsidies are higher in regions with higher household demand elasticity. More importantly, demand elasticity affects different tariffs differently.

In the following pages, we first review background literature on tariff design, cross-subsidization, and economic efficiency. We next cover details on methodology and data in Section 3. Our study's results follow, with results for the zero elasticity case in Section 5 and the non-zero elasticity case in Section 6. Economic efficiency results are discussed separately in Section 7. The paper concludes in Section 8 with notes on policy implications and potential future research.

2. Background and literature review

Electricity is often considered to be a public good for households. Pricing this product has thus been influenced by both politics and economics [2]. For most households, these prices appear as tariff rates from regional retailers. These tariff rates are often designed with specific principles in mind. These include (1) sufficiency of revenue, (2) equity, (3) economic efficiency, (4) transparency, (5) simplicity, (6) stability, (7) consistency with larger regulatory framework, and (8) cost additivity [6]. It is often to simultaneously adhere to all principles; hence, tariff design has been a process of compromise over how well to meet each principle.

Choosing an optimal tariff requires weighting each principle's importance versus others [7]. These weights often depend on assumptions

about the location in which the tariff is applied, e.g. the customer population and the distribution grid. For example, residential consumers have historically been assumed to be demand-inelastic passive price-takers of electricity. Hence, fixed rates charged on a per-kWh basis have been the most common format for pricing electricity [8]. These tariffs are designed to be simple and sufficient in revenue. However, they perform poorly on equity and economic efficiency [4,9–11], which are unlikely to be significant for households with inelastic demand. Hence, most residential electricity pricing in many regions is based on such non-changing per-kWh charges.

D-RES significantly impacts many of the considerations regarding the principles of electricity tariff design [12,13]. Consumers are no longer passive price-takers of electricity; rather, D-RES transforms these users into active and calculating producer–consumers, or "prosumers". For these users, the rates of cross-subsidization within flat-rate tariffs are often comparable to their D-RES return on investment. The economic feasibility of D-RES depends on this value, so it is unlikely these values would be acceptable for regulators or customers.

D-RES affects another aspect of the acceptability of flat-rate pricing. Flat rates often disfavor high consumers for low consumers of electricity. Consumption was thought to correlate with wealth, so this was believed to be an implicit transfer of wealth from the wealthy to the poor. D-RES drastically reduces household consumption, while it is often owned by the wealthy [5]. Thus, there is evidence of socially regressive wealth transfers forming in many high D-RES grids, such as in the US State of California [5] and the Australian States of Queensland [14] and New South Wales [15].

Given these considerations, the cross-subsidies inherent in traditional tariff designs may no longer be acceptable when D-RES is added. However, D-RES affects not only the acceptability of a certain amount of cross-subsidization, but also the amount itself. A retailer's costs are described in SubSection 3.1; in summary, these costs consist of 1) energy-related costs, dependent on consumption volume at each time, 2) capacity-related costs, dependent on maximum power flow over a long timespan, and 3) other costs unrelated to volume or power flow. The latter costs group rarely affect cross-subsidization, whereas the former two groups do. Clastres et al. [16] describe how D-RES can lead to cross-subsidization from energy costs, and quantify these rates for a hypothetical French grid. For capacity-related costs, results from the Australian state of Queensland [14] and United Kingdom [17] show that D-RES significantly increases cross-subsidies. Picciariello et al. [18] simulate multiple grids across the US and investigate cross-subsidies between prosumers and consumers. Fontana [19] similarly simulate this for a Portuguese case.

There are few studies however which include all components of cross-subsidization, when D-RES is considered. Athawale and Felder [20] included both energy and capacity-related costs for New Jersey's volumetric tariffs, finding cross-subsidization between customer groups. However, we miss a study with a comprehensive set of tariffs, focused on the effect of D-RES on tariff fairness.

We likewise miss an explicit study of how D-RES affects economic efficiency for various tariffs. Economic efficiency is generally used to understand how well resources are distributed among consumers. Consumers differ in how much they value a product, thus consuming more or less at any given price. Mispricing, for example due to subsidies or differential pricing, leads to divergences in how much these consumers would consume. Consequently, they would consume more or less than optimal, leading to "deadweight loss". For example, fuel subsidies are known to create massive deadweight losses due to elevated consumption on a global scale [21]. In electricity distribution pricing, Borenstein [4] describes the importance of D-RES for economic efficiency considerations, particularly for grid capacity costs. Wolak [22] uses 1990–2016 data from Californian utilities to measure the effects of residential solar panel installations on electricity prices, which implies some economic inefficiencies from network cost misallocation. Regarding energy costs, Borenstein and Bushnell [9]

compare retailer prices across the United States, finding significant deadweight loss within many regions. These studies clarify aspects of economic efficiency in distribution grid pricing. However, similar to fairness (or equity), no prior study uses real-world data to compare the effects of D-RES on economic efficiency for various tariffs. Hence, we focus on the fairness and economic efficiency aspects of tariffs, and how they are influenced by increases in D-RES.

3. Methods

3.1. Electricity trade: costs and tariffs

A retailer's cost for electricity consists of multiple components. First, the retailer must obtain energy at every instant to meet demand requirements, either from its own generation assets or the wholesale market. Thus, a retailer's observed prices are typically anchored by wholesale market prices and depend on the per-kWh marginal market cost, along with the transmission system operator's costs for electricity transport. The latter costs are generally distributed equally across subscribers and are ignored here. Second, the retailer must distribute this energy to end-users through a distribution grid, owned by itself or another business. The cost of this grid mostly depends on the maximum total power flow the grid is designed to support [23]. Here, we assume these capacity costs are similar to an equally sized commercial and/or industrial customer in the same region. Third, the retailer's overhead costs, such as administration, billing, and marketing, often depend on its number of subscribers in a specific subscriber class. As these costs do not depend on subscriber usage, they can be expected to not contribute to cross-subsidies and are ignored here. Finally, the retailer must also credit the generation of any D-RES owned by its subscribers. This D-RES electricity generation offsets energy requirements and power flow for the retailer and thus interacts in complex ways with energy and capacity costs. This added value depends on multiple factors, including governmental D-RES subsidy schemes, overall deferred investments in capacity expansion, hourly energy requirements and prices, and avoided costs for transport over the transmission grid [24]. For simplicity, we assume that similar to [24] these costs can be accurately accounted for in a flat per-kWh bonus to energy cost. As these cost components are the basis for cross-subsidization within a retailer's subscriber population, D-RES generation can significantly alter the acceptability of a tariff's cross-subsidies.

Cost components do not necessarily align with the variables used in the design of a tariff that recovers those costs (Table 1). We investigate cross-subsidies in 5 tariffs. These tariffs were chosen based on prior analysis and how commonly they are used or discussed for use by electricity retailers around the world:

1. Conventional tariff: We include this as a comparison with the status quo, i.e. what the dataset's population is currently paying. Our Austin, TX, USA, households were subscribed to Austin Energy's residential rates, which is an increasing-block rate tariff for energy consumption with a flat-rate Value of Solar credit for D-RES

generation [24]. More information about the data can be found in Section 4.

2. Flat-rate tariff: Consists of a fixed fee per kWh of electricity consumption. We likewise assume a flat-rate credit per kWh of electricity generation. This tariff is similar to those used in Borenstein [5,4,25], Simshauser and Downer [10], Picciariello et al. [26].

3. Time-of-Use tariff: These tariffs are intended as a middle ground between the simplicity of flat-rate tariffs and real-time pricing. This tariff was designed to be similar to pilot tariffs in the US state of Texas and the Netherlands. As such, we assume higher daytime (6:00–22:00) prices and lower nighttime (22:00–6:00) prices, with hourly pricing for generation credits.

4. Real-Time Pricing: This tariff's pricing depends on hourly wholesale market prices for both generation and consumption prices, similar to Horowitz and Lave [11], Azarova et al. [27], Burger et al. [28].

5. Demand Charge tariff: A real-time pricing scheme with monthly demand charges to recover capacity costs. These demand charges, which depend on a household's monthly peak demand, have been proposed (and contested, e.g. see Borenstein [4]) for recovering fixed grid costs while sending suitable signals for demand response. Examples of past studies of this tariff include Simshauser [14], Passey et al. [29].

These tariffs are calibrated to be cost-sufficient, i.e. recover overall revenue equal to the overall real costs of electricity trade (for an individual household, however, the real costs of electricity trade can differ from its tariff bill).

