UHERO
THE ECONOMIC RESEARCH ORGANIZATION
AT THE UNIVERSITY OF HAWAIʻI

Revenue Decoupling for Electric Utilities: Impacts on Prices and Welfare

BY

Arlan Brucal and Nori Tarui

Working Paper No. 2018-8

November 19, 2018

UNIVERSITY OF HAWAIʻI AT MANOA
2424 MAILE WAY, ROOM 540 • HONOLULU, HAWAIʻI 96822
WWW.UHERO.HAWAII.EDU

Revenue Decoupling for Electric Utilities: Impacts on Prices and Welfare

Arlan Brucal and Nori Tarui*

November 2018

Abstract

Under traditional (cost-of-service) electric utility regulation, regulated utilities may not recover their fixed costs when their sales are lower than expected. Revenue decoupling (RD) is a mechanism that allows price adjustments so that the regulated utility recovers its required revenue. This paper investigates the welfare and distributional impacts of RD. Theoretically, we find that the excess burden of subsidies for distributed generation is larger with RD than without. Contrary to how RD is specified on dockets in many states, electricity prices appear to demonstrate downward rigidity, while statistically significant upward adjustments on average are observed across utilities that experienced decoupling. We also find empirically that RD has generated negative welfare effects in most states even if we consider the social marginal costs of electricity generation given different energy mix across regional markets.

Keywords: utility regulation, decoupling, electricity sector

---

*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.
The authors acknowledge support from the Grantham Foundation and the Economic and Social Research Council (ESRC) through the Centre for Climate Change Economics and Policy and the Japan Science and Technology Agency (JST) CREST Grant Number JPMJCR15K2. Preliminary analysis was funded by U.S. Department of Energy Workforce Training Grant in the Strategic Training and Education in Power Systems through Renewable Energy and Island Sustainability (REIS) Program in the University of Hawaii at Manoa. We thank Jenya Kahn-Lang for sharing the data on revenue decoupling implementations.

1 Introduction

Efforts to enhance energy efficiency and distributed electricity generation—as opposed to generations by large utilities—have received increased attentions by energy policy makers and researchers. Under the traditional natural-monopoly regulation (i.e., cost-of-service or rate-of-return regulation), however, the output 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 because the sales grow more slowly than expected. Among the potential regulatory options, revenue decoupling (RD) emerged as an approach to help utilities overcome the disincentive to support the state's energy-efficiency agenda by disentangling the effect of increased sales volume to the utility's revenues without affecting the design of customer rates (Morgan, 2013). However, the recent adoption of RD among states generated controversies ranging from perceived high rate impacts to reallocation of risks from the utilities to consumers. Despite these controversies, little analytical work has been done to provide clear guidance regarding the effects of RD on electricity prices and economic welfare.[1]

We contribute to the literature in three respects. First, we delineate the potential welfare and distributional impacts of RD using a simple model with distributed generation and an electric service provider. The model allows us to assess the welfare implications of two regimes, (1) traditional rate of return regulation with no RD and (2) the RD regime. Second, we investigate empirically the impacts of RD on electricity prices by exploiting

[1] Knittel (2002), Brennan (2010), Kihm (2009), and Chu and Sappington (2013) provide useful discussions on the performance of revenue decoupling from various perspectives. None of them focuses on how decoupling works in the presence of subsidies for distributed generation or RD's price and welfare impacts. Comprehensive technical reports and anecdotal evidences are available (see, for example, Regulatory Assistance Project, 2011 and Morgan, 2013); however, they present divergent views more than clear guiding principles on the potential impact of RD.

the variations in the timing of RD adoption among utilities. Using quasi-experimental technique based on matching, we were able to establish the causal effect of RD implementation on electricity prices across customers. Finally, we also provide an indication on how RD influences welfare in each state considering the social cost of emissions.

Given the declining costs of distributed generation[2], our analysis suggests that RD could maintain the utility's profits at the expense of households or end-users through higher electricity rates and lower equilibrium output. The risk burden, due to uncertainty in the output of distributed generation, also shifts from the utility to the consumers. While RD can provide welfare gains to high-income earners who can afford to have distributed generation or more efficient appliances, it implies losses to low-income earners (or renters) who do not have distributed generation. Overall, the excess burden of subsidies for distributed generation (such as solar panels) is larger with RD than without.

Our empirical investigation with data on investor-owned utilities in the United States indicates that the magnitude of price adjustments due to decoupling is sizable and that how it works in practice may be different from how it should work nominally. Previous studies indicated that (i) the immediate impacts of decoupling on electricity prices have been small (Morgan, 2013; Kahn-Lang, 2016), and (ii) decoupling adjustments have been symmetric—both upward adjustments due to unexpected decreases in sales and downward adjustments due to unexpected increases in sales have been observed (Morgan, 2013). Morgan's observation is based on the actual size of the decoupling adjustments between 2005 and 2011 (Figure 1) and thus represents the instantaneous impacts of decoupling on electric rates. Building on an empirical study about the short-run impacts of RD on electricity prices (Kahn-Lang, 2016), we estimate the price impacts by adopting an econometric strategy that addresses the endogeneity of RD adoption. We find that decoupling tends to increase the electricity rates rather substantially over months upon imple-

[2]Following convention, we define distributed generation as the process of generating electricity from decentralized—often small-scale but numerous—energy sources. An example is the roof-top solar photovoltaics (PV).

mentation (about 19% on average over two years). We also find that lower adjustments on prices are not statistically significant when the sales increase beyond what is predicted based on the trends. This finding suggests that, contrary to how decoupling is specified on dockets in many states, decoupling adjustments have not been implemented symmetrically. The prices appear to demonstrate downward rigidity as well as statistically significant upward adjustments on average across utilities that experienced decoupling.

