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Saunders Hall 542, 2424 Maile Way,
Honolulu, HI 96822
Phone: (808) 956 -8496
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Revenue Decoupling for Electric Utilities: Impacts on Prices and Welfare

By
Arlan Brucal
Nori Tarui

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Abstract

Revenue decoupling (RD) is a regulatory mechanism that allows adjustments of retail electricity rates so that the regulated utility recovers its required revenue despite fluctuations in its sales volume. The U.S. utility data in 2000-2012 reveals that RD is associated with more than 10% higher electricity prices in two years after RD is implemented relative to similar non-decoupled utilities—an impact significantly higher than previously thought. Theoretically, unexpected sales declines would lead to higher electricity prices while unexpected sales increases would lead to lower prices. RD adjustments have yielded both refunds and surcharges, but the data indicates that electricity prices demonstrate downward rigidity and statistically significant upward adjustments for the utilities subject to RD. Together with the likely negative impacts of RD on low-income (as opposed to high-income) households, this analysis indicates the limitations of decoupling, and fixed-cost recovery practice in general, which involves adjustments in volumetric electricity rates.

Keywords Utility regulation; revenue decoupling; electricity sector
JEL classification L94, Q41, Q48

*Brucal: Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, Houghton Street, London, UK WC2A 2AE. Email: a.z.brucal@lse.ac.uk. Tarui: Department of Economics, University of Hawaii at Manoa and University of Hawaii Economic Research Organization (UHERO), 2424 Maile Way, Saunders Hall 542, Honolulu, HI 96822. E-mail: nori@hawaii.edu.
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1 Introduction

In an effort to curb pollution externalities associated with energy use, policymakers continue to push for improved energy efficiency and distributed electricity generation. Under the traditional natural-monopoly regulation (i.e., cost-of-service or rate-of-return regulation), however, the volumetric electricity prices are set above the marginal costs and hence the profits tend to increase with the sales volume. Therefore, a utility's interest—to sell more electricity—is misaligned with the regulatory agenda of attaining energy efficiency and conservation (Eto et al., 1997). Despite such throughput incentive, the sales of electricity have not been growing over the last decade in the United States, leading to concerns that the utilities are not able to recover the full costs.

Among the potential regulatory options, revenue decoupling (RD) has emerged as an approach to help utilities overcome the disincentive to support the state's energy-efficiency agenda (Morgan, 2013). Revenue decoupling is generally defined as a rate-making mechanism designed to "decouple" the utility's revenues from its sales. By making the utility's revenue independent of sales, RD removes the utility's disincentives to promote customer efforts to reduce energy consumption or to expand distributed generation that often utilizes renewable energy (Kushler et al., 2006) .

Table 1 provides a simple illustration of how RD works.[1] Consider a scenario where the actual sales in the current year are 1 percent lower than the baseline amount of 1 million kWh. Without any revenue adjustment mechanism, this translates to about 1 percent revenue shortfall in the said year. Hence, any shock that lowers demand, be it due to energy efficiency improvement or conservation (or any exogenous income shock), results in lower equity earnings. Under RD, the (volumetric) electricity rate increases so that the required revenue is earned. RD, in effect, provides a mechanisms for customers

[1] This illustration is based on a simple full decoupling mechanism. In reality, there are a number of ways to implement RD, but the guiding mechanism is the same (i.e., except for flat distribution which will be discussed later on, all of them have a true-up mechanism that adjusts the electricity rates in order to collect the allowed revenue). For a more complete discussion of RD, see Regulatory Assistance Project (2011).

to receive refunds or pay surcharges based on whether the revenues the utility actually received from customers were greater or smaller than the revenues required to recover the fixed cost.[2]

Table 1: An example of how RD works.

	No RD in place	**RD in place**
Revenue Requirement	$115,384,615	
(Based on expenses, allowed return, taxes)		
Sales Forecast (kWh)	1,000,000,000	
Actual Sales (kWh)	990,000,000	
Unit Price ($/kWh)	0.1154	0 .1166
Decoupling Adjustment ($/kWh)	−−	0 .0012
Actual Revenue	$114,230,769	$115,384,615

Source: The Regulatory Assistance Project (RAP), 2011.

As of January 2019, 15 states and the District of Columbia have implemented RD for electric utilities.[3]

Many states implemented RD during and immediately after the U.S. financial crisis in 2000. As a growing number of states have ventured into adopting policies and regulations with energy efficiency objectives, debates on the effectiveness of revenue decoupling emerged. Conservation advocates argue that RD can enhance generation and distribution efficiency by providing utilities the incentives to reduce costs and not through increase in sales (Regulatory Assistance Project, 2011; Sullivan et al., 2011). They also argue that RD is necessary, if not sufficient, for utilities to promote energy efficiency and/or invest in renewables (Costello, 2006; Lowry and Makos, 2010). RD improves a utility's financial situation and lowers risks, thus can potentially reduce the cost of capital (Costello, 2006). RD is considered to be less contentious, and hence less costly to set rates and conduct cost recovery, than the Loss Revenue Adjustment (LRA). Other policies includ-

[2]Note, however, that the difference can occur for many reasons, including weather and economic conditions that are not entirely within the control of the customers nor the utility. In this context, it is apparent that RD insulates the utility from business risks that are now absorbed by the customers (Moskovitz et al., 1992).

[3]The data is from https://www.nrdc.org/resources/gas-and-electric-decoupling, retrieved on October 8, 2019.

ing LRA requires sophisticated measurement and/or estimation. Moreover, it is easier for state commissions to administer/monitor as opposed to other alternatives (Costello, 2006; Lowry and Makos, 2010; Moskovitz et al., 1992; Shirley and Taylor, 2006). Recent studies find that the utilities under RD are associated with higher expenditure on demand-side management, indicating larger efforts on energy efficiency improvements (Kahn-Lang, 2016; Datta, 2019).

Critics of RD, on the other hand, argue that the policy is a blunt instrument to promote energy efficiency, particularly on the part of the utility. Because utilities must rebate the difference between price and costs to consumers, they no longer have an incentive to minimize costs under RD (Kihm, 2009). Knittel (2002), for example, showed that RD is not effective in influencing utilities to improve generation efficiency because they do not receive significant economic gains from producing energy more efficiently. Moreover, critics suggest that the policy not only transfers the business risks from the utility to the customers but also may cause customers in one rate class to absorb some of the impact of demand downturns in another class (Lowry and Makos, 2010). Residential electric bills, for instance, may increase due to a downturn in industrial demand.

Despite the controversies, little work has been done to provide clear evidence regarding the effects of RD on electricity prices and, in general, economic welfare.[4] One of the potential consequences of RD, given the trend that electricity sales are not growing in many states, is the increase in retail electricity rates. Previous studies on the effects of RD on electricity rates argue that the associated change in electricity rates have been negligible (Morgan, 2013; Kahn-Lang, 2016). In the U.S. between 2005 and 2012, 23% of the recorded 1,244 RD adjustment cases involve retail rate adjustments between 0 and 1 percent, and more than half of the cases are within the 0-3% range (Morgan, 2013). A caveat

[4]While there exists useful discussions on the performance of RD from various perspectives (Knittel, 2002; Brennan, 2010; Kihm, 2009; Chu and Sappington, 2013), none focused on how decoupling works in the presence of subsidies for distributed generation or the effects of RD on electricity prices and welfare. Comprehensive technical reports and anecdotal evidence are available (Regulatory Assistance Project, 2011; Morgan, 2013); however, they present divergent views more than clear guiding principles on the potential impact of RD.

about this observation is that it captures only the immediate decoupling adjustment similar to the one presented in Table 1. Changes in electricity prices may affect energy users' incentives to invest in energy efficiency improvement (such as efficient appliances or solar panels), which generate feedback effects on the demand for electricity and thus opportunities for further RD adjustments. Thus RD may induce not only immediate electricity rate changes but rate changes over time.

Can we compare electricity prices over time in states with and without RD? Care must be taken because the states and utilities with and without RD may have different economic characteristics, which might explain some of the differences in the prices. In this study, we compare treated investor-owned utilities (those under RD mechanism) with control-group utilities (those that are not subject to RD)[5] with otherwise similar characteristics to assess the impact of RD on residential electricity rates. Our study design examines utility companies in 17 states that had implemented RD mechanism over the 2000-2012 period and compares their monthly electricity rates with control utilities before and after the RD implementation. We find that decoupling tends to increase the electricity rates rather substantially over months upon implementation, i.e., about 9% on average and about 19% after two years. Using a formal economic model that allows for comparison between RD and non-RD regimes, we provide insights on the potential mechanism behind the observed price effect and policy implications on key issues surrounding residential electricity consumption.

In what follows, we provide an empirical evidence of the effect of decoupling on residential rates in Section 2. To explain the potential mechanism and the implications of decoupling on residential energy use and consumer welfare, we apply a simple theoretical framework in Section 3. Section 4 provides a summary and discussion of the policy implications.

[5] We define a utility as an investor-owned electric service provider operating in a particular state, which means that utilities operating in two or more states are treated as unique utilities.

2 Empirical Investigation

2.1 Data

Here we first investigate how revenue decoupling has influenced the electricity prices that consumers face in the United States. To do this, we use US EIA monthly data for the period covering January 2000 - November 2012 on about 160 unique investor-owned utilities to investigate how RD influenced electricity rates. We drop utilities in California from the sample because decoupling was adopted in the state prior to 2010, the beginning of the sample period. The data contain information about the utilities' sales (in kWh), revenues, and the average electricity prices by end-use sector. We combine the EIA data with information about the timing of revenue decoupling implementation by utilities using data from a previous study (Kahn-Lang, 2016). Table 2 presents the descriptive statistics of the sample.

In Table 2, we observe that the utilities that experienced decoupling have higher average prices than those without decoupling. This observation applies to all sectors (i.e. residential, commercial, and industrial), although the difference is highest amongst residential customers. Decoupled utilities have higher sales, except for commercial customers, and higher revenues for all customers.

By simply comparing utilities that were decoupled during the sample period with those that remained non-decoupled, we observed significant divergence in the average residential electricity rates as more utilities get decoupled over time (see Figure 1). Towards the end of 2012, average monthly electricity rates from decoupled utilities increased to \$0.19/kWh, which is significantly higher than the average for non-decoupled utilities (about \$0.12/kWh). This translates to about a \$70 increase in monthly electric bill for an average electric customer, more than 30-fold adjustments compared to the previous estimate of \$2.30 per month.[6] The result holds even if we use nominal prices. In the next

[6]This calculation assumes an average monthly consumption of 1,000kWh, following a previous study that assessed the effect of RD implementation on electricity ratesMorgan (2013).

section, we subject our findings to more robust analyses.