3.2. Tariff and cost formulas

Each tariff's details and calibration methods are described in the coming subsections. Prior to these, we describe the general formulation of costs and cross-subsidization (nomenclature is listed in Table 2). For the billing period T, similar to most past studies, e.g. Burger et al. [28], Azarova et al. [27], we choose a period of 1 year. For each household i in set M and tariff j in set N (which includes real costs and prices as a "tariff" denoted by r), we have

$$\theta_{j,i} = \sum_{t \in T} E_j q_i(t) + \sum_{t \in T} G_j g_i(t) + \sum_{\tau \in T} C_j p(\tau) \tag{1}$$

where E_j is the electricity purchase price for amount $q_i(t)$, G_j is the sale price for D-RES generation of $g_i(t)$, C_j is the price for capacity per unit of power flow p over a time horizon $\tau \in T$, and $\theta_{j,i}$ is the overall costs of tariff j for household i. The total costs for the household population M for tariff j is $\theta_j = \sum_{i \in M} \theta_{j,i}$. All prices are from the perspective of households, i.e. negative prices are a funds transfer from utility to household.

Our study assumes cost sufficiency, i.e. all tariffs return enough revenue to meet the real costs of electricity delivery:

$$\forall j \in N: \theta_j = \theta_r. \tag{2}$$

Given this constraint, cross-subsidies can be defined as the "Net Difference" ratio in individual households, between real and tariffed

Table 1
Tariffs used in this study.

#	Tariff	Consumption	Generation	Capacity	Notes
1	Conventional	Increasing-block pricing	Flat rate	N/A (in consumption prices)	Reference tariff currently in use
2	Flat-rate	Flat rate			Most common
3	2-Tier Time-of-Use (TOU)	High daytime prices, low nighttime prices	Hourly market prices (plus subsidy markup)	Separate fixed charge	Middle-ground between simplicity (Flat-rate) and time variation (RTP)
4	Real-Time Pricing (RTP)	Hourly market prices			–
5	Demand Charge (DC)			Monthly demand charge of household peak	Similar to Simshauser [14], Passey et al. [29]
–	*real costs*	*Real-time market prices*	*Real-time market prices (plus subsidy markup)*	*Fixed charge (at overall demand peak time)*	

Table 2
Nomenclature.

Label	Unit	Description
q	kWh	Consumption
g	kWh	Generation (always >0)
p	kW	Net power flow. First time differential of (q-g)
E	$/kWh	Consumption price
G	$/kWh	Generation price
C	$/kW	Capacity price
P_g	$/kWh	Green Certificate reimbursement price
α	$	Green Certificate reimbursement cost
θ	$	Total costs
i	–	House index
j	–	Tariff index
t	min	Time unit (1 min)
T	–	Time horizon
ν	$	(Cross-subsidization) Net Difference
ϵ	–	Elasticity constant
A	–	Demand elasticity formula constant
C.S.	$	Consumer Surplus
D.W.L.	$	Deadweight Loss

costs:

$$\forall \, j \in N; i \in M: \nu_{j,i} = \theta_{r,i} - \theta_{j,i}. \tag{3}$$

To compute the cross-subsidy $\nu_{j,i}$ in Eq. (3), we find the bill of any household i per tariff j ($\theta_{j,i}$) as well as the real costs for electricity delivery ($\theta_{j,i}$) based on Eq. (1). We next describe how each of these terms are computed.

3.2.1. Real costs

For consumed energy, the real price at each instance E_r is assumed to be equal to real-time locational-marginal prices (RTLMP). These are real-time wholesale market clearing prices at each instance in a location (node), biased by network conditions (e.g. congestion, losses) in the grid. The generation credit G_r is set to E_r, plus a bonus $\alpha_{r,i}$ for internalizing any potential benefits of D-RES, which is based on a per-kWh credit P_g. To simplify, we integrate both as $G_r = E_r + P_g$. Capacity costs of the utility's distribution grid mainly depend on the maximum net power demand over a time horizon [14]. Thus, C_r is taken to be a constant per-kW price per household, which is multiplied by the maximum net power demand of the entire household group M over the time horizon T, $p_{max,M,T}$. These costs are distributed to each household based on Eq. (1).

3.2.2. Conventional tariff

This tariff consists of tiered volumetric consumption prices and a flat-rate "Value of Solar" generation credit. The consumption price $E_{conv,i}$ for household i depends on the total monthly consumption of the household and the month of the year (T_m, $m \in \{1. .12\}$). Hence, each household gets a different price per month, $E_{conv,i}(\sum_{t \in T_m} q_i(t), T_m)$, based on Austin Energy's 2016 residential rates (note: this is the only tariff where consumption prices $E_{conv,i}$ differ among households). The generation price G_{conv} is set to Austin Energy's Value of Solar rate for 2016 (11.3 c/kWh, details in Rábago et al. [24]). Since all values are known, $\theta_{conv,i}$ is known. As all tariff elements are calibrated by Austin Energy, a lump sum L_{conv} is added to households as a fixed charge to ensure cost sufficiency (Eq. (2)) is met. This additional cost is levied equally across all households so that it does not bias the tariff's original cross-subsidization:

$$\theta_r = \theta_{conv} = \sum_{i \in M} (\theta_{conv,i} + L_{conv}). \tag{4}$$

3.2.3. Flat-rate tariff

The conventional tariff is designed by Austin Energy to promote energy efficiency at the expense of equal prices. A flat-rate tariff, which

retains the time-ignorance of the conventional tariff but removes the energy efficiency design choices, would be a fairer comparison to other tariffs that are also not biased by such design choices. In this tariff, E_{flat} and G_{flat} are constant values. Capacity costs are embedded into the flat energy rate E_{flat} (and $C_{flat} = 0$):

$$\theta_{flat} = \sum_{i \in M} \theta_{flat,i} = \sum_{i \in M} \sum_{t \in T} [E_{flat} q_i(t) + G_{flat} g_i(t)] \tag{5}$$

G_{flat} is set based on a fixed rate calculated as the value of D-RES (e.g. in Rábago et al. [24]), including additional subsidies. Thus, the only unknown is E_{flat} and can be calculated by the revenue neutrality constraint, i.e. setting $\theta_{flat} = \theta_r$.

3.2.4. TOU tariff

The Time-of-Use tariff has differing prices for consumption (E_{tou}) according to the hour of day. We investigate a two-tier TOU with separate daytime (T_d) and nighttime (T_n) pricing. With two tiers:

$$E_{tou} = \begin{cases} E_{tou,d} & \text{when } t \in T_d \\ E_{tou,n} & \text{when } t \in T_n \end{cases}. \tag{6}$$

There is no benefit from simpler pricing for generation credits, so G_{tou} is set to the real-time value of solar generation detailed in the Real-time Pricing tariff. We also separate capacity costs here based on p_{max}, similar to C_r. In total, we have:

$$\begin{aligned} \theta_{tou} = & \sum_{i \in M} \sum_{t \in T_d} [E_{tou,d} q_i(t) + G_{tou} g_i(t)] \\ & + \sum_{i \in M} \sum_{t \in T_n} [E_{tou,n} q_i(t) + G_{tou} g_i(t)] + C_r p_{max}. \end{aligned} \tag{7}$$

By setting this equal to real costs θ_r, we have one equation with two unknowns ($E_{tou,n}$ and $E_{tou,d}$), i.e. one degree of freedom. To solve this equation, we add another constraint. We assume that $E_{tou,d}$ and $E_{tou,n}$ are proportionally scaled (with scaling factor r_{tou}) based on average RTLMP prices during daytime (P_d) and nighttime (P_n):

$$\begin{cases} E_{tou,d} = r_{tou} P_d \\ E_{tou,n} = r_{tou} P_n \end{cases}. \tag{8}$$

Eq. (7) can then be solved for r_{tou}.

With this additional constraint, the two time-of-use tiers mainly differ based on r_{tou} which depends on the difference in the average RTLMP prices in daytime and nighttime.