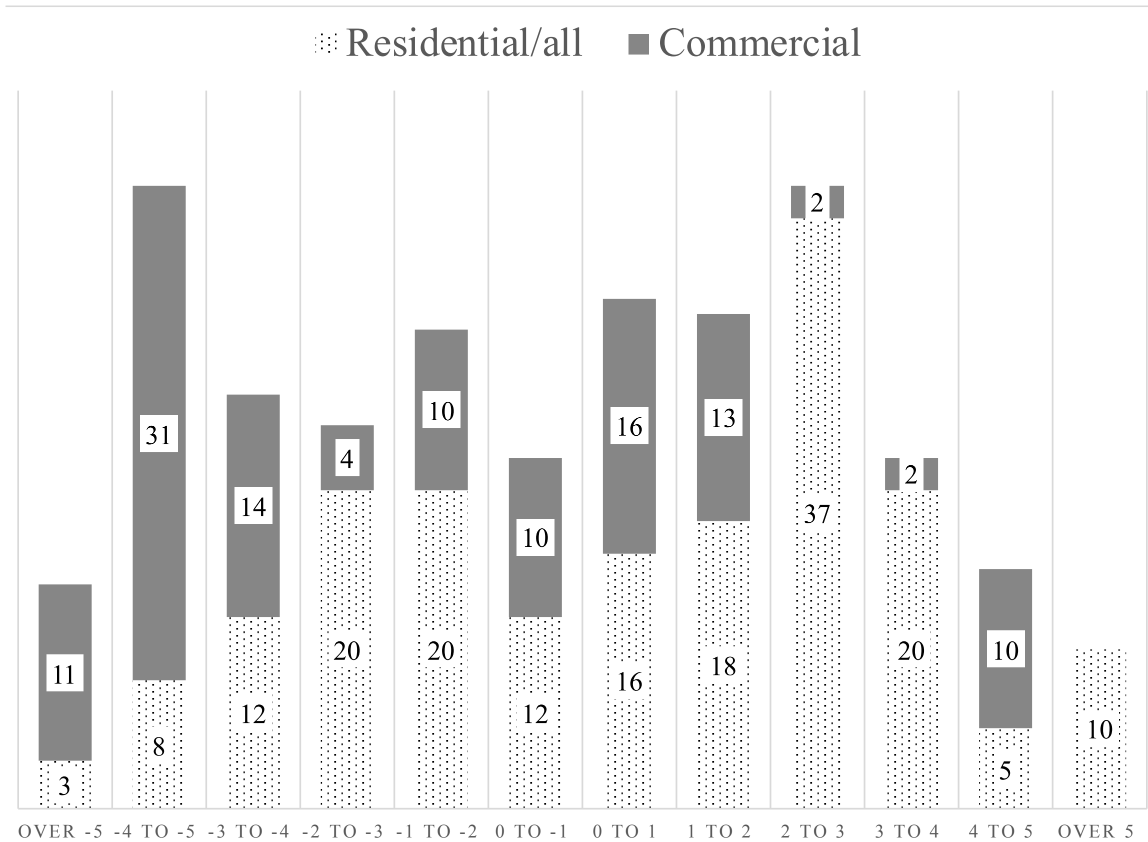
Turning to the welfare impacts of decoupling, we demonstrate empirically that revenue decoupling has generated negative effects in most states. This is because the retail electricity prices tend to exceed the social marginal costs of electricity generation in all states with decoupling in 2011, which implies that further price increases due to RD would amplify the distortions due to gaps in the price and the marginal costs.

In what follows, Section 2 provides a brief overview of RD adoption in the United States. We apply a simple theoretical framework to illustrate RD (Section 3) to study its welfare and distributional impacts (Section 4). We then discuss our empirical strategy and the results regarding the impacts of decoupling on electricity prices (Section 5) and on welfare by taking into account the social marginal costs of electricity generation across the U.S. states that have adopted decoupling (Section 6). Section 7 provides a summary and discussion of the policy implications. The appendix contains additional theoretical properties of revenue decoupling regarding its distributional impacts and risk allocations.

2 An overview of revenue decoupling

2.1 How revenue decoupling works

Revenue decoupling is generally defined as a rate-making mechanism designed to "decouple" the utility's revenues from its sales. By removing the dependence of the utility's earnings from sales, RD essentially removes the utility's disincentives to administer and promote customer efforts to reduce energy consumption or to install distributed genera-



Based on Morgan (2013) page 10. The horizontal axis indicates the ranges of rate adjustments (%) where negative numbers indicate negative adjustments or refunds to rate payers while the positive numbers indicate upward price adjustments. The number of adjustment cases between 2005 and 2011 are indicated in the bar chart.

Figure 1: Monthly electric utility decoupling adjustment rate impacts

tion that often utilizes renewable energy.

Table 1 provides a simple illustration of how RD works[3]. 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. If the state decides to adopt RD, customers' unit price

[3]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., 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).

increases in order to achieve the allowed revenue.

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.

RD, in effect, provides mechanisms for customers to receive refunds or pay surcharges based on whether the revenues the utility actually received from customers were greater or smaller than the revenues the mechanism calculates, respectively.[4]

2.2 Current Implementation

Table 2 describes how RD was implemented across U.S. states over the last decade. California was the first state to implement RD in the 1990s (Morgan, 2013). However, it was during and immediately after the US financial crisis that the policy was widely adopted in many states. Since Vermont approved RD mechanism in 2006, the number of states adopting the policy has increased. As of 2016, 19 states (including the District of Columbia) offer RD to the electric utilities.[5]

2.3 Divergent Views on RD

As a growing number of states have ventured into adopting policies and regulations with energy efficiency objectives, debates on the effectiveness of revenue decoupling flooded

[4]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).

[5]Adoption of RD in a state does not necessarily mean all utilities in the state have revenue decoupling mechanism.

Table 2: Implementation of Revenue Decoupling in the United States

Since 1990's	2006	2007	2008	2009	2010	2011	2012
California	California	California	California	California	California	California	California
	Vermont*	Idaho	Idaho	Connecticut	Connecticut	Connecticut	Connecticut
		Maryland	Maryland	Idaho	Hawaii	Hawaii	Hawaii
		New York	New York	Maryland	Idaho	Idaho	Idaho
		Vermont*	Vermont*	Michigan	Maryland	Maryland	Maryland
				New York	Michigan	Massachusetts	Massachusetts
				Oregon	New York	Michigan	Michigan
				Vermont*	Oregon	New York	New York
				Washington, DC	Vermont	Oregon	Ohio
				Wisconsin	Washington, DC	Vermont*	Oregon
					Wisconsin	Washington, DC	Rhode Island
						Wisconsin	Vermont*
							Washington, DC
							Wisconsin

Note: Based on Morgan (2013). The above implementation reflects each State Commission's approval of the first decoupling mechanism. Passing of a legislation may have been completed earlier. Some states may have pending RD implementation to date.

the energy industry. One of the supporting arguments for RD includes the potential improvement in efficiency among service providers. 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). Decoupling adjustments rates have been "imperceptible" to consumers, which generally stay within the 1-percent band (Morgan, 2013). 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 including 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).

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, the firm no longer has an incentive to minimize costs under RD (Kihm, 2009). Studies such as Knittel (2002) 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.

Thus far, no evidence exists to support RD as necessary for the successful implementation of utility-funded energy efficiency initiatives (Brennan, 2010). As for the long-term effect, if the company's profits-to-capital ratio is regulated at a certain percentage then there is a strong incentive for companies to over-invest in order to increase profits overall.

3 Modeling electricity markets with revenue decoupling

3.1 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 $v_i'' < 0$.[6] This specification, with zero income elasticity of electricity demand, could be justified in light of some recent empirical findings of zero or very small income elasticity.[7]

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

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

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

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.[8] 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 $i, j \in [0, N]$ 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.

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

Now, let

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

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 $px+qn+y \le M$ yields the households' utility-maximizing allocation given p, q. The first-order condition is given by

$$v'(e) = v'(x + h(n)) = p; \tag{1}$$

$$h'(n) = \frac{q}{p}. \tag{2}$$

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.

3.2 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

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

3.3 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.

3.4 Regulation with and without decoupling

We consider two regulatory regimes: (1) traditional rate of return regulation with no revenue decoupling; and (2) the revenue decoupling regime. With no decoupling, the electricity price is held fixed between rate cases[9]. Under revenue decoupling, 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.

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.

3.4.1 Traditional non-RD regulation

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).[10] We can write the regulatory constraint as some fixed price that includes the maximum

[9]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.

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

allowable 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).

3.4.2 Revenue Decoupling

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.

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 $x(p,q)$. Our approach does not deal with how revenue requirement might change over rate cases, but we will discuss an implication of RD on the long-run dynamics beyond rate cases in the conclusion section.

4 Effects of revenue decoupling

4.1 Changes in the cost of solar panels

4.1.1 Effects on electricity price and quantity

Here we study the effect of an exogenous change in the price (or the cost) of solar panels q. We first compare the impacts on electricity price and quantity with and without revenue decoupling.