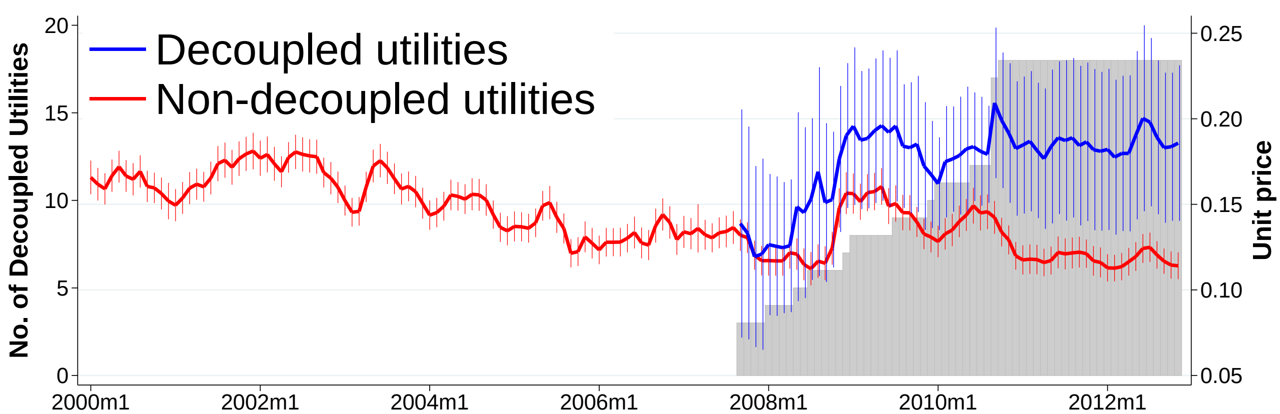
Table 2: Summary Statistics

	Not Decoupled			Decoupled		
	Obs	**Mean**	**SD**	**Obs**	**Mean**	**SD**
Prices ($/kWh)						
Residential	26529	0.10	0.05	2604	0.15	0.08
Commercial	25033	0.09	2.36	2602	0.13	1.20
Industrial	26552	0.09	0.06	2604	0.13	0.07
Total	27076	0.10	1.92	2604	0.13	0.07
No. of unique State-Utilities			192			17
Years			2000-2012			2000-2012

Note: Decoupled utilities are those in a particular state that had adopted RD, which means that the values include pre- and post-RD regime. Non-decoupled utilities are those that had not adopted RD during the sample period.
Source: U.S. Energy Information Administration.

Figure 1: Effect of implementing Revenue Decoupling

(a) Average monthly electricity prices of decoupled and non-decoupled utilities



The curves represent the estimated average electricity price in $/kWh (right axis), with vertical lines indicating the 95% confidence interval. The shaded vertical bars correspond to the number of decoupled utilities (left axis). All prices are deflated using consumer price index.

2.2 Empirical Strategy

Our empirical analysis to identify the effect of revenue decoupling on electricity prices consists of three features. First, we focus on the change from non-RD to RD regime within the same utility operating in a particular state.[7] In particular, we consider utilities that are observed at least 12 months prior to the adoption of RD and 24 months thereafter. By focusing on within state-utility changes we are able to account for the effect of unobserved individual characteristics across utilities that may bias our estimates.

Second, we use difference-in-difference approach (hereafter referred to as DD) to compare electricity prices of decoupled utilities with those that remain in old rate-making schemes. The association between policy changes and subsequent outcomes are easily assessed using pre-post comparisons. This design is valid only if there are no underlying time-dependent trends in outcomes that are correlated to the policy change. In our case, if electricity prices were already increasing even before the implementation of RD, perhaps due to idiosyncractic shocks influencing electricity demand among affected households, then using pre-post study would lead to biased estimates and potentially erroneous association of the change to the implementation of RD. The DD approach solves this issue by taking into account initial difference in prices between decoupled and non-decoupled before the adoption of RD, and the difference in prices between the two groups after the policy adoption, thus implicitly taking into account unobserved factors that may affect prices faced by the treatment or the control group.

Our estimating equation is provided below:

$$p_{it} = \alpha_i + \beta_t + \gamma Post_{it} + \delta RD_{it} + \varepsilon_{it}, \tag{1}$$

where p_{it} is the electricity price charged by utility i in period (month-year) t, $Post$ is equal to 1 when the matched utilities are in the post-RD regime and 0 otherwise, and RD_{it}

[7] We define a utility as an investor-owned electric service provider operating in a particular state, which means that utilities operating in two or more states are treated as unique utilities.

is a dummy variable that turns to unity when a utility starts to implement decoupling. Coefficients α and β represent utility-state and time fixed effects, respectively, to account for the unobserved utility-state characteristics and month-year specific shocks that are common to all utilities (e.g. macroeconomic shocks). The error term ε is assumed to be i.i.d. Coefficient δ measures the effect of implementing RD on the outcome variable.

One major issue in employing DD is that the estimate of δ could be biased if the control and treatment groups have different pre-treatment characteristics (Dehejia and Wahba, 2002). In our context, this can happen if utilities suffering from a decline in sales, possibly due to increased share in distributed generation or improved energy efficiency among customers, lobby for RD implementation. To minimize this concern, for each utility in the treatment group, we identify a control utility of similar electricity price trends (measured in log difference between the electricity price a month before and 6 months before) and is operating in the same time period. This procedure allows us to ensure that the matched utilities most likely faced the same macroeconomic conditions and price trends before RD is adopted. This approach, however, reduces our sample significantly. Fortunately, the number of utility-month-year observations are large enough to generate results with confidence.

We assess the performance of our matching procedure by comparing the sample means of the variables used in the matching of treatment and control groups (see Table 3). We find no statistically significant difference in the pre-RD period for the variables that were used in matching, suggesting that our matched sample exhibit parallel pre-treatment trends in prices. Moreover, we also find no statistically significant difference between the means of the two groups for other variables that were not used in the matching (except that residential revenues are different with marginal significance). Thus our procedure is not subject to potential bias associated with selection on unobservables that affect both assigning of treatment and outcome of interest.

After obtaining the matched pairs, we examine the effect of adopting RD on electricity

Table 3: Balancing test of matched RD and non-RD utilities.

	Unconditional Mean		
	nonRD	**RD**	**p-value**
Pre-RD Prices (in $/kWh)	0.15	0.17	0.597
Pre-RD Price Trend	0.080	-0.010	0.179
Pre-RD Sales (in GWh)	832.28	444.15	0.132
Pre-RD Sales Trend	0.17	0.13	0.527
Pre-RD Revenues (in million $)	119.89	59.56	0.074
Pre-RD Revenue Trend	0.20	0.11	0.255

Notes: Figures reflect the unconditional means of variables for the residential sector for the matched RD and non-RD utilities during the month before they adopted RD, unless otherwise stated. Trends are measured in log difference. p-values are for testing the statistical significance of the mean difference between the two groups.
Source: U.S. Energy Information Administration.

prices using the DD approach (equation 1). More specifically, we estimate the following equation on the matched sample:

2.3 OLS Results

Before we proceed to our results based on our matched sample, we perform a simple OLS regression on the unmatched sample. In this procedure, we ignore potential bias associated with self-selection of utilities to the policy and just controlling for utility- and time-fixed effects. The results, as presented in Table 4, show that residential customers experienced an increase in electricity rates following the utility's adoption of revenue decoupling. in particular, we find an average increase of about 9% in residential electricity prices associated with RD implementation. The estimates are very similar whether we use nominal prices or real prices. The estimated increases in prices are significantly larger than what the previous studies find, which are based only on the size of the actual RD adjustment (Morgan, 2013).

Table 4: The effect of adopting RD on prices, unmatched sample.

	Price (real)		Price (real)	
	Log-transformed	Levels	Log-transformed	Levels
(RD=1)	0.09 **	0.01 *	0.09 **	0.02 ***
	(0.022)	(0.059)	(0.022)	(0.002)
R-sq. (adj.)	0.49	0.40	0.51	0.39
Obs	28877	28953	28877	28953
Time Fixed Effects	yes	yes	yes	yes
Utiliy-State Fixed Effects	yes	yes	yes	yes

Note: The table shows the result of estimating equation 1 on the unmatched sample. Each column in each panel is a separate regression for a particular outcome variable. *, **, *** indicate statistical significance at 0.10, 0.05, and 0.01 level, respectively.

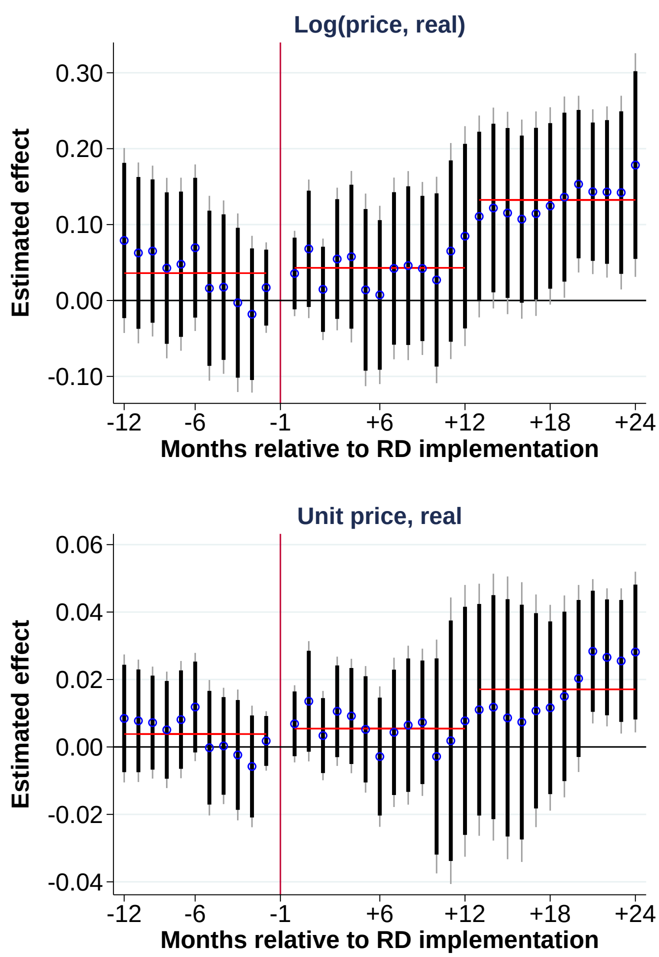
2.4 Results from propensity score matching combined with difference-in-differences

A major issue about the estimated effect presented above is the likelihood that utilities that become subject to RD may be systematically different from average utilities in the US. For example, a state in which utilities experience declining sales due to more aggressive environmental policies may be more inclined to implement RD in order for the utilities to recover their fixed costs. Thus simply comparing decoupled and non-decoupled utilities may lead to selection bias.

To account for this potential bias in the estimated effect, we compare treated (i.e., decoupled) utilities with those control utilities in the same year-month that had almost identical level and trend in their real prices (in $/kWh) and sales (in MWh) over the 12-month period prior to the implementation of RD. The argument is that in the absence of the policy change, the treated and the control utilities would have behaved similarly, and that any change in the outcome variables for all treated utilities is attributed to the policy change. This procedure generates slightly lower and statistically insignificant estimates.

As we explain the mechanism below, RD may have persistent effects on the electricity prices beyond the immediate impacts due to rate adjustments. To test the hypothesis that RD impacts may persist over months, we reformulated our method by looking at the differences between the control and the treated groups in each time period, after RD implementation, while maintaining to account for time-invariant utility-specific characteristics. The results, as illustrated in Figure 2,[8] confirm our hypothesis that the effect grows over time, reaching to about 18% two years after the implementation of RD.

Figure 2: Estimated effect of implementing RD, matched sample



Notes: Estimated effects (blue dots - estimated effect relative to 1 month before the RD implementation; thick black vertical lines -90% confidence interval (CI); thin gray vertical lines - 95% CI; horizontal red line - yearly average effect).
Nominal prices are deflated using consumer price index.

[8]Detailed results are presented in Table F.1

2.5 Asymmetric price responses to unexpected changes in sales

Decoupling as a mechanism is supposed to work symmetrically over unexpected increases in sales (that should result in downward price adjustments) and unexpected decreases in sales (that should result in upward price adjustments). Morgan (2013) reports that both downward and upward price adjustments have been observed. Here we test whether decoupling works symmetrically in events of unexpected changes in sales.