3.2.5. RTP tariff

In this tariff, consumption prices $E_{rtp}(t)$ are taken to be equal to average RTLMP prices per hour. The generation remuneration price G_{rtp} is taken to be E_{rtp} with a bonus element for reimbursements, $G_{rtp} = E_{rtp} + P_g$. Capacity prices C_{rtp} are set equal to C_r. Hence, θ_{rtp} is defined. An extra lump sum (L_{rtp}) is added equally to to ensure cost sufficiency (Eq. (2)):

$$\theta_r = \theta_{rtp} = \sum_{i \in M} (\theta_{rtp,i} + L_{rtp}) \tag{9}$$

which is solved for L_{rtp}.

3.2.6. Demand charge tariff

This tariff combines a real-time pricing of energy costs with a monthly demand charge for capacity costs. Consumption and generation prices are similar to the RTP tariff, $E_{dc} = E_{rtp}$ and $G_{dc} = G_{rtp}$. However, capacity prices differ: for each household $i \in M$, a price (C_{dc}) is assigned per kilowatt of maximum power demand during each month T_m, $p_{max,i}(T_m)$. Total capacity costs for household i over T equals $C_{dc} \sum_{T_m \in T} p_{max,i}(T_m)$.

The per-kilowatt capacity price C_{dc} is set to equal capacity costs with real capacity costs:
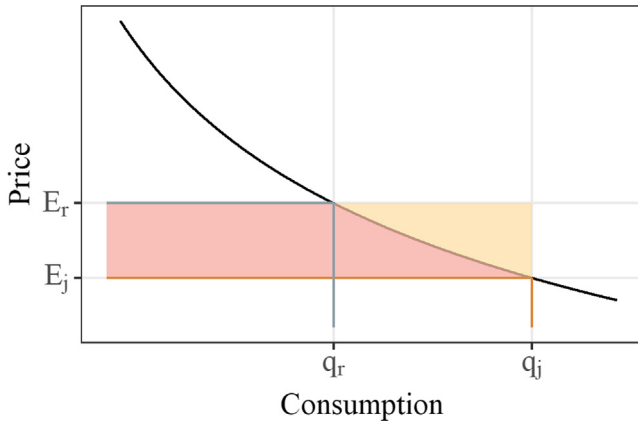
Fig. 1. The Demand Curve (black) shows the relationship between prices and (consumption) quantities. The difference in area between real price and quantity (blue lines) and tariff price and quantity (orange lines) is the difference in consumer surplus between consumption under real and tariff prices (pink area). Deadweight Loss (yellow area) shows the overall welfare loss caused by the difference in price. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$C_r p_{max}(T) = C_{dc} \sum_{T_m \in T} p_{max,i}(T_m). \tag{10}$$

which is solved for C_{dc}.

The overall costs θ_{dc} are defined as equal to real costs θ_r, with a lump sum L_{dc} calibrated to ensure cost sufficiency (Eq. (2)):

$$\theta_r = \theta_{dc} = \sum_{i \in M} \left[\sum_{t \in T} E_{dc} q_i(t) + \sum_{t \in T} G_{dc} g_i(t) + \sum_{T_m \in T} C_{dc} p_{max,i}(T_m) + L_{dc} \right] \tag{11}$$

3.3. Calculating elasticity, consumer surplus, and deadweight loss

Electricity as a product for residential households is generally perceived as a public good and has very low demand elasticity. Similar to Horowitz and Lave [11], Burger et al. [28], Borenstein [30], we assume that each household i is demand-elastic according to a constant elasticity rate ϵ and a constant multiplier A, i.e. $q = AE^\epsilon$ (black curve in Fig. 1), where q is the consumption at price E. We find A by using initial consumption and price values; in our case, the households are initially subscribed to the Conventional tariff, i.e. $A_{i,t} = q_{i,conv,t}/E_{i,conv,t}^\epsilon$.

We make the following assumptions to ensure a change in prices at each instance returns an appropriate change in consumption:

1. We choose elasticity values at the low ($\epsilon = -0.1$) and high ($\epsilon = -0.3$) ends of past empirical results, similar to past research [25,28,30]. These are close to estimates of short- and long-term elasticity (respectively) for residential households [31].
2. The Conventional tariff consists of increasing-block prices, where the marginal price increases as monthly consumption increases. Following from Ito [32], we assume the household's average price per month (rather than its marginal price) to be its initial observed price.
3. In some situations, prices may become negative. If so, we choose the observed price to be 0.1 c/kWh, which, when compared to a new price of 10 c/kWh (and $\epsilon = -0.1$), creates a consumption increase of 58%. This happens most for the RTP tariff, for 1.5% of instances overall.
4. For tariffs that separate capacity costs, we assume these costs are discounted from price estimates of the average conventional price, i.e. $E_{i,conv,t}$ is reduced to reflect that it also contained capacity costs. This follows from past evidence that consumers do not respond to

fixed charges [28].

The Demand Charge tariff is designed to also induce demand elasticity based on the demand charge for capacity costs. Using a similar model, we assume maximum "acceptable" demand over a month is dependent on the change in price of capacity costs per kW of maximum demand. For this scenario, all time slots are checked versus new demand. If lower, all time slots with higher consumption are lowered to the new low, and if higher, consumption is increased to its original value or to the new maximum acceptable demand (whichever is lower). This accounts for the demand charge signal of flattening demand, while allowing for deviations due to exceptionally low (or high) energy prices.

We use these elasticity approaches to calculate a new demand profile per household per tariff. Much of tariff price calibration depends on real costs, which depend on demand profiles, which depend on tariff prices. This requires iteration until an equilibrium is reached. Our algorithm iterated on costs until the sum of absolute changes in household bills was less that 0.1% of all bills combined.

Our consumer surplus calculations follow from prior economic studies of energy prices. Borenstein [4] contains a general explanation, while Burger et al. [28] and Davis [21] describe this approach for two different (albeit energy-related) empirical cases. At each time interval $t \in T$, a household $i \in M$ consumes a specific amount of electricity $q_{i,j,t}$ considering the instance price $E_{i,j,t}$ of tariff j. Consumer surplus can be considered as the area under the demand curve from the maximum allowable price $E_{i,max,t}$ up to $\{E_{i,j,t}, q_{i,j,t}\}$ (in Fig. 1, the area between the demand curve and the orange horizontal line), summed with any credits or costs otherwise added or imposed [28]:

$$C.S._{i,j} = \sum_{t \in T} \int_{E_{i,j,t}}^{E_{i,max,t}} q_{i,j,t} dE + Gen.Cred_{i,j} - Cap.Costs_{i,j} \tag{12}$$

where $Gen.Cred_{i,j}$ and $Cap.Costs_{i,j}$ represent the generation credits and capacity costs for the tariff-household pair. We are most interested in the difference in consumer surplus based on the current tariff and the consumer surplus based on the real costs of electricity trade (in Fig. 1, this is equal to the pink area). This difference for the first term on the right side of Eq. (12) for one timeslot $t \in T$, is:

$$C.S._{i,j,t} - C.S._{i,r,t} = \Delta C.S._{cons,i,j,r,t} = \int_{E_{i,j,t}}^{E_{i,max,t}} q_{i,j,t} dE - \int_{E_{i,r,t}}^{E_{i,max,t}} q_{i,j,t} dE$$
$$= \int_{E_{i,j,t}}^{E_{i,r,t}} q_{i,j,t} dE \tag{13}$$

where $E_{i,r,t}$ is the real price (or value) of electricity at that moment t. Using the elasticity formula $q = AE^\epsilon$ where $A_{i,t} = q_{i,conv,t}/E_{i,conv,t}^\epsilon$, we have

$$\Delta C.S._{cons,i,j,r,t} = \int_{E_{i,j,t}}^{E_{i,r,t}} q_{i,j,t} dE = \frac{A_{i,t}}{1+\epsilon}(E_{i,r,t}^{\epsilon+1} - E_{i,j,t}^{\epsilon+1}). \tag{14}$$

Adding in the generation credits and capacity costs portion and summing over all timeslots in T, we can find the difference in consumer surplus for tariff j and household i as

$$\Delta C.S._{i,j} = \sum_{t \in T} \frac{A_{i,t}}{1+\epsilon}(E_{i,r,t}^{\epsilon+1} - E_{i,j,t}^{\epsilon+1}) + \Delta Gen.Cred_{i,j} - \Delta Cap.Costs_{i,j} \tag{15}$$

where the two latter terms of the right side are differences in generation credit and capacity costs (plus any other lump sum additions) between real and tariffed costs. Note that the change in consumer surplus formula collapses to Net Difference when $\epsilon = 0$.