With no revenue decoupling, the equilibrium condition is given by equations (1) and (2). With revenue decoupling in place, the necessary and sufficient condition for an (interior) equilibrium is given by (1) and (2) 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).*

The proof is in the appendix. In the empirically relevant case with inelastic electricity demand, the grid-supplied electricity consumption decreases, and the price p increases, as q drops.

4.1.2 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

$$W_r = u(x_r + h(n_r)) - p_r x_r - q n_r + [p x_r - c x_r - F] = u(x_r + h(n_r)) - c x_r - q n_r - F.$$

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 (10) and (13) in the proof of Proposition 1 (in the appendix) 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.*

4.2 Changes in the subsidy for solar installation

In the United States, federal tax credits for consumer energy efficiency—including those for solar panels—exist. Many U.S. states also provide state-level tax credits for installing solar panels. For qualified households, these tax credits work as a subsidy for installing solar panels. With subsidy $s > 0$ per unit, the consumer price of solar panels is given by $\bar{q} = q - s$.

4.2.1 Effects on electricity price and quantity

Without revenue decoupling, the interior equilibrium satisfies (1) and (2) with $p = \bar{p}$. Under revenue decoupling, the interior equilibrium satisfies (1), (2) 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.*

4.2.2 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:

$$\frac{dW_{noRD}}{ds} = -(p-c)\eta_{x,q}\frac{x}{\bar{q}} + s\eta_n\frac{n}{\bar{q}}, \tag{3}$$

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' in 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 (15) 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:

$$\frac{dW_{RD}}{ds} = -(p-c)\frac{\eta_{x,q}}{1-|\eta_x|}\frac{x}{\bar{q}} + s\frac{-\left\{-\eta_x + \eta_n\frac{qn}{px}\right\}\eta_n\frac{n}{q}}{1-|\eta_x|} + s\frac{-|\eta_n|\frac{n}{q}}{1-|\eta_x|}. \tag{4}$$

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.*

The appendix contains 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.

4.3 Externalities of electricity generation

We describe how the analysis changes if we assume that the utility's electric portfolio is highly fossil-fuel intensive and the grid-supplied electricity involves negative externalities in the form of air pollution. 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.

5 Effects of RD on electricity prices: empirical evidence

5.1 Empirical strategy

Here we investigate how revenue decoupling has influenced the electricity prices that consumers face in the United States. The empirical analysis in identifying 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.[11] 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

[11]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.

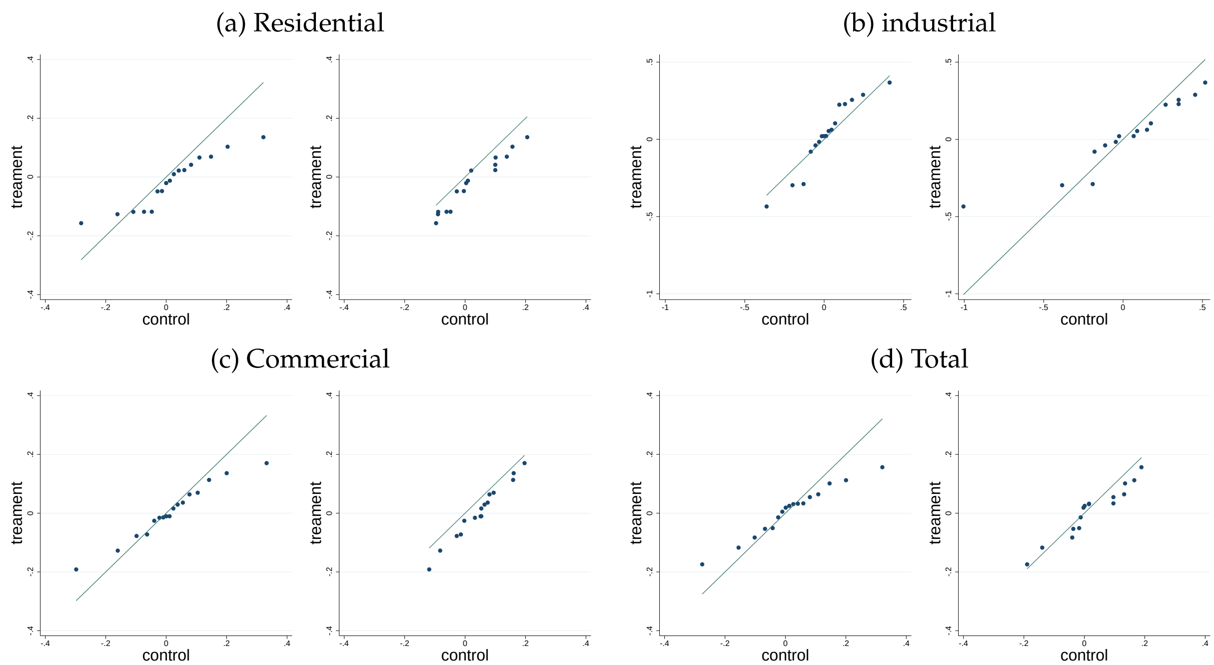
that may bias our estimates.

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.

Third, we employ a one-to-one propensity score matching to develop a reasonable counterfactual, which has been the main challenge in any quasi-experimental study. As pointed out by Dehejia and Wahba (2002), estimates obtained by comparing a treatment group with the rest of the population could be biased if the two groups have different pre-treatment characteristics. In our context, this can happen when utilities suffering from a decline in sales possibly due to increased share in distributed generation or improved energy efficiency among customers have apply for the RD scheme. To address this issue, 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. In this way, we can argue that these 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.

To illustrate how our matching procedure performs, we plot the distribution of the treatment and control group using a quantile-quantile (Q-Q) plot. If the two distributions of pre-treatment price trends are similar, the points in the Q-Q plot will approximately lie on the 45-degree line. We do this for the unmatched and matched sample. Figure 2 illustrates that our matching procedure generally dominates the unmatched approach in making the two groups comparable. In particular, we find that in the unmatched sample the distribution for the treated group is more dispersed and skewed than the control group. This pattern holds for residential, commercial and all customers.

Figure 2: Quantile-quantile plot of log(price)$_{t-1}$ - log(price)$_{t-6}$: Treated (RD) vs. Control (non-RD) utilities



The plot compares the distribution of the log difference in electricity prices between $t-1$ and $t-6$, t being the year-month of the RD adoption, between treatment and control groups using unmatched sample (left panel) and matched sample (right panel). The data covers the period 2001.1-2012.12.

We also 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 prices using the DD approach. More specifically, we estimate the following equation on the matched sample:

$$p_{it} = \alpha_i + \beta_t + \gamma Post_{it} + \delta RD_{it} + \varepsilon_{it}, \quad (5)$$

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} is a dummy variable that turns to unity when a utility is subject to 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). ε is the error term. Coefficient δ measures the effect of implementing RD on the outcome variable.

5.2 Data

We use US EIA monthly data (2000.01-2012.12) on about 200 investor-owned utilities to investigate how decoupling 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 Kahn-Lang (2016). Table 4 presents the descriptive statistics of the entire sample.