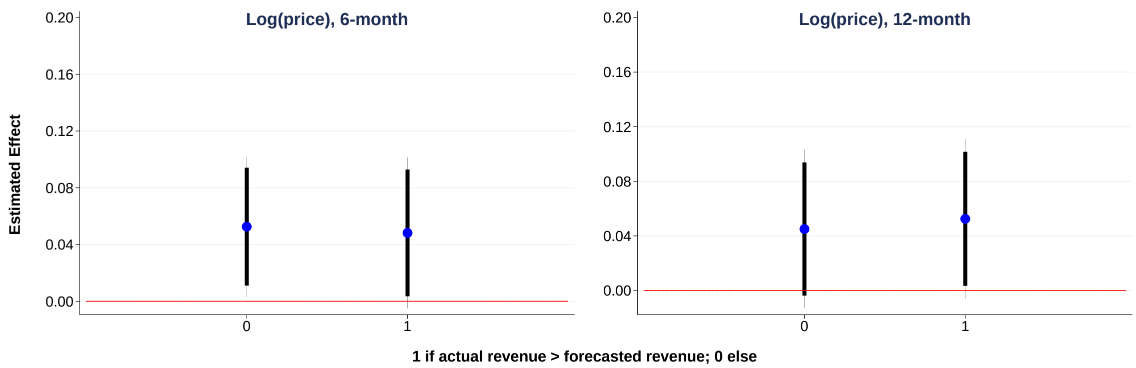
We do not have direct observations on the revenue requirements of each utility. To come up with a proxy for unexpected changes in sales, we first calculated the average growth rate of the relevant prices over the previous 12 months. We then compare the calculated growth rates with those of the previous two months. Afterwards, we generate an indicator variable that turns to unity when the growth rate in the previous 2 months is higher than the rate over the last 12 months. In other words, our indicator variable turns on when the actual demand growth is higher than projected.

We then re-estimated equation 1 but this time with additional controls: the above indicator variable and its interaction with our RD dummy. If RD works symmetrically, we would expect that the sign of the interaction term would be negative and statistically significant. That is, utilities are expected to provide rebates to consumers in the form of lower power rates when actual demand exceeds the projected.

The results are presented in Figure 3[9]. We have two remarkable observations. First, the difference in the estimated effect between those that had higher-than-projected sales growth and those that had lower-than-projected sales growth is very minimal and statistically insignificant. Second, the estimated effect is still positive even for those that had higher-than-projected sales growth. This implies that, at least, utilities experiencing unanticipated sales growth would not have price reductions. Furthermore, there seems to be downward rigidity in electricity prices during periods of unanticipated sales growth such that the customers would still pay higher prices than those who are served by non-

[9]Detailed results are presented in Table **??**

Figure 3: Asymmetric price impact of RD, matched sample



Notes: Estimated effects (blue dots - estimated effect relative to 1 month before the RD implementation; thick black vertical lines -90% confidence interval (CI); thin gray vertical lines - 95% CI). Forecasted revenue is defined as the difference in log-transformed prices between 6 months and 1 month prior to RD; actual revenue is the difference in log-transformed prices between 2 months and 1 month prior to RD. Nominal prices are deflated using consumer price index.

decoupled utilities.

3 Effects of Revenue Decoupling: Theoretical Results

Having established that residential prices had increased after utilities adopted revenue decoupling, we explain in this section a formal economic model to characterize the mechanism behind the estimated effect. We first outline the framework of the model followed by an analysis on the potential effect of revenue decoupling on retail price and welfare.

3.1 Theoretical Framework

3.1.1 Consumers

There is a continuum of consumers of measure $N > 0$. Let u_i be consumer i's utility function. Given total electricity consumption e_i and the consumption of numeraire good y_i, the utility is $u_i(e_i, y_i) = v_i(e_i) + y_i$ where $v_i' > 0$ and $v_i'' < 0$.[10] This specification, with

[10] In a later section, we discuss an extension where electricity generation imposes negative externalities on consumers.

zero income elasticity of electricity demand, could be justified in light of some recent empirical findings of zero or very small income elasticity.[11]

Each household chooses how much electricity to purchase from the utility $x_i \geq 0$ and whether to purchase a solar PV ($d_i = 1$) or not ($d_i = 0$). Upon installing a solar PV, household i's solar output is given by $g_i \geq 0$. We abstract from hourly, day-to-day, and seasonal variations in load profiles as well as intermittency of solar electricity outputs. We thus assume grid-supplied electricity (x_i) and electricity from distributed sources (g_i) are perfect substitutes: $e_i = x_i + d_i g_i$. Existence of provisions such as net energy metering might imply that they are indeed almost perfectly substitutable. As long as they are close substitutes, the main arguments of this paper would be valid.

We also assume there is no peak-load pricing and consumers face a simple two-part tariff, with a unit volumetric electricity rate $p > 0$ and a fixed payment $f > 0$. Household i maximizes its utility subject to a budget constraint $px_i + f + qd_i + y_i \leq m_i$, where $m_i > 0$ is household i's income and q the (rental) price of a solar panel.[12] The income consists of wage income (where labor endowment is fixed and its supply is assumed to be inelastic) and the household's share of the electric utility's profits. Thus, household i's objective function is given by

$$\max_{x_i \geq 0, d_i \in \{0,1\}} v_i(x_i + d_i g_i) + y_i$$

$$\text{s.t.} \quad px_i + f + qd_i + y_i \leq m_i.$$

The first order condition for utility maximization is given by

$$v_i'(x_i + d_i g_i) = p, \quad d_i = 1 \quad \text{if } g_i \geq q/p, \quad d_i = 0 \quad \text{if } g_i < q/p.$$

Now suppose that households are ordered in terms of PV output: $g_i > g_j$ for all $i, j \in$

[11] Reiss and White (2005) estimate the income elasticity for California households to be between -0.01 and +0.02.

[12] If x_i represents the annual electricity consumption, then q represents the annual rental price of a solar panel.

$[0, N]$ such that $i < j$. Let $h(n)$ be the total solar output when households 0 to n install solar panels:

$$h(n) \equiv \int_0^n g_i di \quad \text{(and hence } g_n = h'(n)\text{).}$$

Then all households i with $c_i \geq q/p$ install solar panels and the rest do not.

Now, let

$$v(e) = \max_{(e_i)_{0 \leq i \leq N}} \int_0^N v_i(e_i) di \quad \text{s.t.} \quad \int_0^N e_i \leq e.$$

By construction, v is concave with $v' > 0, v'' < 0$. The consumers' utility-maximizing choice satisfies

$$\int_0^N \{v_i(e_i) + y_i\} di = v(e) + M - fN - p(e - h(n)) - qn,$$

where $M \equiv \int_0^N m_i di$, $v'(X) = p$ and $h'(n) = g_n = q/p$. Therefore, maximizing v subject to an aggregate budget constraint $px + qn + y \leq M$ yields the households' utility-maximizing allocation given p, q. The first-order condition is given by

$$v'(e) = v'(x + h(n)) = p; \tag{2}$$

$$h'(n) = \frac{q}{p}. \tag{3}$$

Solving these conditions for x and n yields the demand for grid-supplied electricity, $x(p, q)$, and the demand for solar panels, $n(p, q)$, given the prices p, q.

3.1.2 Electric Utility

Let $F > 0$ be the fixed cost of providing electricity services (fixed and given at least in the short run). Though not essential for the analysis, assume that the marginal cost $c > 0$ is constant. Thus the utility's service is subject to increasing returns to scale. The utility's profit can then be expressed as

$$\pi = px + Nf - cx - F.$$

3.1.3 Supply of solar panels

We assume that production of solar panels exhibits constant returns to scale and that the solar panels are supplied competitively. We could imagine a small open economy, with a limited option for trading electricity internationally, which faces a constant price of solar panels q.

3.1.4 Regulation with and without decoupling

We consider two regulatory regimes: (1) traditional rate of return regulation with no revenue decoupling (no RD); and (2) the RD regime. With no RD, the electricity price is held fixed between rate cases[13].

Under RD, the electricity price is allowed to change for the utility to earn a fixed, pre-approved level of revenue. We assume that the number of customers N, as well as the fixed fee per customer, f is fixed throughout the analysis. In many cases, the fixed payment is much smaller than the fixed cost of operating the utility. With F redefined appropriately, the rest of the analysis assumes away the presence of the term Nf.[14]

Under the traditional rate-of-return utility regulation, electricity rates are fixed in the short run at the levels approved by the public utilities commissions (Joskow, 1974).[15] We can write the regulatory constraint as some fixed price that includes the maximum allow-

[13]Electricity rates are held constant fixed between rate cases, where the utility files before the public utility commission (PUC) for rate adjustments usually due to changes in operating and maintenance costs of electric distribution.

[14]Our focus is on residential electricity markets. We abstract away from electricity markets for industry and commercial sectors, and cross-subsidization across sectors in electricity pricing—issues to be investigated in future studies.

[15]Fuel cost adjustments are allowed between rate cases for many utilities, where the rates are adjusted upon short-term fluctuations in the fuel prices.

able mark-up over incurred production costs, $\bar{p}$:

$$\bar{p} \leq (1+\alpha)AC = (1+\alpha)\frac{F+cx}{x}.$$

The utility's profit is thus given by

$$\pi = \bar{p}x(\bar{p}, q) - cx(\bar{p}, q) - F.$$

We assume that $\bar{p} > c$ throughout the analysis. This is based on the observation that the volumetric electricity rates tend to exceed the marginal cost of electricity, and that the monthly fixed fees for residential electricity are not sufficient to cover the fixed cost of electricity services (Friedman, 2011). The same has been observed in residential natural gas markets (Borenstein and Davis, 2012).

While some RD methods include an explicit procedure for changing the level of authorized revenue during years between rate cases, we will only focus on the balancing accounts that guarantee the exact collection of a fixed authorized revenue for a given time period.

Let $\bar{R}$ be the revenue level associated with the initial price level and equilibrium level of x. In this case the electric rate is adjusted so that the revenue is balanced when demand changes: $\bar{R} = px(p, q)$. We can therefore write the utility's profit as

$$\pi = \bar{R} - cx(p, q) - F.$$

In this representation of an equilibrium between rate cases, the decision of the producer is limited: given p, q, it supplies output $x(p, q)$.

3.2 Effects of revenue decoupling

Here we study the effect of an exogenous change in the price (or the cost) of solar panels q.[16] This indicates what would happen to household electricity consumption and welfare when PV penetration increases as a result of lower costs of PV. We first compare the impacts on electricity price and quantity with and without revenue decoupling to highlight the potential mechanism at play in relation to the observed increase in retail prices. We then assess their implications on consumer welfare.

3.2.1 Effects on electricity price and quantity

With no revenue decoupling, the equilibrium condition is given by equations (2) and (3). With revenue decoupling in place, the necessary and sufficient condition for an (interior) equilibrium is given by (2) and (3) with $px - \bar{R} = 0$. Total differentiation of the equilibrium conditions in the two cases yield the following proposition about the effect of a decrease in the cost of solar panels on the equilibrium price and quantity of grid-supplied electricity.

Proposition 1 *Without RD, a decrease in the cost of solar panels reduces the equilibrium electricity sales. With RD, a decrease in the cost of solar panels reduces the equilibrium electricity sales, and increases the electricity price, if and only if the demand for electricity is inelastic (i.e., the price elasticity is less than one in absolute value).*[17]

Total differentiation of (2) and (3) yields

$$v''(x + h(n))dx + v''(x + h(n))h'(n)dn = 0; \tag{4}$$

$$h''(n)dn = \frac{1}{p}dq. \tag{5}$$

[16] Between rate cases, the equilibrium outcome is the same with or without revenue decoupling as long as the utility's sales volume (x) is the same. Differences arise when the sales change.

[17] Details of the proof is presented in –.