The deadweight loss per household-tariff-instance triple $\{i, j, t\}$ can be considered as the (almost) triangular yellow area in Fig. 1. This represents the entire system's total loss (overall welfare loss) due to inaccurate pricing of electricity [4]. We can find this value at each instance by subtracting the pink area (equal to $\Delta C.S._{cons,i,j,r,t}$ from Eq.

(14)) from the rectangle consisting of pink and yellow areas in Fig. 1 (see Burger et al. [28] for details). Summing over all timeslots, we find the total deadweight loss as

$$D.W.L._{\cdot i,j} = \sum_{t \in T} \left[(E_{i,r,t} - E_{i,j,t}) q_{i,j,t} - \frac{A_{i,t}}{1+\epsilon} (E_{i,r,t}^{\epsilon+1} - E_{i,j,t}^{\epsilon+1}) \right]. \tag{16}$$

Sometimes, particularly for the flat-rate and demand charge tariffs, the quantity of electricity consumed can be distorted by an additional factor: the misrepresentation of capacity costs in the tariff. This may cause a household's consumed energy to be higher or lower than they would otherwise choose based on the energy price signal. In mathematical terms, at price $E_{i,j,t}$ the household i consumes quantity $q_{i,k,t}$ rather than $q_{i,j,t}$ (red and orange lines in Fig. 2, respectively). To compute deadweight loss for these scenarios, we find $E_{i,k,t}$ based on the demand function and replace the j-index values for k-index values in the relevant formulas (see Fig. 2 for a visual representation). The change in consumer surplus is adjusted in a similar way. However, there is an additional change, as the consumer also pays a different price ($E_{i,j,t}$) compared to what they would pay at quantity $q_{i,k,t}$, i.e. $E_{i,k,t}$. This difference in costs (red rectangular area in Fig. 2)) is also subtracted from the consumer surplus at each instance. In mathematical terms, Eq. (14) becomes

$$\Delta C.S._{\cdot cons, i,k,r,t} = \frac{A_{i,t}}{1+\epsilon} (E_{i,r,t}^{\epsilon+1} - E_{i,k,t}^{\epsilon+1}) + (E_{i,k,t} - E_{i,j,t}) q_{i,k,t}. \tag{17}$$

All other calculation details remain unchanged.

4. Data

To quantify cross-subsidies in a household population, we require pricing and energy data from a distribution grid and its end-users. We gathered per-minute household generation and consumption data from the Pecan Street Dataport with an academic license.[1] We used the following criteria to clean this dataset:

1. Household contains solar photo-voltaic panels (335 households)
2. Location is Austin, TX, US (282 of 335 households)
3. Household registered for data collection for entire year of 2016. Tariff design and utility costs calculations are conducted on an annual basis, so a duration of one year was chosen as a representative period. 2016 was chosen due to higher data availability (216 of 282 households).
4. Consumption and generation data contained less than 5% missing or erroneous data points, after data cleaning operations (144 of 216 households). These operations included
   (a) Identifying and relabelling mislabelled time stamps,
   (b) Identifying and fixing implausible but recoverable values (e.g. generation traces that are negative), and
   (c) Identifying and removing implausible and unrecoverable values (e.g. consumption values equal to very low numbers over long time periods, which indicate a recording failure or an empty household).

After cleaning operations, this dataset consisted of 144 households in Austin, TX, USA, for the year of 2016. Each household consisted of 527,040 data points for consumption and solar photo-voltaic panel generation.

We use pricing data from the same locale and time period to calibrate the tariffs. This data consisted of tariff rates of Austin Energy, a local publicly-owned retailer,[2] and real-time locational-marginal prices from the transmission grid and wholesale market operator (Electricity Reliability Council of Texas) for the Austin load zone.[3] This data for

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[1] More details at https://www.pecanstreet.org/dataport/
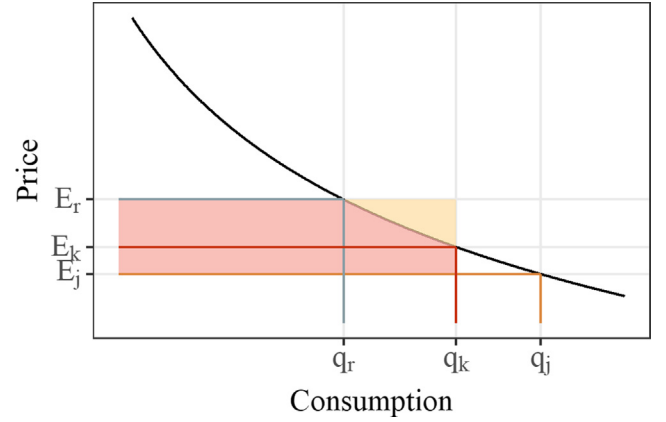[2] More details at https://austinenergy.com/ae/rates

Fig. 2. Similar to Fig. 1; consumer surplus change (pink area) and deadweight loss (yellow area) in scenario where actual consumption and price (q_k and E_j) is not .on demand curve. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2016 contained no missing values. The data was narrowed down for the Austin load zone and timestamps were added based on the day, hour, and minute columns.

5. Cross-subsidization and increased renewables

We first look at the effects of increasing D-RES on the cross-subsidies of each tariff, absent demand elasticity. To do this, we increase D-RES by randomly assigning solar PV panels to consumer households in a stepwise fashion, from 0 to 100% of households owning solar panels. This process is repeated 10 times to separate the effect of randomness from trends related to increasing D-RES penetration.

With zero elasticity, cross-subsidization can be considered as the "net difference" between the real costs for each household's electricity trade and its tariffed revenue. Fig. 3 shows the disparity in net difference between households, sorted per tariff (note the difference in vertical axes). All tariffs show extreme cases with households having very high or very low cross-subsidization relative to other households. For the Flat-rate and Conventional tariffs (Fig. 3a and b), cross-subsidization is more pronounced when households are more heterogeneous in D-RES ownership. For a population split equally between consumers and prosumers (generation ratio = 0.5), there are worse cross-subsidies than with solely prosumers (generation ratio = 1) or consumers (generation ratio = 0). In particular, these cross-subsidies form between the group of prosumers and consumers. Most D-RES owners (colored blue in Fig. 3) are shifted to the "winning side" of the cross-subsidization curve, where they pay less than their fair share of costs, while consumers (colored red) are shifted to the losing side. However, as generation ratio continues to increase and all households implement D-RES generation, cross-subsidization rates decrease again. This is explicitly shown in Fig. 4, which indicates that the sum of prosumer net differences are significantly high, but only for the Conventional and Flat-rate tariffs. There are extra discriminatory cost transfers between owners and non-owners of D-RES, particularly when consumers and prosumers are roughly balanced. In such a scenario, these benefits for prosumers are about $16 k, or 22–23% of the household population's overall costs for electricity. From the perspective of D-RES, over one-fourth (28–29%) of the credits earned by prosumers for their D-RES generation comes from non-prosumer households. Since solar D-RES owners are often high-income households [5,15], these tariff designs can produce socially regressive wealth transfers during the renewable energy transition.