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

	Unconditional Mean		
	nonRD	**RD**	**p-value**
Pre-RD Prices (in $/kWh)			
Residential	0.15	0.17	0.597
Commercial	0.14	0.15	0.837
Industrial	0.12	0.12	0.988
Total	0.14	0.15	0.705
Pre-RD Price Trend			
Residential	0.080	-0.010	0.179
Commercial	0.080	0.040	0.196
Industrial	0.060	0.040	0.997
Total	0.200	0.140	0.621
Pre-RD Sales (in GWh)			
Residential	832.28	444.15	0.132
Commercial	435.21	352.33	0.577
Industrial	294.46	177.61	0.446
Total	1567.18	974.32	0.229
Pre-RD Sales Trend			
Residential	0.17	0.13	0.527
Commercial	0.00	0.07	0.259
Industrial	0.05	-0.07	0.525
Total	0.12	0.05	0.246
Pre-RD Revenues (in million $)			
Residential	119.89	59.56	0.074
Commercial	56.81	43.22	0.444
Industrial	24.07	14.30	0.401
Total	201.17	117.11	0.132
Pre-RD Revenue Trend			
Residential	0.20	0.11	0.255
Commercial	0.05	0.08	0.746
Industrial	0.08	-0.04	0.545
Total	0.15	0.06	0.262

Notes: Figures reflect the unconditional means of 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: US-EIA.

In Table 4, we observe that the utilities that experienced decoupling have higher average prices than those without decoupling. This observation applies to all sectors (i.e.

Table 4: 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
Sales (in GWh)						
Residential	26965	339.44	581.02	2604	421.31	423.64
Commercial	26495	242.13	348.25	2604	229.38	309.81
Industrial	26963	319.67	575.54	2604	380.06	448.34
Total	27169	898.52	1,388.56	2604	1,035.95	1,086.13
Revenues (million $)						
Residential	26903	34.43	65.10	2604	53.06	60.19
Commercial	26496	13.60	20.73	2602	16.10	20.28
Industrial	26935	28.03	59.82	2604	42.13	57.17
Total	27126	75.83	137.74	2604	111.86	124.41
No. of unique State-Utilities			192			17
Years			2000-2011			2000-2011

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: US-Energy Information Administration.

residential, commercial, and industrial). Decoupled utilities have higher sales, except for commercial customers, and higher revenues for all customers.

5.3 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 panel A of Table 5, show that customers within each sector experienced an increase in electricity rates following the utility's adoption of revenue decoupling. However, only the effect on the residential sector's electricity price is significant.

In panel B, we additionally control for pre-RD trends in the average price of each sector. With this control, the effect of RD on the electricity price remains the same for the residential sector while the overall impact is estimated more precisely. This result suggests that there may be some unobserved non-random utility-state-level characteristics associated with the adoption of RD which may influence pricing for each customer group. The results indicate that it is important to address this selection bias in the analysis.

Table 5: The effect of adopting RD on prices, unmatched sample.

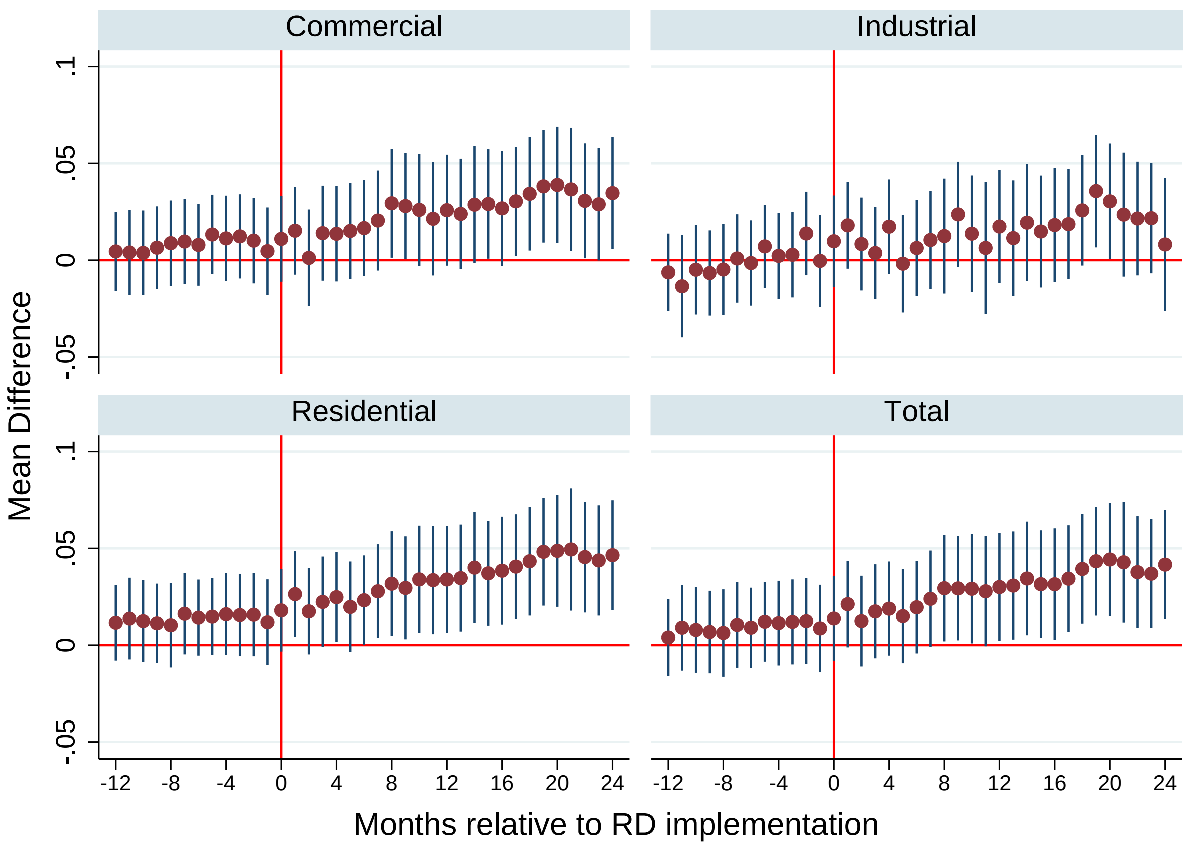
	Residential	Industrial	Commercial	Total
A. Basic OLS	0.013**	0.008	0.040	0.039
	(0.006)	(0.006)	(0.028)	(0.031)
R-sq. (within)	0.37	0.13	0.01	0.01
Observations	27041	27064	25595	27588
B. OLS with Matching Variables	0.013**	0.010	0.020	0.013**
	(0.006)	(0.006)	(0.015)	(0.006)
R-sq. (within)	0.40	0.18	0.01	0.04
Observations	25575	25665	24210	26101
Time Fixed Effects	yes	yes	yes	yes
Utiliy-State Fixed Effects	yes	yes	yes	yes

Note: The table shows the result of estimating equation 5 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.

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

As a first step, we present the impact of revenue decoupling on electricity prices graphically by plotting the average price difference between the treated and control utilities over time (Figure 3). The plots have two features worth discussing. First, it appears that our matching procedure generated matched pairs that are very similar prior to the treated group's adoption of RD. Both groups display very similar price paths prior to the policy change, as reflected by the flat and statistically insignificant difference in pre-RD average prices. This similarity in pre-RD price trends holds true for all customers. Second, the difference starts to go up two to three months after the policy change, suggesting that decoupled utilities start to charge higher prices immediately after the policy change. Note that the difference continues to grow over time, which provides an indication that perhaps there is some rigidity in the downward movement of prices after the policy change. We will come back to this issue shortly.