From (9), we have $\frac{dn}{dq} = \frac{1}{ph''(n)} < 0$. Substitute this into (8) and we obtain

$$v''(x + h(n))\frac{dx}{dq} + v''(x + h(n))h'(n)\frac{1}{ph''(n)} = 0. \tag{6}$$

It follows that

$$\frac{dx_{noRD}}{dq} = -\frac{h'(n)}{ph''(n)} > 0, \tag{7}$$

which implies that, under the traditional rate-of-return regulation, any decrease in the cost of solar panels reduces the equilibrium output of grid-supplied electricity.

Next we consider the case with RD. Totally differentiate the system (with respect to endogenous variables x, n, p and an exogenous variable q) and yiels a similar comparative statics on p:

$$\frac{dp_{RD}}{dq} = \frac{-v'v''h'}{D} = -\frac{p}{x}\frac{dx}{dq}\begin{cases} < 0 & \text{if } |\eta_x| < 1; \\ \geq 0 & \text{if } |\eta_x| \geq 1. \end{cases}$$

Therefore, in the empirically relevant case with inelastic electricity demand, the grid-supplied electricity consumption decreases, and the price p increases, as q drops.

To explain how RD impacts electricity prices upon unexpected changes in the sales of electricity, it is useful to consider the demand for electricity as well as the supply and the demand of investment in energy efficiency (such as energy-efficient appliances and solar panels). Suppose that there is a supply shock to energy-efficiency investment due to technological innovation (lowering the costs) or policies to encourage such investment (increasing the demand). The induced increase in energy-efficiency investment reduces the demand for electricity. Without RD, the price would stay at the initial level. With RD, the retail electricity price is adjusted upwards (as long as the price elasticity of demand is less than one in absolute value). This is the immediate price impact of RD. However, the increase in electricity price raises the demand for energy efficiency. This secondary impact shifts the demand for electricity further, thereby raising the electricity price further under RD. This explains the positive effect of RD on electricity prices over months after RD implementation (Figure 1).

4 Discussion

Several U.S. states adopted revenue decoupling as one of the many policy measures to provide utilities with incentives to invest in energy efficiency and conservation. Whether decoupling improves efficiency of the electricity sector has been a subject of debate (Kihm, 2009; Brennan, 2010; Morgan, 2013), but few studies have investigated the policy's welfare property theoretically and empirically. By combining the empirical evidence with a formal economic model, we demonstrate below the potential welfare consequences of RD as it links with several pressing welfare issues in the US residential electricity consumption. The detailed theoretical exposition is found in Appendices.

Effect when combined with increased subsidies for distributed generation or energy efficiency. The United States government provides federal tax credits for consumer energy efficiency including investment in solar panels. Many U.S. states also offer state-level tax credits for installing solar panels. For qualified households, these tax credits work as a subsidy for installing solar panels. We examined how the adoption of RD impacts households when the implied subsidies increased. Our model reveals that RD amplifies the negative welfare impact of solar subsidies (see Appendix B) through an increase in the unit price of electricity distributed through the grid and the corresponding consumer adjustments for grid-supplied electricity. Under the non-RD regime, an increase in the amount of subsidy, say for solar panels, will create (1) excess burden for a subsidy (called the 'primary welfare effect' (Goulder and Williams, 2003)) and (2) the 'electricity mark up effect', which is an extra distortion on the use of grid-supplied electricity when price exceeds the marginal costs. Both of these distortionary effects are exacerbated under the RD regime.

Potential Distributional Effect. We also examined how the adoption of revenue decoupling impacts households with and without distributed generation (or solar panels, Supplementary Section Appendix D). We find that RD will unambiguously benefit those high-income households that can afford to install capital-intensive solar panels and energy efficiency, but adversely affect low-income households that do not. Given inelastic demand for electricity, low-income and presumably credit-constrained households would be adversely affected by the increase in price. This finding is in line with earlier studies that find policies that reduce the cost of solar panels, including production subsidies and tax credits, are generally regressive.**??**

Precise welfare expressions would include the share of profits of the utility for each consumer. Because the profit is increasing in a drop in the cost of solar panels or energy efficiency and in the subsidy under RD, this consideration tends to increase the welfare impacts on those with solar panels, and may alleviate the negative welfare impacts on those without solar panels.

Effect of Uncertainty. We consider uncertainty regarding output from solar panels in order to examine how the associated risk is shared between consumers and the utility under the alternative regulation (Appendix E). We find that, without RD, any increase in the degree of uncertainty regarding output from solar panels will not change the utility's equilibrium profits nor the consumers' equilibrium expected utility. With RD in place, an increase in the degree of uncertainty will result in an increase in the expected profits of the utility and a decrease in consumers' equilibrium expected utility. Taken together, the results imply that the demand-based risk burden shifts from the utility to the consumers when RD is in place.

Potential welfare effects. Economic efficiency, which incorporates the pollution externalities of electricity generation, implies that the retail prices should be set equal to the social marginal cost (SMC) of electricity services. Increases in electricity prices would lead to lower consumer surplus, but whether it induces negative welfare impacts is not clear once we take into account negative externalities associated with utility-scale electricity generation (damages due to emissions of CO_2 and other air pollution from fossil fuel combustion). On the one hand, under conventional pricing, the electricity price tends to exceed the (private) marginal costs of electricity generation. As discussed earlier, this implies that RD amplifies the distortionary impacts of above-marginal-cost pricing. On the other hand, if the social marginal costs (i.e., including the marginal external costs of electricity generation based on fossil fuel) exceed the retail electricity price, then a price increase due to RD would make the price closer to SMC and generate positive welfare impacts.

A recent paper by Bushnell and Borenstein**?** reveals that, in most of the states that have adopted RD, the marginal price exceeds SMC. To the extent that the price-SMC relationship does not change significantly in the period 2000-2012, this finding indicates that RD tends to generate negative welfare impacts for most states that implemented this policy. This is particularly true for states like California, New York, and Massachusetts where electricity prices exceed SMC. Over time, the grids can become more efficient and cleaner across states. Coupled with RD, these additional investments may necessitate further increases in prices. Therefore, such changes in the grids may magnify the negative welfare effects of RD.

Moving forward: Flat Distribution. The empirical evidence and the policy insights presented above suggest that the current design of RD for electric utilities is not the ideal policy provision to enhance efficiency of the electricity sector nor resort to more renewable energy in the form of distributed power. The question remains: what alternatives would be more efficient while aligning electricity utilities' incentives with societal goals?

There are two main types of designing RD for public utilities. The first one, which is discussed here, applies frequent true-ups on volumetric rates to ensure that the utility's actual revenue is equal to its revenue requirement. The second one, called the straight-fixed variable (SFV) rate design, sets fixed charges (such as the monthly customer charge) to recover the full fixed costs of service delivery while variable costs are recovered through variable charges. At the moment, the second type of RD is more common in natural gas than in electric utilities (Lazar, 2015).

Covering revenue shortfalls through the SFV does not come without costs. These costs include the potential increase in consumption with lower volumetric charges and possible distributional concerns when low-earning households would pay fixed monthly charges similar to high-income earners. While our analysis does not promote the use of fixed cost to cover the entire revenue shortfall, we argue, based on the evidence presented above, that fixed charges can be used to cover at least part of the shortfall. Doing so may prevent electricity prices to be so high to increase distortions in the markets for electricity and energy efficiency.

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Supplementary Notes

(for Online Publication)

Appendix A Effects of changes in the cost of solar panels

Effect on equilibrium price and quantity (Proof of Proposition 1)

Proof. Total differentiation of (2) and (3) yields

$$v''(x+h(n))dx + v''(x+h(n))h'(n)dn = 0; \tag{8}$$

$$h''(n)dn = \frac{1}{p}dq. \tag{9}$$

From (9), we have $\frac{dn}{dq} = \frac{1}{ph''(n)} < 0$. Substitute this into (8) and we obtain

$$v''(x+h(n))\frac{dx}{dq} + v''(x+h(n))h'(n)\frac{1}{ph''(n)} = 0. \tag{10}$$

It follows that

$$\frac{dx_{noRD}}{dq} = -\frac{h'(n)}{ph''(n)} > 0, \tag{11}$$

which implies that, under the traditional rate-of-return regulation, any decrease in the cost of solar panels reduces the equilibrium output of grid-supplied electricity.

Next we consider the case with RD. Totally differentiate the system (with respect to endogenous variables x, n, p and an exogenous variable q) and obtain

$$\begin{pmatrix} v'' & -1 & v''h' \\ v''h' & 0 & v''(h')^2 + v'h'' \\ p & x & 0 \end{pmatrix} \begin{pmatrix} \frac{dx}{dq} \\ \frac{dp}{dq} \\ \frac{dn}{dq} \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}. \tag{12}$$

Hence, we have

$$\frac{dx_{RD}}{dq} = \frac{v''h'x}{D},$$

where

$$D \equiv \begin{vmatrix} v'' & -1 & v''h' \\ v''h' & 0 & v''(h')^2 + v'h'' \\ p & x & 0 \end{vmatrix} = -v'\{v''(h')^2 + v'h''\} - v'v''h''x.$$

To evaluate these expressions, we derive the price elasticities of demand for electricity and solar panels. Totally differentiate the first order conditions for the consumer's utility maximization (2) and (3) (with respect to x, n and p) to obtain

$$\begin{pmatrix} v'' & v''h' \\ v''h & v''(h')^2 + v'h'' \end{pmatrix} \begin{pmatrix} \frac{\partial x}{\partial p} \\ \frac{\partial n}{\partial p} \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}. \tag{13}$$

Thus we have $\frac{\partial x}{\partial p} = \frac{v''(h')^2 + v'h''}{v'h''v''}$ and hence the price elasticity of demand for utility-generated electricity satisfies

$$\eta_x \equiv \frac{\partial x}{\partial p}\frac{p}{x} = \frac{v''(h')^2 + v'h''}{v''h''x} < 0.$$

Plugging the above elasticity in to dx_{RD}/dq yields

$$\frac{dx_{RD}}{dq} = \frac{\frac{v''h'x}{xv'h''v''}}{-\frac{v''(h')^2+v'h''}{v''xh''} - 1} = \frac{-\frac{h'}{v'h''}}{1+\eta_x} \begin{cases} > 0 & \text{if } |\eta_x| < 1; \\ \leq 0 & \text{if } |\eta_x| \geq 1. \end{cases} \tag{14}$$

A similar comparative statics on p yields

$$\frac{dp_{RD}}{dq} = \frac{-v'v''h'}{D} = -\frac{p}{x}\frac{dx}{dq} \begin{cases} < 0 & \text{if } |\eta_x| < 1; \\ \geq 0 & \text{if } |\eta_x| \geq 1. \end{cases}$$

■

Therefore, in the empirically relevant case with inelastic electricity demand, the grid-supplied electricity consumption decreases, and the price p increases, as q drops.

Effects on welfare

Now we turn to the welfare effects with and without RD. We assume that the utility's profit is returned to consumers as dividends: household i receives a profit share $s_i\pi$ where $s_i \geq 0$ for all i and $\int_0^N s_i di = 1$. Let W_r denote the representative consumer's welfare under policy regime r ($r \in \{RD, noRD\}$). In the absence of distortions other than the markup in electricity pricing, the welfare is given by

$$W_r = u(x_r + h(n_r)) - p_r x_r - qn_r + [px_r - cx_r - F] = u(x_r + h(n_r)) - cx_r - qn_r - F.$$

Under traditional rate-of-return regulation with no revenue decoupling, we have:

$$\begin{aligned}\frac{dW_{noRD}}{dq} &= v'\frac{dx_{noRD}}{dq} + v'h'\frac{dn_{noRD}}{dq} - n - q\frac{dn_{noRD}}{dq} - c\frac{dx_{noRD}}{dq} \\ &= (\bar{p} - c)\frac{dx_{noRD}}{dq} - n_{noRD}.\end{aligned}$$

If $\bar{p}$ is set close enough to c, the welfare is expected to increase as q declines. However, with a sufficiently large markup, the welfare may decrease as q drops.