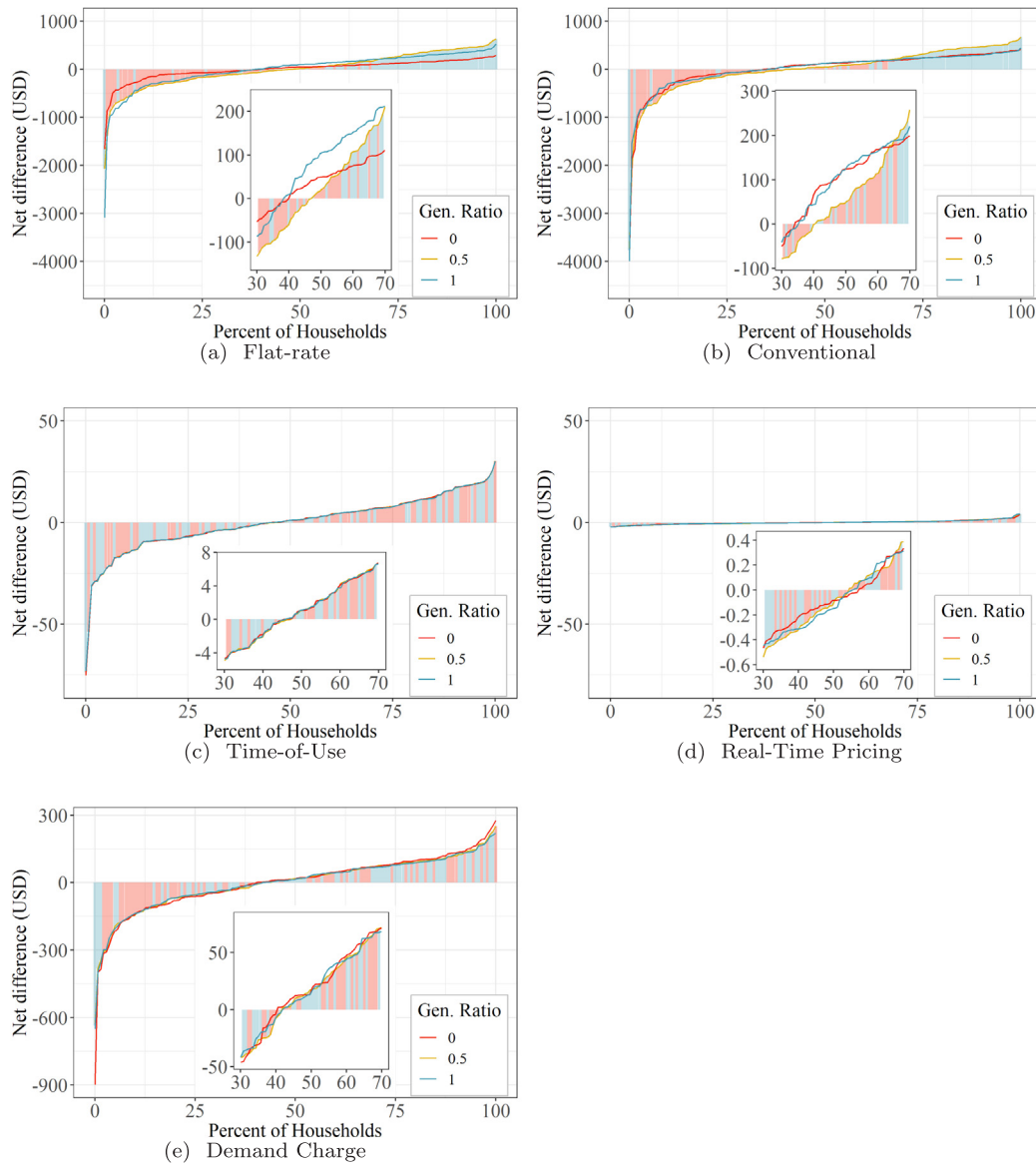---

[3] More details at http://www.ercot.com/

Fig. 3. Cross-subsidization per household for Flat-rate (a), Conventional (b), Time-of-Use (c), Real-time Pricing (d), and Demand Charge (e) tariffs. Bar colors show (for Generation Ratio = 0.5) whether a household owns solar PV panels (blue) or not (red). Plots for Generation Ratio = 0.5 are for one sample run. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

These observations do not apply to the TOU, RTP, and DC tariffs. While the DC tariff also shows high cross-subsidies, these tariffing schemes do not significantly favor prosumers or consumers (Fig. 4). Thus, there is little change in the distribution of cross-subsides as generation ratio increases. The main reason for this difference between tariffs is capacity costs. The Conventional and Flat-rate tariffs integrate these costs into the per-kWh charge. Prosumers own generation units and purchase fewer kWhs of electricity from the retailer. Consequently, they cover less of the fixed capacity costs compared to non-owners of D-RES. The TOU, RTP, and DC tariffs separately account for capacity costs. Thus, their prosumers do not contribute less towards capacity costs simply due to owning D-RES units.

The cross-subsidies from the Demand Charge tariff warrant extra explanation. This tariff is designed as an extension of the RTP tariff, with a monthly demand charge per kilowatt of household peak demand for capacity cost recovery. However, overall grid costs depend on overall peak demand, rather than each household's individual peak demand. Thus, this scheme creates some cross-subsidization to send a "suitable" economic signal for end-users to flatten their demand curves.

Consequently, cross-subsidies from the DC tariff are far higher than the RTP tariff. A median subscriber to the DC tariff on the winning side pays $76.26 less while the median loser pays $70.82 more. The same values for the median subscriber to the RTP tariff are $0.57 and $0.47. Compared to the Flat-rate tariff, which has medians of $183.52 and $229.57, respectively, the DC tariff's cross-subsidization remains low. In the next section, we will discuss per-tariff differences in detail.

In short, a zero demand elasticity scenario shows that cross-subsidies for the Flat-rate and Conventional tariffs are significantly altered by increased D-RES installations. In addition, prosumers appear to be usual beneficiaries of these cross-subsidies, at the detriment of consumers. To avoid socially regressive cost transfers [5] during the renewable energy transition, we need tariffs that do not disproportionately favor D-RES owners. Separating capacity costs appears particularly important in this respect. Time-based pricing for energy costs a la the RTP tariff appears less consequential here.
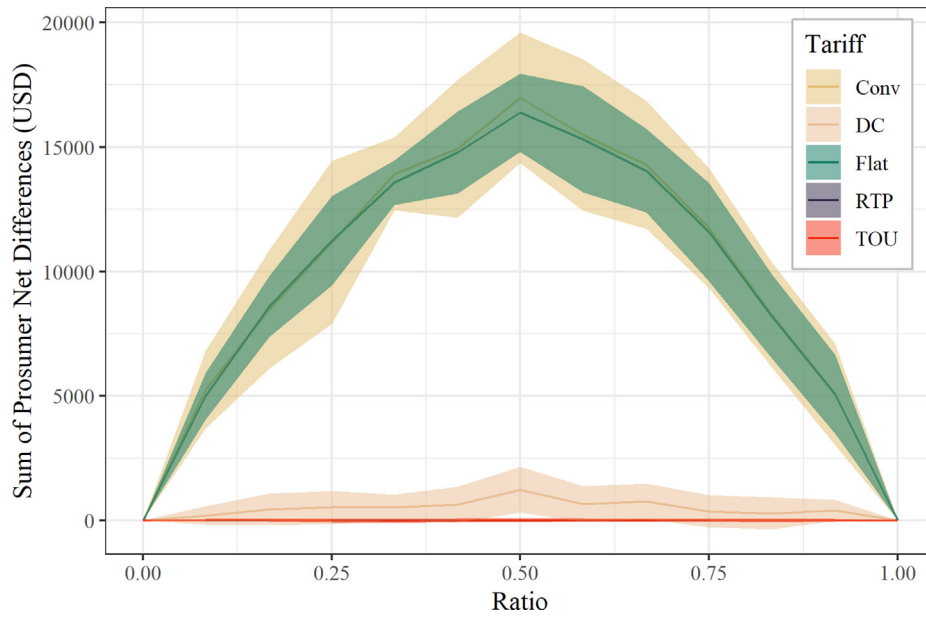
Fig. 4. Sum of prosumer net differences per ratio per tariff (colors). Lines show average value and ribbons show one standard deviation. Note that RTP and TOU results coincide. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6. Elasticity effects

We next relax our zero-demand-elasticity assumption in investigating the effects of D-RES on tariff cross-subsidies. Our dataset's households have adjusted their initial consumption values to their current subscription, the Conventional tariff. A change to the Flat-rate, TOU, RTP, or DC tariff would create a change in demand, which would affect cross-subsidization. Similar to Borenstein [25], Burger et al. [28], we model demand elasticity with an exponential demand curve based on two elasticity values at the low and high ends of prior estimates for residential electricity consumption, $\epsilon = -0.1$ and $\epsilon = -0.3$ (details in Section 3). Short-term elasticity is often closer to the former [33] and long-term elasticity appears close to the latter [28]. The former mostly represents behavioral choices (e.g. using devices during low-price periods) while the latter primarily reflects investment choices (e.g. energy efficiency or appliance investments).

To understand the effects of cross-subsidies for these households, we consider the changes in consumer surplus. Put simply, this is the difference between the benefit a consumer receives from consuming electricity at one price, versus the benefit he/she would receive at another price. We here compare the consumer surplus based on real prices versus the surplus from tariff prices. Since consumption profiles change, the population's total costs and thus the retailer's revenue needs may change. Hence, each tariff may find a different total sum of consumer surplus over all households. To focus on the differences between households, we rescale the values of consumer surplus to be zero-sum (over all households) by removing averages. The sum of the absolute values of rescaled consumer surplus changes gives a measure of overall cross-subsidization. For a zero-elasticity scenario, this value corresponds to the area between the horizontal axis and the Net Difference curves in the subfigures of Fig. 3.