Figure 3: Mean differences in electricity prices between utilities with and without decoupling.



Note: Each point correspond to unconditional mean difference between utilities that adopted RD and those that remain in the old rate-making scheme. The whiskers correspond to 1-standard-error bands.

We test the effect of decoupling on each sector's price level by estimating equation (5) using our matched sample. The results suggest that all customers of decoupled utilities experienced a statistically significant increase in electricity prices relative to the control group (Table 6). The magnitude seems to be economically significant. For example, residential electricity rates in decoupled utilities increase, on average, by $0.02/kWh relative to the baseline. The figure translates to about 19% increase from the mean residential price of non-decoupled utilities. The relative increase in industrial and commercial is also significant.

Table 6: The effect of RD on electricity prices, matched sample.

	Residential	Industrial	Commercial	Total
RD	0.020**	0.016*	0.016*	0.019**
	(0.008)	(0.008)	(0.008)	(0.008)
R-sq. (within)	0.14	0.09	0.04	0.13
Observations	1176	1176	1174	1176
Time Fixed Effects	yes	yes	yes	yes
Utiliy-State Fixed Effects	yes	yes	yes	yes

Note: The table shows the result of estimating equation 5 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.

5.5 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 5 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.

Table 7 summarizes the results. RD remains positive and significant. In the mean time, the indicator variable for actual demand exceeding 12-month projection is negative but estimated imprecisely, except for residential electricity prices. Surprisingly, the interaction term is positive and marginally significant for commercial and residential prices. We therefore find no strong evidence to suggest that electricity prices are adjusted downward in a significant way when the sales grow beyond the trend, and that the decoupling adjustments appear to be asymmetric. Even if we assume that demand projection is done every 6 months, we do not find strong evidence to suggest that RD works symmetrically.

6 Welfare implication of RD

6.1 Welfare impacts of RD and externalities of electricity generation

The preceding analysis established that the adoption of revenue decoupling increases electricity rates. This price increase 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. On the one hand, under traditional non-dynamic pricing, the electricity price tends to exceed the (private) marginal costs

Table 7: Tests for symmetry in revenue decoupling adjustments.

	Residential	Industrial	Commercial	Total
RD	0.013**	0.013**	0.011*	0.014**
	(0.006)	(0.006)	(0.006)	(0.005)
Higher growth (12 months)	-0.006*	-0.000	-0.004	-0.004
	(0.003)	(0.003)	(0.003)	(0.003)
RD*Higher growth (12 months)	0.008*	0.004	0.008*	0.006
	(0.005)	(0.004)	(0.005)	(0.004)
R-sq. (within)	0.26	0.16	0.23	0.25
N	1176	1174	1176	1176
RD	0.018**	0.019**	0.017**	0.019***
	(0.007)	(0.007)	(0.007)	(0.007)
Higher growth (6 months)	-0.001	0.001	0.000	-0.000
	(0.002)	(0.003)	(0.002)	(0.002)
RD*Higher growth (6 months)	-0.002	-0.007	-0.003	-0.003
	(0.003)	(0.004)	(0.003)	(0.002)
R-sq. (within)	0.25	0.17	0.22	0.25
N	1176	1174	1176	1176
Time Fixed Effects	yes	yes	yes	yes
Utiliy-State Fixed Effects	yes	yes	yes	yes

Note: The table shows the result of estimating equation 5 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.

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 (SMC, 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. Here we investigate the welfare impacts of RD by incorporating the relationship between retail electricity prices and SMC across U.S. states.

Indeed, the price-SMC relationship differs across states because differences in the fuel mix imply different marginal external costs. While the marginal external costs of air pollution may be small in a state that relies on hydropower, a state with large presence of coal-fired power plants would face higher marginal external costs. There are also differences in terms of exposure to risk, which greatly depends on the current demographics of the state at a certain time period as well as on the proximity of the emitter to the recipient of energy-related pollution, among others. These differences across states imply that solar subsidy in one state may have different welfare implications in another.

6.2 Computing the social marginal costs of electricity generation

In order to compute the average SMC per state, we use the average daily marginal damage per kWh (global and local pollutants) available for nine North American Electric Reliability Corporations (NERC) regions from Holland et al. (2016). The data was generated from hourly emissions of CO2, SO2, NOx, and PM2:5 at 1486 power plants as well as hourly electricity consumption (i.e., electricity load) for each of our nine NERC regions from 2010-2012. Based on the emissions and demographic data, Holland et al. (2016) use the AP2 model (an integrated assessment air pollution model) to link the ambient concentrations of these pollutants to exposures, physical effects, and monetary damages. For the purpose of our state-level analysis, we map out the states in each NERC region following the concordance provided in Holland et al. (2016), which matches county Federal

Information Processing Standard (FIPS) to the 9 NERC regions. In cases where a state is served by two or more NERC regions, we apply the estimates of the NERC region that serves the largest number of counties in a particular state.

Next, we apply the system lambda reported to the Federal Energy Regulatory Commission (FERC) to estimate (private) marginal costs of electricity at the state level.[12]. Data from FERC in 2011 is based on hourly system lambda by the balancing authority (BA).[13] To estimate system lambda by state, we take the average system lambda across all BAs situated in each state, weighted by the monthly peak load of each BA. We then apportion the weighted-average marginal external costs to each state, following NERC regions and balancing authorities mapping as of 2012 (see Figure A.1 in the Appendix).

The last piece of information to assess price-SMC relationship is the retail price. We obtain average retail prices from EIA and express all values in 2011US$ using consumer price index (CPI) for energy from the Federal Reserve Economic Data (FRED). We then calculate the value of retail electricity price in excess of SMC.

6.3 Results on the price-SMC relationship across states

The main results are summarized in Figure 4 (Table A.9 in the appendix describes the detail). First, we observe considerable heterogeneity in the retail price in excess of the SMC. The difference can be large and positive, large and negative, or negligible, depending on the location. For example, we find that customers in California were paying about $0.11 per kWh in excess of SMC in 2011. In contrast, Wisconsin electricity users were short of $0.01 per kWh to fully cover the marginal damage of emissions associated with energy use.