Under revenue decoupling, we have:

$$\frac{dW_{RD}}{dq} = (\bar{p} - c)\frac{dx_{RD}}{dp} - n_{RD}.$$

Consider the case where $|\eta_x| < 1$. It follows from (11) and (14) in the proof of Proposition 1 that

$$\frac{dx_{RD}}{dq} = \frac{1}{1 - |\eta_x|}\frac{dx_{noRD}}{dq} > \frac{dx_{noRD}}{dq}.$$

This implies that, with revenue decoupling, the negative effect of a decrease in q on total welfare is exacerbated by the amount of consumer adjustment for x if the electricity demand is inelastic.

Proposition 2 *Without revenue decoupling, the total economic welfare increases as the cost of* *installing solar panels goes down, provided $\frac{\partial \pi}{\partial q}$ is sufficiently low (or if $\bar{p}$ is set close enough to c). Under revenue decoupling, the negative effect of a decrease in q on total welfare is exacerbated by the amount of consumer adjustment for x, provided that the electricity demand is inelastic.*

Appendix B Changes in the subsidy for solar installation

With subsidy $s > 0$ per unit of solar panel, the consumer price of solar panels is given by $\bar{q} = q - s$.

Effects on electricity price and quantity

Without revenue decoupling, the interior equilibrium satisfies (2) and (3) with $p = \bar{p}$. Under revenue decoupling, the interior equilibrium satisfies (2), (3) and

$$px - \bar{R} = 0.$$

The effect of an increase in the solar subsidy on electricity prices and quantities is the same as that of a decline in the cost of solar panels.

Proposition 3 *Without RD, an increase in the subsidy for solar panels reduces the equilibrium electricity sales. With RD, an increase in the subsidy for solar panels reduces the equilibrium electricity sales, and increases the electricity price, if and only if the demand for electricity is inelastic.*

Proof. For the case with no RD, a simple modification of the analysis in section 3.2.1 yields

$$\frac{dx_{noRD}}{ds} = \frac{h'(n)}{ph''(n)} < 0.$$

For the case with RD, totally differentiate the system (with respect to endogenous variables x, n, p and an exogenous variable s) and obtain

$$\begin{pmatrix} v'' & -1 & v''h' \\ v''h' & 0 & v''(h')^2 + v'h'' \\ p & x & 0 \end{pmatrix} \begin{pmatrix} \frac{dx}{ds} \\ \frac{dp}{ds} \\ \frac{dn}{ds} \end{pmatrix} = \begin{pmatrix} 0 \\ -1 \\ 0 \end{pmatrix}.$$

Hence, we have

$$\frac{dx_{RD}}{ds} = \frac{-v''h'x}{D} = \frac{\frac{h'}{v'h''}}{1+\eta_x} \begin{cases} < 0 & \text{if } |\eta_x| < 1; \\ \geq 0 & \text{if } |\eta_x| \geq 1. \end{cases},$$

where D is as defined in section 3.2.1. A similar comparative statics on p yields

$$\frac{dp_{RD}}{ds} = \frac{v'v''h'}{D} = -\frac{p}{x}\frac{dx}{dq} \begin{cases} > 0 & \text{if } |\eta_x| < 1; \\ \leq 0 & \text{if } |\eta_x| \geq 1. \end{cases}$$

■

Effects on welfare

Under solar subsidy with policy regime r, the welfare is given by

$$W_r = u(x_r + h(n_r)) - px_r - \bar{q}n_r + [px_r - cx_r - F] - sn_r = u(x_r + h(n_r)) - cx_r - qn_r - F,$$

where $\bar{q} = q - s$. Differentiate the above expression with respect to s:

$$\frac{dW_r}{ds} = v'(x_r + h(n_r)) \left\{ \frac{dx_r}{ds} + h'(n_r)\frac{dn_r}{ds} \right\} - c\frac{dx_r}{ds} - q\frac{dn_r}{ds}$$

$$= (p-c)\frac{dx_r}{ds} + v'(x_r + h(n_r))h'(n_r)\frac{dn_r}{ds} - q\frac{dn_r}{ds} = (p-c)\frac{dx_r}{ds} - s\frac{dn_r}{ds}.$$

With no revenue decoupling, we obtain the following intuitive expression:

$$\frac{dW_{noRD}}{ds} = -(p-c)\eta_{x,q}\frac{x}{\bar{q}} + s\eta_n\frac{n}{\bar{q}}, \tag{15}$$

where $\eta_{x,q}$ is the cross-price elasticity of the demand for electricity with respect to the price of solar panels. The second term is the usual Harberger excess burden formula for a subsidy (called the 'primary welfare effect' (Goulder and Williams, 2003). The first term, which would not exist under marginal-cost (or competitive) pricing with $p = c$, captures the effect of a solar subsidy on the demand for solar panels (due to an increase in solar subsidies). We call this the 'electricity markup effect.' To the extent that the electricity price exceeds the marginal cost, the subsidy on solar panels generates an extra distortion on the use of grid-supplied electricity.

Next, we consider the welfare impact under revenue decoupling. It follows from (**??**) that

$$\frac{dW_{RD}}{ds} = (p-c)\frac{dx_{RD}}{ds} - s\frac{dn_{RD}}{ds}.$$

The appendix shows that we can rewrite the expression to the following:

$$\frac{dW_{RD}}{ds} = -(p-c)\frac{\eta_{x,q}}{1-|\eta_x|}\frac{x}{\bar{q}} + s\frac{-\left\{-\eta_x + \eta_n\frac{qn}{px}\right\}\eta_n\frac{n}{q}}{1-|\eta_x|} + s\frac{-|\eta_n|\frac{n}{q}}{1-|\eta_x|}. \tag{16}$$

The above formula reveals how revenue decoupling amplifies the welfare impact of solar subsidies. The first and the third terms (the electricity markup effect and the primary welfare effect) are negative while the second term is positive. The third term represents the usual Harberger excess burden formula for a subsidy, but it is multiplied by $1/(1-|\eta_x|)$. The first term was also present in the absence of decoupling, but is also now multiplied by $1/(1-|\eta_x|)$. The second term is positive, but the sum of the second and the third term is negative. The second term is likely smaller in magnitude than the first and the third term because it involves a product of elasticities on the numerator. Therefore, depending on the size of the price elasticity of electricity demand, revenue decoupling exacerbates the excess burden due to solar subsidies.

Proposition 4 *With no revenue decoupling, the excess burden due to an increase in the subsidy on solar panels exceeds the primary welfare effect due to a markup in electricity pricing. Under revenue decoupling, both the primary welfare effect and the electricity markup effect are exacerbated when demand is inelastic.*

Proof.

With no RD,

$$\frac{dW_{noRD}}{ds} = (p-c)\frac{h'(n)}{ph''(n)} - s\frac{-1}{ph''(n)} < 0.$$

To interpret this expression, note that $\frac{h'(n)}{ph''(n)} = -\eta_{x,q}\frac{x}{\bar{q}} < 0$ and $\frac{-1}{ph''(n)} = -\eta_n\frac{n}{\bar{q}} > 0$. This yields equation (15).

With RD, the first term on the right-hand side of

$$\frac{dW_{RD}}{ds} = (p-c)\frac{dx_{RD}}{ds} - s\frac{dn_{RD}}{ds}$$

reduces to

$$(p-c)\frac{dx_{RD}}{ds} = (p-c)\frac{-v''h'x}{D} = (p-c)\frac{\frac{h'}{v'h''}}{1+\eta_x} = -(p-c)\frac{\eta_{x,q}}{1-|\eta_x|}\frac{x}{\bar{q}}.$$

The second term satisfies

$$\frac{dn_{RD}}{ds} = \frac{p+v''x}{D} = \frac{(p+v''x)/(xv'v''h'')}{D/(xv'v''h'')} = \frac{\frac{p}{xv'v''h''} + \frac{v''x}{xv'v''h''}}{\frac{-v'\{v''(h')^2+v'h''\}}{xv'v''h''} - \frac{v'v''h''x}{xv'v''h''}}$$

$$= \frac{-\frac{1}{xv''h''}}{1+\eta_x} - \frac{\frac{dn}{dq}\frac{q}{n}\frac{n}{q}}{1+\eta_x} = \frac{-\frac{1}{xv''h''}}{1-|\eta_x|} - \frac{\eta_n\frac{n}{q}}{1-|\eta_x|}.$$

To evaluate the numerator of the first term $-\frac{1}{xv''h''}$, note that

$$\frac{\partial x}{\partial p}=\frac{v''(h')^2+v'h''}{v'h''v''}=\frac{(h')^2}{v'h''}+\frac{1}{v''},$$

where $h'(n)=q/p$. and $\frac{1}{v'h''}=\frac{\partial n}{\partial q}$. Thus

$$\frac{1}{v''}=\frac{\partial x}{\partial p}-\frac{\partial n}{\partial q}\left(\frac{q}{p}\right)^2.$$

We also have $\frac{1}{h''}=\frac{\partial n}{\partial q}p$. Hence,

$$-\frac{1}{xv''h''}=-\left\{\frac{\partial x}{\partial p}\frac{1}{x}-\frac{\partial n}{\partial q}\left(\frac{q}{p}\right)^2\frac{1}{x}\right\}\frac{\partial n}{\partial q}p=-\left\{\frac{\partial x}{\partial p}\frac{p}{x}-\frac{\partial n}{\partial q}\frac{q}{n}\frac{n}{q}\left(\frac{q}{p}\right)^2\frac{p}{x}\right\}\frac{\partial n}{\partial q}\frac{q}{n}\frac{n}{q}$$

$$=-\left\{-\eta_x+\eta_n\frac{qn}{px}\right\}(-1)\eta_n\frac{n}{q}=\left\{-\eta_x+\eta_n\frac{qn}{px}\right\}\eta_n\frac{n}{q}(<0).$$

From (13), we have $\frac{\partial n}{\partial p}=\frac{-v''h'}{v'h''v''}=-\frac{h'}{ph''}$. Hence

$$\eta_{n,p}\equiv\frac{dn}{dp}\frac{p}{n}=-\frac{h'}{ph''}\frac{p}{n}>0$$

is the cross-price elasticity of the demand for solar panels with respect to electricity price. Therefore, the welfare impact of a marginal increase in the solar subsidy is given by equation 16. ■

Appendix C Externalities of electricity generation

We describe how the analysis changes if we assume that the utility's electricity services involve negative externalities due to fossil fuel use for electricity generation. Let $\delta>0$ represent the marginal external damages associated with the production and delivery of grid-supplied electricity x. We assume that, in the absence of emissions prices, each household does not take into account the external effects of its consumption. The welfare expression under no RD is given by

$$W_{nonRD} = v(x(\bar{p},q) + h(n(\bar{p},q))) - qn(\bar{p},q) - cx(\bar{p},q) - F - \delta(x(\bar{p},q)).$$

Under RD, the welfare is now expressed as:

$$W_{RD} = v(x(p,q) + h(n)) - cx(p,q) - F - \delta x(p,q)$$

Therefore,

$$\begin{aligned}\frac{dW_{nonRD}}{dq} &= v'\frac{dx}{dq} + v'h'\frac{dn}{dq} - n - q\frac{dn}{dq} - c\frac{dx}{dq} - \delta\frac{\partial x}{\partial q} \\ &= (\bar{p} - c - \delta)\frac{\partial x}{\partial q} - n\end{aligned}$$

under no RD while

$$\frac{dW_{RD}}{dq} = \left([v' - c - e]\frac{\partial x}{\partial p}\frac{dp}{dq} + \frac{\partial x}{\partial q}\right) - n$$

holds under RD. To the extent that the markup $p - c$ exceeds the marginal external damages δ, the qualitative results are the same as in the previous section.