We first focus on cross-subsidization rates per tariff separately, as shown in Fig. 5. Each tariff creates very different total absolute consumer surplus changes in the household group, based on elasticity and generation ratio. The Conventional and Flat-rate tariffs both show relatively high cross-subsidization at low D-RES rates. These values grow significantly as the ratio of prosumers to consumers increases. Cross-subsidies peak when prosumers become a two-thirds majority of households (i.e. generation ratio near 66%, Fig. 5)). This is mainly from wealth transfers due to capacity costs from D-RES non-owners

(consumers) to D-RES owners (prosumers), as discussed in the prior section. Cross-subsidies then decrease as the household population becomes less different in their ownership of D-RES (i.e. Ratio approaches 1). However, irrespective of elasticity, the values continue to stay high for a high D-RES population (i.e. Ratio = 1). On the median, the loser in this cost transfer would see a loss of $183 per year based on the Flat-rate tariff. A median Austin, TX, household's annual income of $63,717 [34] is far larger than this amount. However, these values are significant when compared against D-RES generation remunerations for an average household in our study population ($819 based on their actual tariff subscription, Austin Energy's Value of Solar rate). Hence, losing 22% of potential earnings to cross-subsidization may not be acceptable to the median household in such a high-D-RES scenario.

The TOU and RTP tariffs show cross-subsidies which are comparatively stable (i.e. do not change versus D-RES increases) in low-elasticity situations (Fig. 5c and d). In high elasticity, the TOU and RTP tariffs show increasing cross-subsidies at high D-RES ratios, mainly due to the time-dependence of energy costs. In addition, a median loser subscribed to the TOU or RTP tariff sees far lower losses of potential earnings, at 0.9% (TOU) or 0.06% (RTP) of the average D-RES generation remuneration. Hence, switching to a TOU or RTP tariff appears to largely fix the two primary cross-subsidization issues inherent in the Conventional and Flat-rate tariffs.

For the DC tariff, we find decreasing cross-subsidies as generation ratio increases (Fig. 5e). The cross-subsidies of the DC tariff are mainly due to the demand charge, which is in quantity dependent on overall capacity costs. As D-RES generation increases, the household population's peak demand slightly decreases. The consequent decrease in capacity costs leads to less influential cross-subsidies from demand charges. Hence, irrespective of elasticity, we find decreasing cross-subsidies for the DC tariff.

Similar to Burger et al. [28], we also find that elasticity appears to have differing effects on cross-subsidization, depending on tariff. The Conventional and Flat-rate tariff's cross-subsidization shows relatively similar trends and similar values per elasticity rate (Fig. 5b). The TOU and RTP tariffs, however, show increasing cross-subsidies in a high-elasticity scenario, but lower and stable cross-subsidies in low-elasticity and zero-elasticity scenarios (Fig. 5c and d). The DC tariff's cross-subsidies are, in value, strongly dependent on elasticity. However, trends do not differ: cross-subsidies for this tariff decrease as D-RES increases.
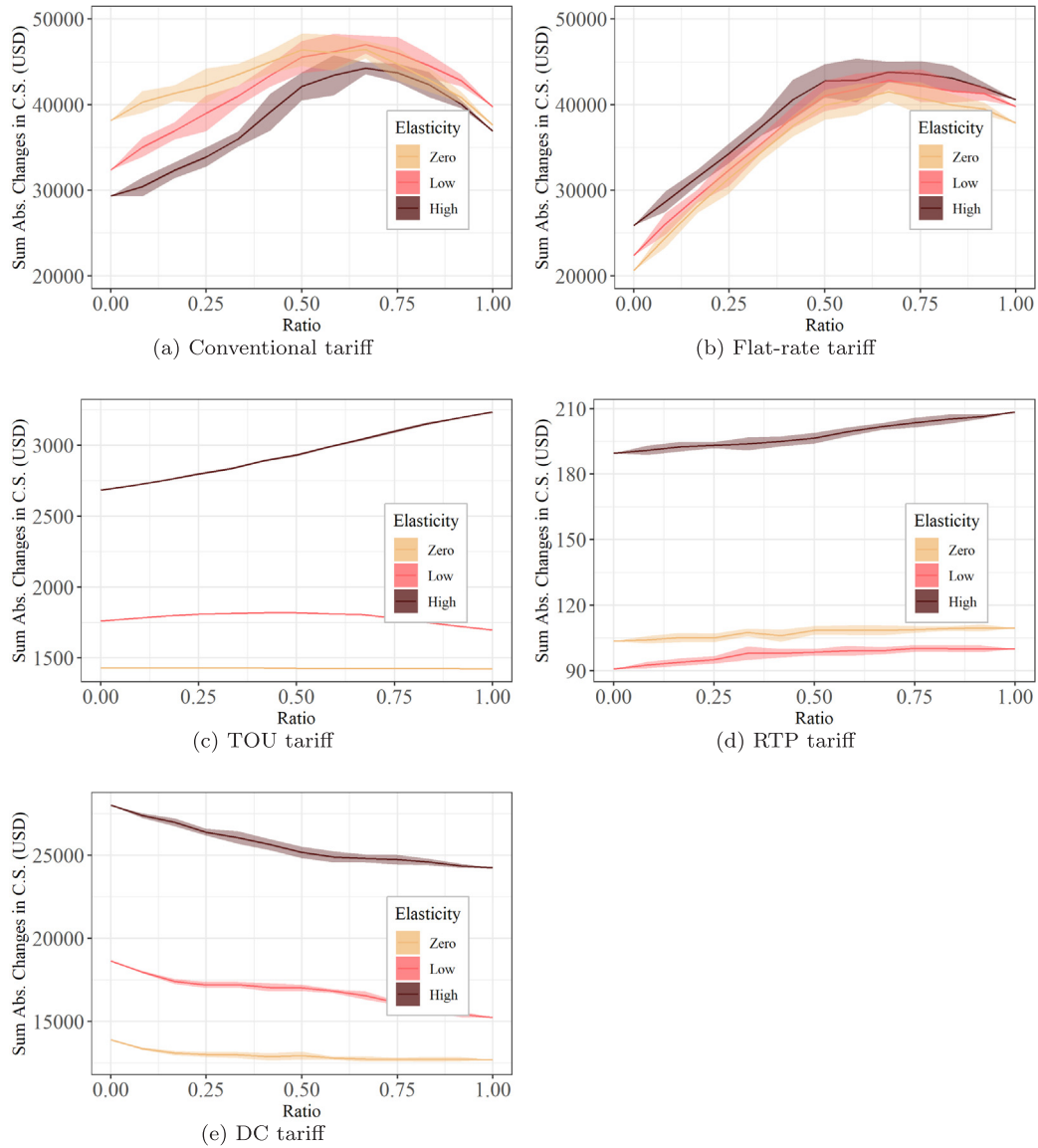
Fig. 5. Sum of absolute changes in consumer surplus per household for Conventional (a), Flat-rate (b) Time-of-Use (c), Real-time Pricing (d), and Demand Charge (e) tariffs per generation ratio (prosumer ratio). Colors show elasticity rate. Ribbons indicate one standard deviation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For the TOU and RTP tariffs, the higher price volatility (compared to the Flat-rate and Conventional tariffs) creates larger opportunities for consumption changes. Responses to changing energy prices are dependent on a household's prior use, with larger changes in consumption coming from high-consuming households, and thus also larger changes in final bills. Hence, elasticity increases the divergence in costs between high- and low-consuming households, leading to more cross-subsidization. As mentioned in the prior paragraph, capacity costs decrease as D-RES increases. As energy costs make a larger portion of the population's bills, their influence on cross-subsidies also increases. These portions are larger in a high-elasticity scenario, leading to the increasing cross-subsidies seen in Fig. 5c and d.

We next compare overall cross-subsidization changes per D-RES generation ratio between tariffs (Fig. 6). There are large differences in the sums of absolute consumer surplus changes between the various tariffs with any measure of household elasticity. We witness an order-of-magnitude difference between the RTP tariff and the TOU tariff, and between the TOU tariff and other tariffs. For example, the low elasticity scenario's (Fig. 6b) averages are $97.4, $1780, $36,500, $41,500, and $16,800 for the RTP, TOU, Flat-rate, Conventional, and DC tariffs

respectively.