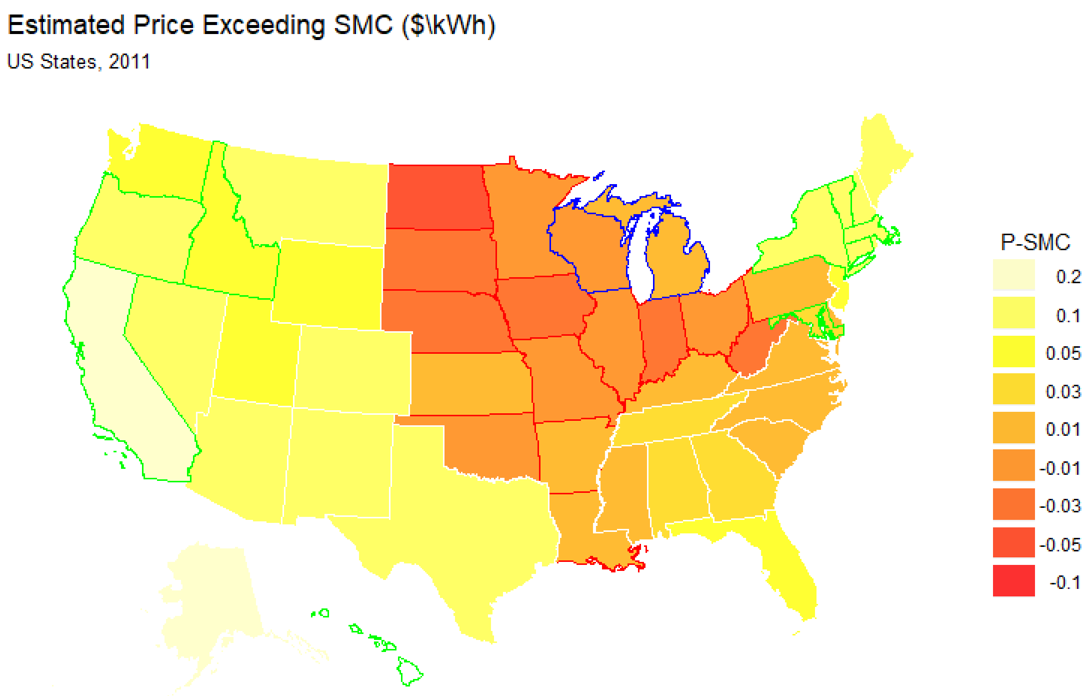
Second, in most of the states that have adopted RD, the retail electricity prices exceed

[12] FERC defines system lambda as the single incremental cost of energy measured in $MWh.

[13] The NERC defines a balancing authority as "the responsible entity that integrates resource plans ahead of time, maintains load-interchange-generation balance within a Balancing Authority Area, and supports Interconnection frequency in real-time". BAs could be electric utilities.

the SMC. In fact, Michigan and Wisconsin are the only the decoupled states where the electricity retail rates are lower than the respective SMC. To the extent that the P-SMC relationship does not change significantly in 2000-2012, this finding indicates that RD tends to generate negative welfare impacts for most states that implemented the policies. This is particularly true for Hawaii and California where electricity retail prices in 2011 exceed SMC by at least $0.11 per kWh. Over time, the grids can become more efficient and cleaner across states. Such changes in the grids may magnify the negative welfare effects of RD.

Figure 4: Average retail electricity prices and estimated social marginal costs.

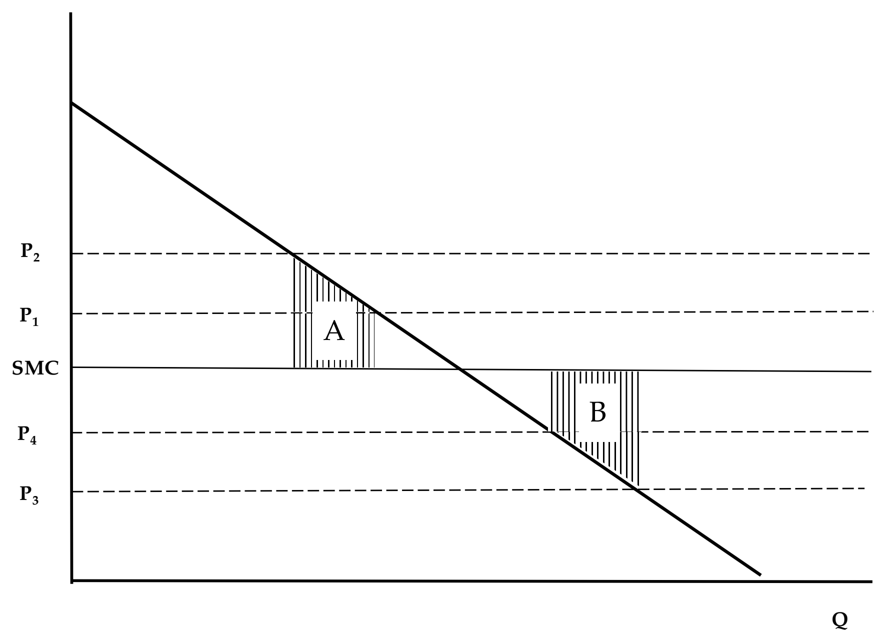


Note: All figures are in US$2011. States with red borders have P<SMC, while those with P>SMC have white borders. States with blue borders are decoupled states with P<SMC. States with green borders are decoupled states with P>SMC. Details are in Table A.9.

6.4 Welfare implications of Decoupling Non-Decoupled States

In order to quantify how revenue decoupling might influence the welfare of each state that have not implemented this policy, we now compute the potential deadweight loss or efficiency gains associated with the policy change. As illustrated in Figure 5, we approximate the demand to be linear around the observed prices and quantities. For example, a price increase from P_1 to P_2 induces a welfare loss of size A while a price increase from P_3 to P_4 increases welfare by size B in the figure. For each state s, the welfare change associated with decoupling is then given by

Figure 5: Illustration of deadweight loss (efficiency gains) with revenue decoupling.



$$\Delta W_s = (\Delta Q_s \cdot (P_s - SMC_s)) + \frac{1}{2}(\Delta Q_s \cdot \Delta P_s) \tag{6}$$

where Q_s and P_s are quantity demanded and price of electricity, respectively; and SMC is the social marginal cost as previously defined. Table 8 summarizes the results. If non-decoupled states would decide to adopt RD, aggregate welfare would be reduced by about \$190 million to \$237 million, assuming $\eta_x = 0.2$ and $\eta_x = 0.25$, respectively. This translates to about 0.64 to 0.77 percent of the total electric expenditure of the country or an extra cost of about $70-$83 per household in 2011.[14]

Table 8: Calculated changes in welfare due to decoupling for non-decoupled states at an assumed demand elasticity

Assumed elasticity	0.05	0.1	0.15	0.2	0.25	0.30
Change in welfare	-47,436	-94,873	-142,309	-189,745	-237,182	-284,618

Source: Authors' calculation. Figures are in 2011 1,000 U.S. dollars.

7 Discussion

Several U.S. states adopted revenue decoupling, which facilitates fixed cost recovery for utilities, over the last decade in the face of slow growth in electricity consumption. 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. Our theoretical analysis reveals that, provided that the demand for electricity is inelastic, revenue decoupling is expected to lower the utility's sales of electricity and increase the unit price of electricity as households invest in energy efficiency or distributed generation. The adoption of revenue decoupling also has negative impacts on the total economic welfare, relative to the traditional rate-of-return regulation.

We validated our theoretical findings by empirically examining the effect of RD adoption on electricity prices across different end-user sectors. We find robust and statistically strong evidence to suggest that adopting RD increases residential electricity prices. The results from employing a difference-in-differences approach on our matched sample suggests that RD increases prices for all sectors by about 18-20% compared to the baseline. In most states that have adopted RD, the retail prices exceed the marginal social costs of

[14] A typical US household consumed 10,986 kWh in 2011. Valued at $.99/kWh, the total electric expenditure of an average US household is $10,787.

electricity. This observation suggests that decoupling, and accompanying price increases, has resulted in negative welfare impacts in those states.

We analyzed the potential impact of adopting revenue decoupling on the welfare of households and the utility when there is uncertainty in distributed generation. Specifically, we found that the household's expected utility is adversely affected by an increase in the degree of uncertainty when revenue decoupling is in place. On the other hand, the adoption of revenue decoupling will not increase the expected losses for the utility when the degree of uncertainty in distributed generation increases. This observation supports the claim that the policy essentially transfers any demand-based risks from the utility to the consumers.