We now discuss additional results regarding the distributional impacts of decoupling on households with different income levels (and different propensity to purchase solar panels) as well as the effects of decoupling on risk allocations between electricity consumers and producers when there is uncertainty about electricity generation from renewable energy sources.

Appendix D Distributional Impacts of Decoupling

We evaluate the distributional impacts of changes in q (or subsidy if that is what underlies the change in $\bar{q}$).

Proposition 5 *Under RD, a decrease in the cost of solar panels (due to technological improvement or government subsidy) is welfare-improving to those consumers who install solar panels, and welfare-reducing to those who did not install solar panels.*

Proof. For those without solar panels, we have

$$\frac{du_i}{dq} = \frac{d}{dq}\{v_i(x_i) - m_i - px_i\} = -\frac{dp}{dq}x_i > 0,$$

when demand is inelastic. (The equality follows from the envelope theorem.)

For those with solar panels, we have

$$\frac{du_i}{dq} = \frac{d}{dq}\{v_i(x_i + g_i) - m_i - px_i - q\} = -\frac{dp}{dq}x_i - 1$$

Note that $\frac{dp}{dq} = \frac{-p\frac{\partial x}{\partial q}}{x(1-|\eta_x)|}$.

Therefore,

$$\begin{aligned}\frac{du_i}{dq} &= \frac{-p\frac{\partial x}{\partial q} - 1 + |\eta_x|}{(1-|\eta_x)|} \\ &< 0 \text{ if } |\eta_x| < 1.\end{aligned}$$

Precise welfare expressions would include the share of profits of the utility for each consumer. Because the profit is increasing in a (drop in) $\bar{q}$ and in the subsidy under RD, this consideration tends to increase the welfare impacts on those with solar panels, and may alleviate the negative welfare impacts on those without solar panels. ■

Appendix E Decoupling under uncertainty

Here we provide an extensions of the model to incorporate uncertainty associated with distributed generation.

Here we consider uncertainty regarding output from solar panels in order to examine how the associated risk is shared between consumers and the utility under the alternative regulation. Given installation n, suppose the output from distributed generation is given by

$$x^d = \theta h(n),$$

where θ is a random variable with a set of nonnegative realizations $\{\theta_s\}$, $s \in S$, such that $E\theta = \bar{\theta}$. The household chooses n before uncertainty is realized and chooses how much electricity to buy from the utility upon realization of uncertainty, i.e., it chooses a state-contingent electricity consumption plan.

The household's problem is

$$\max_{\{x_s\}_{s \in S}, n} E[u(e, y)]$$

subject to

$$e_s = x_s + \theta_s h(n), \quad x_s \geq 0, \quad p_s x_s + qn + y_s \leq M \quad \text{for each } s \in S.$$

The objective function in this case is

$$E[v(x + \theta h(n)) - px] + M - qn.$$

The first order conditions for an interior solution are

$$v'(x_s + \theta_s h(n)) = p_s \quad \text{for all } s \in S,$$

$$E[v'(x + \theta h(n))\theta]h'(n) = q.$$

Proposition 6 *Without revenue decoupling, any increase in the variance of θ will not change the utility's equilibrium expected profits.*

Proof. The utility's expected profit under uncertainty without RD can be expressed as:

$$\begin{aligned} E[\pi] &= E[\bar{p}x - \bar{c}x] \\ &= (\bar{p} - \bar{c})E[x]. \end{aligned}$$

Without RD, The electricity price is fixed irrespective of the realization of uncertainty. Note that under this regulatory scheme, consumer demand satisfies $v'(e_s^*) = \bar{p}$ for all s, i.e., $e_s^* = e^*$ for all s. This implies that:

$$e^* = x_s + \theta_s h(n), \quad \forall s \in S. \tag{17}$$

Note further that $E[\theta h(n)] = \bar{\theta}h(n)$ because $E[\theta_s] = \bar{\theta}$. Therefore,

$$\begin{aligned} E[\pi] &= E[(\bar{p} - c)(e^* - \theta h(n))] = (\bar{p} - \bar{c})[e^* - E(\theta)h(n)] \\ &= (\bar{p} - c)[e^* - \bar{\theta}h(n)], \end{aligned}$$

which is independent of the variance of θ. ■

To evaluate the effect of uncertainty under revenue decoupling, we assume that (with slight abuse of notation) $S = \{1, 2\}$, $\theta_1 = \theta + \varepsilon$, $\theta_2 = \theta - \varepsilon$, with $p_1 = p_2 = 1/2$, where $\varepsilon \in (0, \theta)$.

Proposition 7 *With revenue decoupling in place, an increase in the variance of θ will result in an increase in the expected profits of the utility.*

Proof. With RD, the utility's expected profit is now expressed as:

$$E[\pi] = E[\bar{R} - \bar{c}x_s] \tag{18}$$

Evaluate the derivative of (18) with respect to ε to obtain

$$\frac{dE[\pi]}{d\varepsilon} = -\bar{c}E[\frac{dx}{d\varepsilon}].$$

To evaluate $\frac{dx}{d\varepsilon}$, take the derivative of the consumer's expected utility with respect to ε:

$$\frac{dE[U]}{d\epsilon} = E\left[v'(X_s)\left\{\frac{dx_s^u}{d\varepsilon} + \frac{d\theta_s}{d\varepsilon}h(n)\right\}\right] = E\left[\frac{R}{x_s}\left\{\frac{dx_s^u}{d\varepsilon} + \frac{d\theta_s}{d\varepsilon}h(n)\right\}\right]$$

Total differentiation of the first-order condition for the consumer's utility maximization, $v'(x_s + \theta_s h(n)) = \frac{R}{x_s}$ for $s = 1, 2$, yields

$$\left(v'' + \frac{R}{(x_1)^2}\right) dx_1 + v''(\theta - \varepsilon)h'(n)dn = v''h(n)d\varepsilon \tag{19}$$

$$\left(v'' + \frac{R}{(x_2)^2}\right) dx_2 + v''(\theta + \varepsilon)h'(n)dn = -v''h(n)d\epsilon \tag{20}$$

Utility maximization also implies $E[v'\theta_s]h'(n) = q$. Thus

$$\sum_s \pi_s[v'(x_s + \theta_s h(n))\theta_s] = \frac{q}{h'(n)}$$

Totally differentiating the above conditions and manipulating terms, we obtain

$$\begin{aligned}\frac{1}{2}\left[v''(\theta - \varepsilon)dx_1 + v''(\theta + \varepsilon)dx_2\right] + \left[v''h(n)[(\theta^2 + \varepsilon^2) + \frac{q}{h'(n)^2}h''(n)\right] dn \\ = \left[-v''h(n)\varepsilon + \frac{1}{2}[v_1' - v_2']\right] d\varepsilon\end{aligned} \tag{21}$$

where $v_1' \equiv v'(e_1)$, $v_2' \equiv v'(e_2)$. Solving for $\frac{dE[U]}{d\varepsilon}$ will entail solving (19), (20), and (21) in a system of equations. Re-writing the problem into a matrix form will yield the following:

$$\begin{pmatrix} v'' + \frac{R}{(x_1)^2} & 0 & v''(\theta-\varepsilon)h'(n) \\ 0 & v'' + \frac{R}{(x_2)^2} & v''(\theta+\varepsilon)h'(n) \\ \frac{1}{2}v''(\theta-\epsilon) & \frac{1}{2}v''(\theta+\varepsilon) & v''h'(n)(\theta^2+\varepsilon^2) + \frac{q}{h'(n)^2}h''(n) \end{pmatrix} \begin{pmatrix} \frac{dx_1}{d\varepsilon} \\ \frac{dx_2}{d\varepsilon} \\ \frac{dn}{d\varepsilon} \end{pmatrix} = \begin{pmatrix} v''h(n) \\ -v''h(n) \\ -v''h(n) + \frac{1}{2}[v_1' - v_2']\varepsilon \end{pmatrix}$$

Let D_A be the determinant of the coefficient matrix and D_{xi} be the determinant formed by replacing the ith column of the matrix on the left-hand side with the vector on the left-hand side. Applying Cramer's Rule, we can compute for $\frac{dx_1}{d\epsilon}$ by:

$$\frac{dx_1}{d\varepsilon} = \frac{D_{x1}}{D_A}$$

Where:

$$D_{x1} = \det \begin{bmatrix} v''h(n) & 0 & v''(\theta-\varepsilon)h'(n) \\ -v''h(n) & v'' + \frac{R}{(x_2)^2} & v''(\theta+\varepsilon)h'(n) \\ -v''h(n)\epsilon + \frac{1}{2}[v_1' - v_2'] & \frac{1}{2}v''(\theta+\varepsilon) & v''h'(n)(\theta^2+\varepsilon^2) + \frac{q}{h'(n)^2}h''(n) \end{bmatrix},$$

$$D_A = \det \begin{bmatrix} v'' + \frac{R}{(x_1)^2} & 0 & v''(\theta-\epsilon)h'(n) \\ 0 & v'' + \frac{R}{(x_2)^2} & v''(\theta+\epsilon)h'(n) \\ \frac{1}{2}v''(\theta-\epsilon) & \frac{1}{2}v''(\theta+\epsilon) & v''h'(n)(\theta^2+\epsilon^2) + \frac{q}{h'(n)^2}h''(n) \end{bmatrix}.$$

To show that $E\left[\frac{dx_s}{d\varepsilon}\right] < 0$ when $D_A < 0$, we note that:

$$
\begin{aligned}
E\left[\frac{dx_s}{d\varepsilon}\right] = & \frac{1}{2D_A}\left[\frac{R}{(x_2)^2}(v'')^2 h' h\theta(\theta+\varepsilon) + \left(v'' + \frac{R}{(x_2)^2}\right) v'' h q \frac{h''}{h'^2}\right] \\
& + \frac{1}{2D_A}\left[-\frac{1}{2}(v_1' - v_2')(v'' + \frac{R}{(x_2)^2})(v''(\theta-\varepsilon)h')\right] \\
& + \frac{1}{2D_A}\left[-\frac{R}{(x_1)^2}(v'')^2 h' h\theta(\theta-\varepsilon) - \left(v'' + \frac{R}{(x_1)^2}\right) v'' h q \frac{h''}{h'^2}\right] \\
& + \frac{1}{2D_A}\left[-\frac{1}{2}(v_1' - v_2')(v'' + \frac{R}{(x_1)^2})(v''(\theta+\varepsilon)h')\right].
\end{aligned}
$$

Note that terms in the square brackets can be expressed as:

$$
= \left[\frac{p_2}{x_2}(\theta+\varepsilon) - \frac{p_1}{x_1}(\theta-\varepsilon)\right] v'' h' h\theta \tag{22}
$$

$$
+ \left[\frac{p_2}{x_2} - \frac{p_1}{x_1}\right] v'' h q \frac{h''}{h'^2} \tag{23}
$$

$$
+ \left[\left(v'' + \frac{R}{(x_2)^2}\right)(\theta-\varepsilon) + \left(v'' + \frac{R}{(x_1)^2}\right)(\theta+\varepsilon)\right]\left[-\frac{1}{2}(v_1' - v_2') v'' h'\right]. \tag{24}
$$

Here (22) is positive since $\frac{p_2}{x_2} > \frac{p_1}{x_1}$ (note that $p_1 < p_2$ and $x_1 > x_2^U$) and $(\theta+\varepsilon) > (\theta-\varepsilon)$. For the same reason, (23) is positive. For (24), we assume that $(v'' + \frac{R}{x_s}) < 0$ which makes the sum of the terms in the first bracket to be negative. Since $p_1 < p_2$, the term outside the bracket is negative. This makes the whole expression negative. Overall, $E\left[\frac{dx_s}{d\varepsilon}\right] < 0$ when $D_A < 0$. Therefore, $E[\pi] > 0$ when $D_A < 0$. ■