Comparisons of cross-subsidization between tariffs appear to depend very little on elasticity; all three subfigures in Fig. 6 appear somewhat similar in shape. The DC tariff is an exception; its cross-subsidies are far lower than the Flat-rate and Conventional tariffs in a zero-elasticity scenario (Fig. 6a). However, when higher elasticity is considered (e.g. Fig. 6c), the former tariff's curve increases to those of the latter two tariffs. Since the DC tariff is an extension of the RTP tariff with a demand charge for capacity costs, these cross-subsidization effects (compared to the RTP tariff's lines) are entirely due to the demand charge. The distortion in observed price created by the demand charge can make the DC tariff very close to the traditional tariff designs. Hence, not considering elasticity can mask the potentially higher cross-subsidization of a DC tariff and make it appear more acceptable as a new tariff design.

To summarize, we find that each tariff shows different rates of cross-subsidization based on elasticity. The Conventional and Flat-rate tariffs generally have the highest cross-subsidization, followed by the DC, TOU, and RTP tariffs. All cross-subsidization rates appear to depend on how much D-RES is in the household population. In addition, the DC
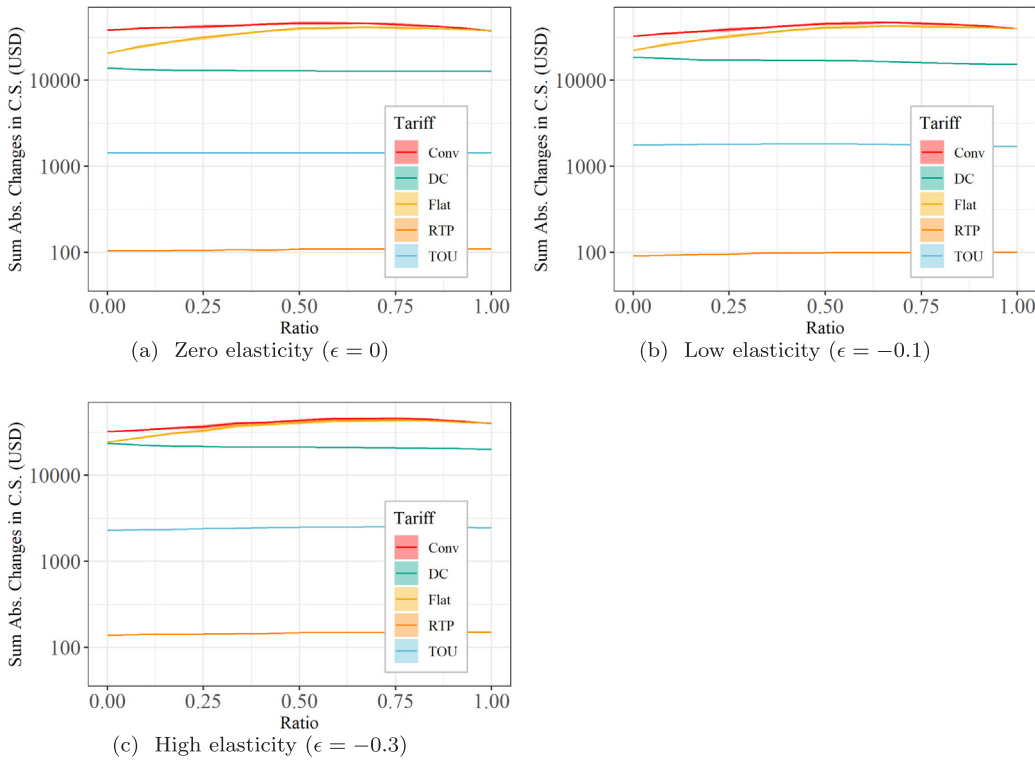
(a) Zero elasticity ($\epsilon = 0$)

(b) Low elasticity ($\epsilon = -0.1$)

(c) High elasticity ($\epsilon = -0.3$)

Fig. 6. Sum of absolute values of change in consumer surplus over all households (y axes), per generation ratio (x axes) and per tariff (colors), for zero (a), low (b), and high (c) elasticity cases. Ribbons indicate one standard deviation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tariff is particularly sensitive to changes in elasticity.

7. Economic efficiency

Economic efficiency is an important consideration in tariff design. The most efficient allocation of resources is when each marginal amount of the resource is allocated to the consumer who values it most. For a public good such as electricity, this is often ensured through having consumers pay exactly the costs of the delivered product. To summarize Borenstein [4], any deviation from this pricing creates higher use for those who have little value for the resource, or lower use for those who have high value for it. The economic loss of welfare from these deviations can be measured as dead-weight loss (detailed in Section 3). An example of deadweight loss for the TOU tariff is plotted in Fig. 7. For all tariffs, deadweight loss per household is relatively stable around median values, with some extreme cases at the high end.

Deadweight loss is strongly dependent on elasticity [30]. Hence, we check total deadweight loss rates for the low elasticity and high elasticity cases separately. We can add the deadweight loss of individual households together to find a measure of total economic efficiency losses for the entire population. This is akin to the area under the curves of Fig. 7, per generation ratio and per tariff. With low elasticity (Fig. 8a), we see similar and low numbers for the RTP and DC tariffs, and similar and high numbers for the Flat-rate and Conventional tariffs. The TOU tariff reaches a middle-ground between the two extremes. The demand charge tariff's capacity pricing does not appear to create significant deadweight loss, compared to the RTP tariff. This implies that most deadweight loss is a consequence of energy pricing, rather than capacity pricing.

Comparing total deadweight loss to total household bills paints a different picture (Fig. 9). In our low-elasticity scenario, all tariffs show an increase in deadweight loss relative to total bills. These changes are particularly drastic for the Conventional and Flat-rate tariffs. While the total deadweight loss stays the same (Fig. 8a), the total bill decreases significantly as D-RES generation increases. Consequently, deadweight loss becomes relatively larger, reaching a maximum of about 8.6%.

These trends are relatively similar in a high elasticity scenario

(Fig. 8b). The Conventional tariff's losses decrease with prosumer ratio. For the Flat-rate tariff, however, it remains comparatively similar. The TOU, RTP, and DC tariffs experience increases in deadweight loss, mainly due to the deviations in consumption patterns between high- and low-consumption households, discussed previously in Section 6. When compared to total bills, in a high-elasticity scenario we witness more significant deadweight loss (Fig. 9b). For the Conventional and Flat-rate tariffs, deadweight loss is near 10% without any D-RES. This value more than doubles as prosumers dominate the population. For the RTP and DC tariffs, changes are near zero, as in the low-elasticity scenario. The TOU tariff once again reaches a middle-ground between the two extremes.

In total, we find that the deadweight loss of the tariffs differ, some by two orders of magnitude. With low D-RES, these numbers appear low when compared against the total bills of the household population. However, we find that D-RES can significantly increase relative deadweight loss, for some tariffs by a factor of 2 or more. For higher-elasticity scenarios, deadweight loss increases significantly. Total deadweight loss is exponentially related to elasticity rate [30], but total household bills does not similarly increase. Hence, relative deadweight loss is far higher in a high-elasticity scenario. When high elasticity is considered, economic inefficiencies are far more prominent in tariff design; they appear particularly important for tariffs do not match costs with prices. More importantly, the importance appears significantly increased due to D-RES increases. Currently, household demand elasticity is believed to be low [4]. As AMI proliferates and increases demand elasticity, we can expect to see a gradual transition from lower elasticity rates to higher ones. Thus, the future holds results more similar to the high-elasticity plots rather than the low-elasticity ones.