We also examined how the adoption of revenue decoupling impacts households with and without distributed generation. Revenue decoupling will unambiguously benefit those usually high-income households who can afford to install capital-intensive solar panels but adversely affect low-income households that do not. An implication is that policies that reduce the cost of solar panels, including production subsidies and tax credits, are generally regressive. We leave the estimation of the magnitude of the distributional consequence of RD to future researchers.

We note some additional directions in which our analysis can be extended in the future. First, our analysis is based on short-term periods (i.e., between rate cases) where the allowed revenues are held fixed. In practice, allowed revenues can increase (or decrease) if there are significant changes in either the demand or the cost due to the utility's conservation or efficiency programs. A study that incorporates how short-term fluctuations in demand would affect long-term prices and profits would be very useful. Second, many studies have established that revenue decoupling is not necessarily the driver of efficiency. Nonetheless, revenue decoupling may help promote efficiency by neutralizing the potential opposition through profit guarantees (Brennan, 2010). To the extent that revenue decoupling, even with its unintended consequences, may still be economically beneficial overall instead of not having state-spearheaded energy efficiency, conservation and sustainability programs is beyond the scope of the study. Finally, revenue decoupling is not compatible with a push for introducing real-time pricing (where the prices would reflect the contemporaneous social marginal costs of electricity services). Given that RD is not an ideal policy provision to enhance efficiency of the electricity sector, what alternatives would be more efficient while aligning electricity utilities' incentives with social goals? Analyzing this question is left for future research.

References

Borenstein, S. and Davis, L. W. (2012). The equity and efficiency of two-part tariffs in us natural gas markets. Journal of Law and Economics, 55(1):75–128.

Brennan, T. J. (2010). Decoupling in electric utilities. Journal of Regulatory Economics, 38(1):49–69.

Chu, L. Y. and Sappington, D. E. (2013). Motivating energy suppliers to promote energy conservation. Journal of Regulatory Economics, 43(3):229–247.

Costello, K. (2006). Revenue decoupling for natural gas utilities. National Regulatory Research Institute, April.

Dehejia, R. H. and Wahba, S. (2002). Propensity score-matching methods for nonexperimental causal studies. The Review of Economics and Statistics, 84(1):151–161.

Eto, J., Steven, S., and Belden, T. (1997). The theory and practice of decoupling utility revenues from sales. Utilities Policy, 6(1):43–55.

Friedman, L. S. (2011). The importance of marginal cost electricity pricing to the success of greenhouse gas reduction programs. Energy Policy, 39(11):7347–7360.

Goulder, L. H. and Williams, R. C. I. (2003). The substantial bias from ignoring general equilibrium effects in estimating excess burden, and a practical solution. Journal of Political Economy, 111(4):898–927.

Holland, S. P., Mansur, E. T., Muller, N. Z., and Yates, A. J. (2016). Are there environmental benefits from driving electric vehicles? The importance of local factors. American Economic Review, 106(12):3700–3729.

Joskow, P. L. (1974). Inflation and environmental concern: Structural change in the process of public utility price regulation. Journal of Law and Economics, 17:291.

Kahn-Lang, J. (2016). The effects of electric utility decoupling on energy efficiency. The Energy Journal, 37(4).

Kihm, S. (2009). When revenue decoupling will work ... and when it won't. The Electricity Journal, 22(8):19–28.

Knittel, C. R. (2002). Alternative regulatory methods and firm efficiency: stochastic frontier evidence from the us electricity industry. Review of Economics and Statistics, 84(3):530–540.

Lowry, M. N. and Makos, M. (2010). Review of distribution revenue decoupling mechanisms. PACIFIC ECONOMICS GROUP RESEARCH LLC.

Morgan, P. (2013). A decade of decoupling for us energy utilities: Rate impacts, designs, and observations. Technical report, Graceful Systems LLC.

Moskovitz, D., Harrington, C., and Austin, T. (1992). Decoupling vs. lost revenues: Regulatory considerations. The Regulatory Assistance Project.

Regulatory Assistance Project (2011). Revenue regulation and decoupling: A guide to theory and application. www.raponline.org/document/download/id/902.

Reiss, P. C. and White, M. W. (2005). Household electricity demand, revisited. Review of Economic Studies, 72(3):853–883.

Shirley, W. and Taylor, M. (2006). Decoupling utility profits from sales. In Prepared for Arizona Decoupling Stakeholder Meeting, Regulatory Assistance Project (RAP).

Sullivan, D., Wang, D., and Bennett, D. (2011). Essential to energy efficiency, but easy to explain: Frequently asked questions about decoupling. The Electricity Journal, 24(8):56 – 70.

Appendix

A Proof of Proposition 1

Total differentiation of (1) and (2) yields

$$v''(x+h(n))dx + v''(x+h(n))h'(n)dn = 0; \tag{7}$$

$$h''(n)dn = \frac{1}{p}dq. \tag{8}$$

From (8), we have $\frac{dn}{dq} = \frac{1}{ph''(n)} < 0$. Substitute this into (7) and we obtain

$$v''(x+h(n))\frac{dx}{dq} + v''(x+h(n))h'(n)\frac{1}{ph''(n)} = 0. \tag{9}$$

It follows that

$$\frac{dx_{noRD}}{dq} = -\frac{h'(n)}{ph''(n)} > 0, \tag{10}$$

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

$$\begin{pmatrix} v'' & -1 & v''h' \\ v''h' & 0 & v''(h')^2 + v'h'' \\ p & x & 0 \end{pmatrix} \begin{pmatrix} \frac{dx}{dq} \\ \frac{dp}{dq} \\ \frac{dn}{dq} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}. \tag{11}$$

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 (1) and (2) (with respect to x, n and p) to obtain

$$\begin{pmatrix} v'' & v''h' \\ v''h & v''(h')^2 + v'h'' \end{pmatrix} \begin{pmatrix} \frac{\partial x}{\partial p} \\ \frac{\partial n}{\partial p} \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}. \tag{12}$$

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

$$\frac{dx_{RD}}{dq} = \frac{\frac{v''h'x}{xv'h''v''}}{-\frac{v''(h')^2 + v'h''}{v''xh''} - 1} = \frac{-\frac{h'}{v'h''}}{1 + \eta_x} \begin{cases} > 0 & \text{if } |\eta_x| < 1; \\ \leq 0 & \text{if } |\eta_x| \geq 1. \end{cases} \tag{13}$$

Therefore, in the empirically relevant case with inelastic electricity demand ($|\eta_x| < 0$), the grid-supplied electricity consumption decreases as q drops. A similar comparative statics on p yields

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

B Proof of Proposition 3

For the case with no RD, a simple modification of the analysis in section 4.1.1 yields

$$\frac{dx_{noRD}}{ds} = \frac{h'(n)}{ph''(n)} < 0. \tag{14}$$

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

$$\begin{pmatrix} v'' & -1 & v''h' \\ v''h' & 0 & v''(h')^2 + v'h'' \\ p & x & 0 \end{pmatrix} \begin{pmatrix} \frac{dx}{ds} \\ \frac{dp}{ds} \\ \frac{dn}{ds} \end{pmatrix} = \begin{pmatrix} 0 \\ -1 \\ 0 \end{pmatrix}. \tag{15}$$

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 4.1.1. A similar comparative statics on p yields

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

C Proof of Proposition 4

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 3.