Proposition 8 *With no RD, an increase in the variance of θ (i.e., having a mean-preserving spread of θ) does not change the household's equilibrium expected utility.*

Proof. Under traditional regulation, we have $p_s = \bar{p}$ for all $s \in S$: between rate cases, the electricity price is fixed irrespective of the realization of uncertainty. In this case, we have

$$
e_s = e_{s'} = e^* \text{for all } s, s' \in S,
$$

where, e^* solves $v'(e^*) = \bar{p}$, and $\bar{p}\bar{\theta}h'(n) = q$; i.e. $h'(n) = \frac{q}{\bar{p}\bar{\theta}}$, where $\bar{\theta} \equiv E[\theta]$. In this case, the household's utility satisfies

$$E[v(e^*) + M - \bar{p}\{e^* - \theta h(n^*)\}] - qn^* = v(e^*) + M - \bar{p}[e^* - \bar{\theta} h(n*)] - qn^*.$$

Note that e^* and n^* are independent of the variance of θ. Hence, a change in the variance of θ_s has no effect on the household's equilibrium expected utility.[18] ■

Proposition 9 *Under RD, an increase in the variance of θ (or, equivalently, an increase in ε) reduces the expected utility of consumers.*

Proof. Evaluate D_A as defined in the previous proof:

$$\begin{aligned} D_A = & \left(v'' + \frac{R}{(x_1)^2}\right)\left(v'' + \frac{R}{(x_2)^2}\right)\left(v''h'(n)(\theta^2 + \epsilon^2) + \frac{q}{h'(n)^2}h''(n)\right) \\ & - \left(\frac{1}{2}v''(\theta - \epsilon)\right)\left(v'' + \frac{R}{(x_2)^2}\right)(v''(\theta - \epsilon)h'(n)) \\ & - \left(\frac{1}{2}v''(\theta + \epsilon)\right)(v''(\theta + \epsilon)h'(n))\left(v'' + \frac{R}{(x_1^2)^2}\right). \end{aligned}$$

Note that D_A can be simplified:

$$\begin{aligned} D_A \; = \; & 0.5\left(v'' + \frac{\bar{R}}{(x_1)^2}\right)\left[\frac{\bar{R}}{(x_2)^2}v''h'(\theta + \varepsilon)^2 + \left(v'' + \frac{\bar{R}}{(x_2)^2}\right)v'(X_2)(\theta + \varepsilon)h''/h'\right] \\ + \; & 0.5\left(v'' + \frac{\bar{R}}{(x_2)^2}\right)\left[\frac{\bar{R}}{(x_1)^2}v''h'(\theta - \varepsilon)^2 + \left(v'' + \frac{\bar{R}}{(x_1)^2}\right)v'(X_1)(\theta - \varepsilon)h''/h'\right]. \end{aligned} \quad (25)$$

Note that $(x_s)(v'' + \frac{R}{(x_s)^2}) = p_s' x_s + p_s = MR_s$. When demand is inelastic, MR is negative because to sell a marginal (infinitesimal) unit the firm would have to lower the selling price so much that it would lose more revenue on the pre-existing units than it would gain on the incremental unit. Thus, under inelastic demand, $v'' + \frac{R}{(x_1)^2} < 0$ (because $x_1 > 0$).

[18] This result is due to the quasilinearity assumption on the utility function, i.e., no income effects. If the household's utility depends nonlinearly on y, then an increase in the variance of θ may impact the household's utility.

For D_{x1}:

$$D_{x1} = \frac{R}{(x_2)^2}(v'')^2 hh'\theta(\theta+\varepsilon) + \left(v'' + \frac{\bar{R}}{(x_2)^2}\right) v'' hq \frac{h''}{h'^2} \\ - \left(\frac{1}{2}(v_1' - v_2')\right)\left(v'' + \frac{R}{(x_2)^2}\right)(v''(\theta-\varepsilon)h') \tag{26}$$

Applying the same method above, we can compute for $\frac{dx_2}{d\varepsilon}$ by applying $\frac{dx_2}{d\varepsilon} = \frac{D_{x2}}{D_A}$, where

$$D_{x2} = \det \begin{bmatrix} v'' + \frac{R}{(x_1)^2} & v''h(n) & v''(\theta-\varepsilon)h'(n) \\ 0 & -v''h(n) & v''(\theta+\epsilon)h'(n) \\ \frac{1}{2}v''(\theta-\epsilon) & -v''h(n)\varepsilon + \frac{1}{2}[V_1' - V_2'] & v''h'(n)(\theta^2+\varepsilon^2) + \frac{q}{h'(n)^2}h''(n) \end{bmatrix}$$

As for D_{x2}, we have

$$D_{x2} = -\frac{R}{(x_1)^2}(v'')^2 hh'\theta(\theta-\varepsilon) - \left(v'' + \frac{R}{(x_1)^2}\right) v'' hq \frac{h''}{h'^2} \\ - \left(\frac{1}{2}(v_1' - v_2')\right)\left(v'' + \frac{R}{(x_1)^2}\right)(v''(\theta+\varepsilon)h'). \tag{27}$$

Now evaluate $\frac{dEU}{d\varepsilon}$:

$$\begin{aligned} \frac{dEU}{d\varepsilon} &= E\left[\frac{R}{x_s}\left(\frac{dx_s^u}{d\varepsilon} + \frac{d\theta_s}{d\varepsilon}h(n)\right)\right] \\ &= E\left[\frac{R}{x_s}\frac{dx_s^u}{d\varepsilon}\right] + E\left[v'(X_s)\frac{d\theta_s}{d\varepsilon}h(n)\right], \end{aligned} \tag{28}$$

where $\frac{dx_s^u}{d\varepsilon} = \frac{D_{xs}}{D_A}$.

We first evaluate the $E\left[\frac{R}{x_s}\frac{dx_s^u}{d\varepsilon}\right]$ by substituting (26) and (27) into $\frac{dx_s^u}{d\varepsilon}$:

$$\begin{aligned}E\left[\frac{R}{x_s}\frac{dx_s^u}{d\varepsilon}\right] = {} & \frac{\bar{R}}{2D_A x_1^u x_2^u}\left[p_2(v'')^2 h' h\theta(\theta+\varepsilon) + x_2\left(v'' + \frac{\bar{R}}{(x_2)^2}\right)\left(v'' hq\frac{h''}{h'^2}\right)\right] \\ & + \frac{\bar{R}}{2D_A x_1^u x_2^u}\left[-\frac{1}{2}(v_1' - v_2')x_2\left(v'' + \frac{\bar{R}}{(x_2)^2}\right)(v''(\theta-\varepsilon)h')\right] \\ & + \frac{\bar{R}}{2D_A x_1^u x_2^u}\left[-p_1(v'')^2 h' h\theta(\theta-\varepsilon) - x_1\left(v'' + \frac{\bar{R}}{(x_1)^2}\right)\left(v'' hq\frac{h''}{h'^2}\right)\right] \\ & + \frac{\bar{R}}{2D_A x_1^u x_2^u}\left[-\frac{1}{2}(v_1' - v_2')x_1\left(v'' + \frac{\bar{R}}{(x_1)^2}\right)(v''(\theta+\varepsilon)h')\right],\end{aligned}$$

where the expressions inside the square brackets are all equal to

$$[p_2(\theta+\varepsilon) - p_1(\theta-\varepsilon)]\,(v'')^2 h' h\theta \tag{29}$$

$$+\left[x_2^u\left(v'' + \frac{\bar{R}}{(x_2)^2}\right) - x_1^u\left(v'' + \frac{\bar{R}}{(x_1)^2}\right)\right] v'' hq\frac{h''}{h'^2} \tag{30}$$

$$+\left[x_2^u\left(v'' + \frac{\bar{R}}{(x_2)^2}\right)(\theta-\varepsilon) + x_1^u\left(v'' + \frac{\bar{R}}{(x_1)^2}\right)(\theta+\varepsilon)\right]\left(-\frac{1}{2}\right)(v_1' - v_2')v'' h'. \tag{31}$$

We will show that the terms (29) - (31) are all positive. Given $n > 0$, we have $x_1^u > x_2^u$ and $p_1 < p_2$. The first order condition for x_s satisfies

$$v'(x_s + \theta_s h) = p_s = R/x_s.$$

Totally differentiate both sides with respect to x_s and θ_s:

$$v'' dx_s + v'' h d\theta_s = -R x_s^{-2} dx_s, \quad \text{i.e.,} \quad \frac{\partial x_s}{\partial \theta_s} = \frac{-v'' h}{v'' + \frac{R}{x_s^2}}.$$

The last expression is negative when $v'' + \frac{R}{x_s^2} < 0$. Because $\theta_1 = \theta - \varepsilon < \theta + \varepsilon = \theta_2$, we have $x_1^u > x_2^u$ and $p_1 < p_2$.

The term (29) is positive because $p_1 < p_2$ and $\theta - \varepsilon < \theta + \varepsilon$ while term (30) implies $[v''(x_2 - x_1) + (p_2 - p_1)]v'' hq\frac{h''}{h'^2} > 0$. Term (31) is positive when $v'' + \frac{R}{x_s^2} < 0$. Therefore,

$\frac{dx_s}{d\varepsilon} < 0$ if $D_A < 0$.

Next, we can evaluate the last term of equation (28).

$$
\begin{aligned}
E[v' \frac{d\theta_s}{d\varepsilon} h] &= \frac{1}{2}[v_1'(-h) - v_2'(h)] \\
&= \frac{1}{2}[p_2 - p_1]h > 0.
\end{aligned}
$$

Therefore, we need to evaluate the sum of the two terms in (28).

$$
\frac{dEU}{d\varepsilon} = E[v' \frac{dx_s}{d\varepsilon}] + E[v' \frac{d\theta_s}{d\varepsilon} h] = E[v' \frac{dx_s}{d\varepsilon}] + D_A(x_1 - x_2)h.
$$

We also have

$$
\begin{aligned}
& D_A(x_1 - x_2)h \\
& = \frac{1}{2}\left[\left(v'' + \frac{R}{(x_1^U)^2}\right)\frac{R}{(x_2^U)^2}v''h'(\theta+\varepsilon)^2 + \left(v'' + \frac{R}{(x_2^U)^2}\right)\frac{R}{(x_1^U)^2}v''h'(\theta-\varepsilon)^2\right](x_1 - x_2)h \qquad (32) \\
& - \frac{1}{2}x_2\left(v'' + \frac{R}{(x_1^U)^2}\right)\left(v'' + \frac{R}{(x_2^U)^2}\right)hq\frac{h''}{h'^2} + \frac{1}{2}x_1\left(v'' + \frac{R}{(x_1^U)^2}\right)\left(v'' + \frac{R}{(x_2^U)^2}\right)hq\frac{h''}{h'^2}. \qquad (33)
\end{aligned}
$$

We can verify that (32) is positive. If we sum up (30) and (33), we have:

$$
\begin{aligned}
\text{Eqs. (30) + (33)} &= x_2\left(v'' + \frac{R}{(x_2^U)^2}\right)hq\frac{h''}{h'^2}\left[v'' - \frac{1}{2}\left(v'' + \frac{R}{(x_1^U)^2}\right)\right] \\
&- x_1\left(v'' + \frac{R}{(x_1^U)^2}\right)hq\frac{h''}{h'^2}\left[v'' - \frac{1}{2}\left(v'' + \frac{R}{(x_2)^2}\right)\right] \\
&= \frac{1}{2}hq\frac{h''}{h'^2}\left[(v'')^2 x_2 + v''\frac{R}{x_2} - v''\frac{R}{x_1} + \frac{R}{x_1 x_2}\right] \\
&- \frac{1}{2}hq\frac{h''}{h'^2}\left[(v'')^2 x_1 + v''\frac{R}{x_1} - v''\frac{R}{x_1} + \frac{R}{x_1 x_2}\right] \\
&= \frac{1}{2}hq\frac{h''}{h'^2}\left[(v'')^2(x_2 - x_1) + v''(p_2 - p_1)\right] \\
&> 0. \qquad (34)
\end{aligned}
$$

It follows from $\theta_1 = \theta - \varepsilon < \theta + \varepsilon = \theta_2$ that $x_1 > x_2 \to p_1 < p_2$. Therefore, we conclude that $\frac{dEU}{d\varepsilon} < 0$ if $D_A < 0$.