8. Conclusions

The advent of D-RES has raised concerns about the fairness (or equity) and economic efficiency of distribution grid tariffs. Here we quantify the former as cross-subsidization and the latter as deadweight loss. Each end-user's cross-subsidies and deadweight loss depend on costs and prices, which are both dependent on two volatile factors:
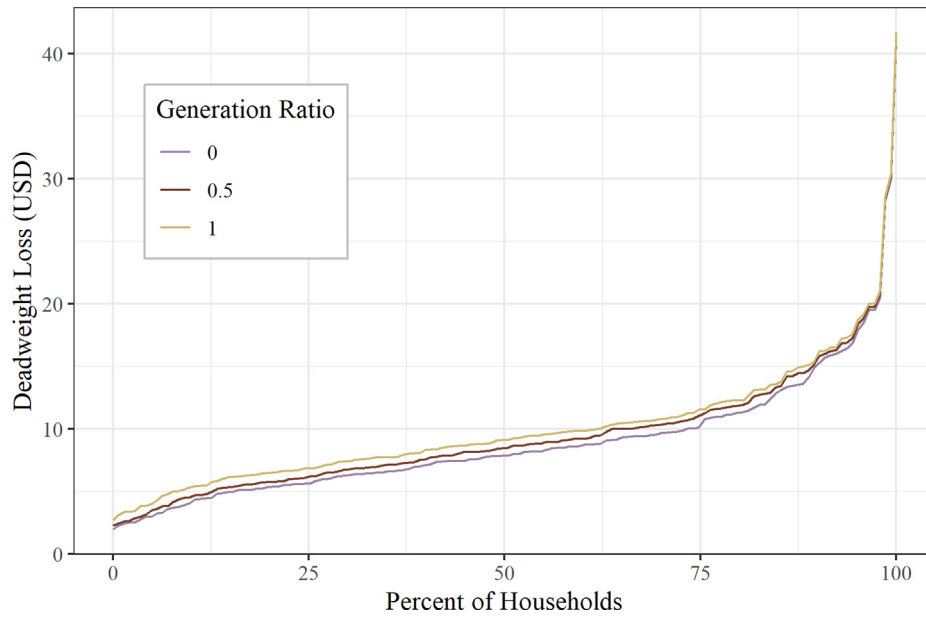
Fig. 7. Deadweight loss sorted per household (x) for 3 generation ratios (colors) for TOU tariff in low elasticity scenario ($\epsilon = -0.1$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

household consumption and D-RES generation. Time resolution for these variables significantly affects the outcomes of policy design analyses, and low resolution in data can inhibit accurate policy-making (see e.g. Hu et al. [35]). However, smart meter pilot programs in many regions have recently made high resolution (per-minute per-household) data, especially of D-RES generation, available. Our study uses such data to quantify cross-subsidization under high D-RES to a degree that was previously rare. Measuring equity accurately in this manner can lead to more accurate policy designs and pricing choices in the distribution grid, especially those with a rapid growth of D-RES.

Our analysis uses data on household consumption, D-RES generation, and pricing from Austin, TX, USA, for the year of 2016. Our choice of tariffs included the status quo (Conventional tariff, based on increasing-block pricing), the most common option (Flat-rate tariff), a common simple alternative piloted in the same region and popular in Europe (a 2-tier Time-of-Use tariff), and two common (and strongly debated) proposals for change (real-time dynamic pricing, and peak demand charges). Given data availability, our methods can be similarly applied to other regions and tariffs.

8.1. Policy implications

In our study, the flat-rate and increasing-block pricing (Conventional) tariffs show significant cross-subsidization between prosumers and consumers. These cross-subsidies are especially high when the two groups are evenly divided. Absent demand elasticity, the median loser in this trade, often a D-RES non-owner, may pay $183 per year over its fair share of costs. These funds are often transferred to solar PV owners, who tend to have higher wealth [5]; this hints at a socially regressive cost transfer. However, these effects disappear when time-of-use pricing or real-time pricing is used. An additional demand charge significantly increases cross-subsidization, but the inequity does not disproportionately favor consumers or prosumers.

Our analysis also considers scenarios where households respond to price changes with consumption changes. A population with more elasticity usually has more overall cross-subsidization, irrespective of D-RES generation amount. However, the observations from a zero-elasticity case also appear in low and high elasticity scenarios. Elasticity mostly does not change the fairness comparisons between tariffs. The notable exception is the demand charge tariff, whose cross-subsidization significantly increases in a high elasticity scenario. An analysis of fairness which ignores elasticity may misplace this tariff as a middle ground between time-invariant (e.g. flat-rate) and time-based (e.g. real-time pricing) tariffs. However, if elasticity is high, this tariff can show similar cross-subsidization values to time-invariant tariffs.

Economic efficiency also appears to differ greatly between tariffs and D-RES amounts. D-RES growth appears to worsen relative inefficiencies, especially for the Flat-rate and Conventional tariffs. Hence,
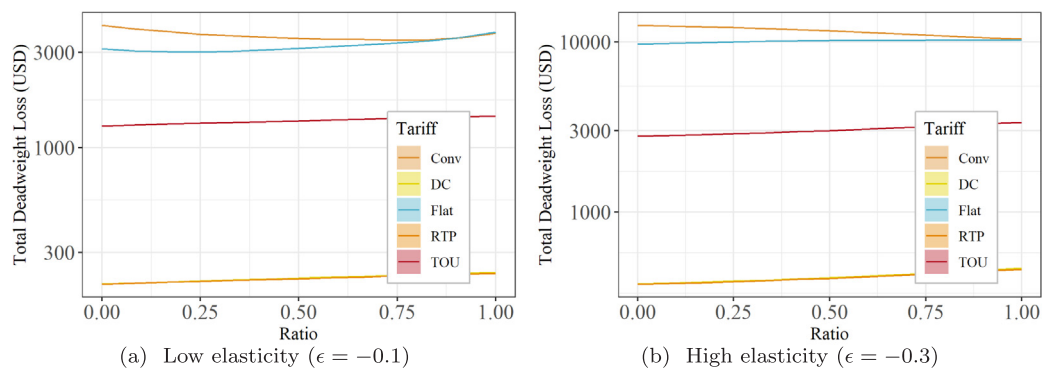

(a) Low elasticity ($\epsilon = -0.1$)

(b) High elasticity ($\epsilon = -0.3$)

Fig. 8. Total deadweight loss, per generation ratio (x) and per tariff (color). Ribbons show one standard deviation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
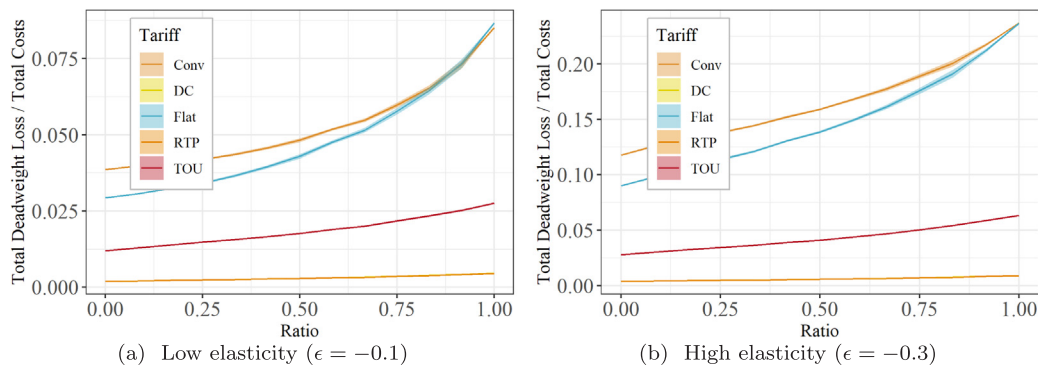
(a) Low elasticity ($\epsilon = -0.1$) (b) High elasticity ($\epsilon = -0.3$)

Fig. 9. Total deadweight loss as a ratio of total costs, per generation ratio (x) and per tariff (color). Ribbons show one standard deviation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tariff designers may become more concerned with economic efficiency as D-RES expands across its intended subscriber population. This concern is particularly sensitive to elasticity, as higher-elasticity regions are expected to show far higher economic inefficiencies. As theorized in Borenstein [4], D-RES indeed appears to significantly alter the economic efficiency of distribution network tariffs.

8.2. Limitations and future work

Our results are highly sensitive to consumption and generation patterns and electricity prices. Both datasets depend strongly on weather, household behavioral patterns, and geography. Hence, similar results can be found in regions with similar weather, households, and geography, to Austin, TX, USA. An in-depth study of cross-subsidization rates in a region with high D-RES generation but differing geographical patterns and tariffs, such as Germany, would make for excellent follow-up research. The economic inefficiencies from D-RES installations due to clean energy subsidy schemes have been hinted at in past research [5,15]. An explicit analysis of these economic inefficiencies would make a suitable complement to the economic efficiency analysis conducted here.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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