To show $D_A < 0$, we totally differentiate the FOCs with respect to x_1^u, x_2^u, n, p_1, and divide both sides by dp_1:

$$\begin{pmatrix} v'' & 0 & v''(\theta-\varepsilon)h'(n) \\ 0 & v'' & v''(\theta+\varepsilon)h'(n) \\ \frac{1}{2}v''(\theta-\epsilon) & \frac{1}{2}v''(\theta+\varepsilon) & v''h'(n)(\theta^2+\varepsilon^2)+q\frac{h''(n)}{h'(n)^2} \end{pmatrix} \begin{pmatrix} \frac{dx_1}{dp_1} \\ \frac{dx_2}{dp_1} \\ \frac{dn}{dp_1} \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}.$$

Let $\frac{dx_1^u}{d_p 1} = \frac{Dx_1}{Du}$, where

$$Dx_1 = det \begin{bmatrix} 1 & 0 & v''(\theta-\varepsilon)h'(n) \\ 0 & v'' & v''(\theta+\varepsilon)h'(n) \\ 0 & \frac{1}{2}v''(\theta+\varepsilon) & v''h'(n)(\theta^2+\varepsilon^2)+q\frac{h''(n)}{h'(n)^2} \end{bmatrix},$$

$$Du = det \begin{bmatrix} v'' & 0 & v''(\theta-\varepsilon)h'(n) \\ 0 & v'' & v''(\theta+\varepsilon)h'(n) \\ \frac{1}{2}v''(\theta-\epsilon) & \frac{1}{2}v''(\theta+\varepsilon) & v''h'(n)(\theta^2+\varepsilon^2)+q\frac{h''(n)}{h'(n)^2} \end{bmatrix}.$$

Solving for Dx_1 yields:

$$Dx_1 = v''\left[v''h'(\theta^2+\varepsilon^2)+q\frac{h''}{(h')^2}\right] - \frac{1}{2}(v'')^2(\theta+\varepsilon)^2h'. \tag{35}$$

As for Du, we have

$$Du = (v'')^2\left[v''h'(\theta^2+\varepsilon^2)+q\frac{h''}{(h')^2}\right] - \frac{1}{2}(v'')^3(\theta-\varepsilon)^2h' - \frac{1}{2}(v'')^3(\theta+\varepsilon)^2h' = (v'')^2 q\frac{h''}{(h')^2}.$$

Thus, we can express $\frac{dx_1^u}{dp_1}$ as:

$$\frac{dx_1^u}{dp_1} = \frac{v''\left[v''h'(\theta^2+\varepsilon^2)+q\frac{h''}{(h')^2}\right]-\frac{1}{2}(v'')^2(\theta+\varepsilon)^2h'}{(v'')^2q\frac{h''}{(h')^2}} = \frac{\frac{1}{2}h'(\theta-\varepsilon)^2}{q\frac{h''}{(h')^2}}+\frac{1}{v''}.$$

Assuming inelastic demand (the empirically relevant case), we know that $\frac{dx_1^u}{dp_1}\frac{p_1}{x_1^u}<1$. This implies that;

$$\frac{dx_1^u}{dp_1}\frac{p_1}{x_1^u} = \frac{p_1}{x_1^u}\left[\frac{\frac{1}{2}h'(\theta-\varepsilon)^2}{q\frac{h''}{(h')^2}}+\frac{1}{v''}\right] > -1 \Leftrightarrow \frac{p_1}{x_1^u}\left[\frac{v''\frac{1}{2}h'(\theta-\varepsilon)^2+q\frac{h''}{(h')^2}}{v''x_1^uq\frac{h''}{(h')^2}}\right] > -1. \tag{36}$$

Because $v''x_1^uq\frac{h''}{(h')^2}>0$, it follows from (36) that

$$p_1v''\frac{1}{2}h'(\theta-\varepsilon)^2+p_1q\frac{h''}{(h')^2} > -v''x_1^uq\frac{h''}{(h')^2}.$$

We divide both sides by x_1^u, while noting that $p_1=v'(X_1)$, to obtain

$$\begin{aligned}-\frac{dx_1^u}{dp_1}\frac{p_1}{x_1^u}<1 &\Leftrightarrow \frac{v'(X_1)}{x_1^u}v''\frac{1}{2}h'(\theta-\varepsilon)^2+\frac{v'(X_1)}{x_1^u}q\frac{h''}{(h')^2}+v''q\frac{h''}{(h')^2}>0\\ &\Leftrightarrow \frac{R}{(x_1^u)^2}v''\frac{1}{2}h'(\theta-\varepsilon)^2+\left(\frac{R}{x_1^u}+v''\right)q\frac{h''}{(h')^2}>0.\end{aligned}$$

Similarly, we can have

$$\begin{aligned}-\frac{dx_2^u}{dp_2}\frac{p_2}{x_2^u}<1 &\Leftrightarrow \frac{v'(X_2)}{x_2^u}v''\frac{1}{2}h'(\theta+\varepsilon)^2+\frac{v'(X_2)}{x_2^u}q\frac{h''}{(h')^2}+v''q\frac{h''}{(h')^2}>0\\ &\Leftrightarrow \frac{R}{(x_2^u)^2}v''\frac{1}{2}h'(\theta+\varepsilon)^2+\left(\frac{R}{x_2^u}+v''\right)q\frac{h''}{(h')^2}>0.\end{aligned}$$

Recall that:

$$\begin{aligned}D_A = &\left(v''+\frac{\bar{R}}{(x_1)^2}\right)\left[0.5\frac{\bar{R}}{(x_2)^2}v''h'(\theta+\varepsilon)^2+0.5\left(v''+\frac{\bar{R}}{(x_2)^2}\right)q\frac{h''}{(h')^2}\right]\\ &+\left(v''+\frac{\bar{R}}{(x_2)^2}\right)\left[0.5\frac{\bar{R}}{(x_1)^2}v''h'(\theta-\varepsilon)^2+0.5\left(v''+\frac{\bar{R}}{(x_1)^2}\right)q\frac{h''}{(h')^2}\right].\end{aligned}$$

If the demand for $x_s, s \in S$ is inelastic, then we have the following conditions:

$$
\begin{aligned}
&\left(v'' + \frac{\bar{R}}{(x_s)^2}\right) < 0 \quad \text{for all } s \in S; \\
&\left[0.5\frac{\bar{R}}{(x_1)^2}v''h'(\theta - \varepsilon)^2 + \left(v'' + \frac{\bar{R}}{(x_1)^2}\right) q\frac{h''}{(h')^2}\right] > 0; \\
&\left[0.5\frac{\bar{R}}{(x_2)^2}v''h'(\theta + \varepsilon)^2 + \left(v'' + \frac{\bar{R}}{(x_2)^2}\right) q\frac{h''}{(h')^2}\right] > 0.
\end{aligned}
$$

Taken together, the results in this subsection imply that the risk burden shifts from the utility to the consumers under revenue decoupling. ■

Appendix F Supplementary Figures and Tables

Table F.1: The effect of adopting RD on prices, matched sample.

	Price (real)		Price (real)	
	Log-transformed	Levels	Log-transformed	Levels
$(RD = 1)$	0.05	0.01	0.05	0.01
	(0.311)	(0.480)	(0.124)	(0.317)
R-sq. (adj.)	0.01	0.00	0.06	0.06
Obs	1184	1184	1184	1184
Time Fixed Effects	yes	yes	yes	yes
Utiliy-State Fixed Effects	yes	yes	yes	yes

Note: The table shows the result of estimating equation 1 on the matched sample. Each column in each panel is a separate regression for a particular outcome variable. *, **, *** indicate statistical significance at 0.10, 0.05, and 0.01 level, respectively.

Table F.2: The effect of adopting RD on prices, matched sample.

	Price (real)		Price (real)	
	Log-transformed	Levels	Log-transformed	Levels
$(RD = 1)$	0.003	0.045	0.005	0.053**
	(0.008)	(0.030)	(0.008)	(0.025)
$(R_{actual,12} > R_{projected,12})$	-0.021	0.136*		
	(0.014)	(0.090)		
$(RD = 1)$*$(R_{actual,12} > R_{projected,12})$	0.007	0.007		
	(0.005)	(0.022)		
$(R_{actual,6} > R_{projected,6})$			-0.029***	-0.129***
			(0.002)	(0.011)
$(RD = 1)$*$(R_{actual,6} > R_{projected,6})$			0.001	-0.004
			(0.004)	(0.013)
R-sq. (adj.)	0.36	0.54	0.38	0.55
Obs	1184	1184	1184	1184
Time Fixed Effects	yes	yes	yes	yes
Utiliy-State Fixed Effects	yes	yes	yes	yes

Note: The table shows the result of estimating equation 1 on the matched sample, with time-$(R_{actual} > R_{projected})$ dummy, where R_actual and $R_projected$ are actual and projected revenues, respectively . Each column in each panel is a separate regression for a particular outcome variable. *, **, *** indicate statistical significance at 0.10, 0.05, and 0.01 level, respectively.

Table F.3: Retail electricity prices relative to social marginal cost (SMC), by state, 2011.

Statecode	State	P-SMC	Decoupled?
AK	Alaska	0.183	
AL	Alabama	0.010	
AR	Arkansas	-0.007	
AZ	Arizona	0.071	
CA	California	0.111	Yes
CO	Colorado	0.068	
CT	Connecticut	0.091	Yes
DE	Delaware	0.006	
FL	Florida	0.048	
GA	Georgia	0.015	
HI	Hawaii	0.435	Yes
IA	Iowa	-0.038	
ID	Idaho	0.039	Yes
IL	Illinois	-0.023	
IN	Indiana	-0.033	
KS	Kansas	-0.002	
KY	Kentucky	-0.009	
LA	Louisiana	-0.004	
MA	Massachusetts	0.069	Yes
MD	Maryland	0.010	Yes
ME	Maine	0.054	
MI	Michigan	-0.009	Yes
MN	Minnesota	-0.027	
MO	Missouri	-0.030	
MS	Mississippi	0.007	
MT	Montana	0.057	
NC	North Carolina	0.006	
ND	North Dakota	-0.038	
NE	Nebraska	-0.034	
NH	New Hampshire	0.075	
NJ	New Jersey	0.034	
NM	New Mexico	0.062	
NV	Nevada	0.064	
NY	New York	0.087	Yes
OH	Ohio	-0.019	
OK	Oklahoma	-0.012	
OR	Oregon	0.055	Yes
PA	Pennsylvania	-0.005	
RI	Rhode Island	0.058	
SC	South Carolina	0.007	
SD	South Dakota	-0.033	
TN	Tennessee	0.012	
TX	Texas	0.074	
UT	Utah	0.046	
VA	Virginia	0.007	
VT	Vermont	0.066	Yes
WA	Washington	0.042	
WI	Wisconsin	-0.011	Yes
WV	West Virginia	-0.030	
WY	Wyoming	0.040	