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 (12), 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 4.

D Distributional Impacts of Decoupling

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

Proposition 5 *When revenue decoupling is in place, 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,

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

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. ■

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

$$v'(x_s + \theta_s h(n)) = p_s \quad \text{for all } s \in S, \tag{16}$$

$$E[v'(x + \theta h(n))\theta]h'(n) = q. \tag{17}$$

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:

$$\begin{aligned} E[\pi] &= E[\bar{p}x - \bar{c}x] \\ &= (\bar{p} - \bar{c})E[x]. \end{aligned} \tag{18}$$

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:

$$e^* = x_s + \theta_s h(n), \quad \forall s \in S. \tag{19}$$

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

$$E[\pi] = E[(\bar{p} - c)(e^* - \theta h(n))] = (\bar{p} - \bar{c})[e^* - E(\theta)h(n)]$$
$$= (\bar{p} - c)[e^* - \bar{\theta}h(n)], \tag{20}$$

which is independent of the variance of θ. ■

To evaluate the effect of uncertainty under revenue decoupling, we assume that (with a 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:

$$E[\pi] = E[\bar{R} - \bar{c}x_s] \tag{21}$$

If we take the derivative of (21) with respect to ε, we get

$$\frac{dE[\pi]}{d\varepsilon} = -\bar{c}E[\frac{dx}{d\varepsilon}]. \tag{22}$$

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

$$\frac{dE[U]}{d\epsilon} = E\left[v'(X_s)\left\{\frac{dx_s^u}{d\varepsilon} + \frac{d\theta_s}{d\varepsilon}h(n)\right\}\right] = E\left[\frac{R}{x_s}\left\{\frac{dx_s^u}{d\varepsilon} + \frac{d\theta_s}{d\varepsilon}h(n)\right\}\right] \tag{23}$$

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

$$\left(v'' + \frac{R}{(x_1)^2}\right) dx_1 + v''(\theta-\varepsilon)h'(n)dn = v''h(n)d\varepsilon \tag{24}$$
$$\left(v'' + \frac{R}{(x_2)^2}\right) dx_2 + v''(\theta+\varepsilon)h'(n)dn = -v''h(n)d\epsilon \tag{25}$$

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

$$\sum_s \pi_s[v'(x_s+\theta_s h(n))\theta_s] = \frac{q}{h'(n)} \tag{26}$$

Totally differentiating the above conditions and manipulating terms, we obtain

$$\frac{1}{2}\left[v''(\theta-\varepsilon)dx_1 + v''(\theta+\varepsilon)dx_2\right] + \left[v''h(n)[(\theta^2+\varepsilon^2) + \frac{q}{h'(n)^2}h''(n)\right] dn$$
$$= \left[-v''h(n)\varepsilon + \frac{1}{2}[v'_1 - v'_2]\right] d\varepsilon \tag{27}$$

where $v'_1 \equiv v'(e_1)$, $v'_2 \equiv v'(e_2)$. Solving for $\frac{dE[U]}{d\varepsilon}$ will entail solving (24), (25), and (27) 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:

$$\frac{dx_1}{d\varepsilon} = \frac{D_{x1}}{D_A} \tag{28}$$

Where:

$$D_{x1} = \det \begin{bmatrix} v''h(n) & 0 & v''(\theta-\varepsilon)h'(n) \\ -v''h(n) & v'' + \frac{R}{(x_2)^2} & v''(\theta+\varepsilon)h'(n) \\ -v''h(n)\epsilon + \frac{1}{2}[v_1' - v_2'] & \frac{1}{2}v''(\theta+\varepsilon) & v''h'(n)(\theta^2+\varepsilon^2) + \frac{q}{h'(n)^2}h''(n) \end{bmatrix}, \tag{29}$$

$$D_A = \det \begin{bmatrix} v'' + \frac{R}{(x_1)^2} & 0 & v''(\theta-\epsilon)h'(n) \\ 0 & v'' + \frac{R}{(x_2)^2} & v''(\theta+\epsilon)h'(n) \\ \frac{1}{2}v''(\theta-\epsilon) & \frac{1}{2}v''(\theta+\epsilon) & v''h'(n)(\theta^2+\epsilon^2) + \frac{q}{h'(n)^2}h''(n) \end{bmatrix}. \tag{30}$$

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

$$\begin{aligned} E\left[\frac{dx_s}{d\varepsilon}\right] &= \frac{1}{2D_A}\left[\frac{R}{(x_2)^2}(v'')^2h'h\theta(\theta+\varepsilon) + \left(v'' + \frac{R}{(x_2)^2}\right)v''hq\frac{h''}{h'^2}\right] \\ &+ \frac{1}{2D_A}\left[-\frac{1}{2}(v_1'-v_2')(v''+\frac{R}{(x_2)^2})(v''(\theta-\varepsilon)h')\right] \\ &+ \frac{1}{2D_A}\left[-\frac{R}{(x_1)^2}(v'')^2h'h\theta(\theta-\varepsilon) - \left(v'' + \frac{R}{(x_1)^2}\right)v''hq\frac{h''}{h'^2}\right] \\ &+ \frac{1}{2D_A}\left[-\frac{1}{2}(v_1'-v_2')(v''+\frac{R}{(x_1)^2})(v''(\theta+\varepsilon)h')\right]. \end{aligned} \tag{31}$$

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

$$= \left[\frac{p_2}{x_2}(\theta+\varepsilon) - \frac{p_1}{x_1}(\theta-\varepsilon)\right]v''h'h\theta \tag{32}$$

$$+ \left[\frac{p_2}{x_2} - \frac{p_1}{x_1}\right]v''hq\frac{h''}{h'^2} \tag{33}$$

$$+ \left[\left(v'' + \frac{R}{(x_2)^2}\right)(\theta-\varepsilon) + \left(v'' + \frac{R}{(x_1)^2}\right)(\theta+\varepsilon)\right]\left[-\frac{1}{2}(v_1'-v_2')v''h'\right]. \tag{34}$$

Note that (32) 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, (33) is positive. For (34), 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 *Under the traditional regulation, 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.[15] ■

Proposition 9 *With revenue decoupling in place, 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:

$$\begin{aligned} D_A = &\left(v'' + \frac{R}{(x_1)^2}\right)\left(v'' + \frac{R}{(x_2)^2}\right)\left(v''h'(n)(\theta^2 + \epsilon^2) + \frac{q}{h'(n)^2}h''(n)\right) \\ &- \left(\frac{1}{2}v''(\theta - \epsilon)\right)\left(v'' + \frac{R}{(x_2)^2}\right)(v''(\theta - \epsilon)h'(n)) \\ &- \left(\frac{1}{2}v''(\theta + \epsilon)\right)(v''(\theta + \epsilon)h'(n))\left(v'' + \frac{R}{(x_1^2)^2}\right). \end{aligned} \quad (35)$$

[15] 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.

Note that D_A can be simplified:

$$
\begin{aligned}
D_A &= 0.5\left(v'' + \frac{\bar{R}}{(x_1)^2}\right)\left[\frac{\bar{R}}{(x_2)^2}v''h'(\theta+\varepsilon)^2 + \left(v'' + \frac{\bar{R}}{(x_2)^2}\right)v'(X_2)(\theta+\varepsilon)h''/h'\right] \\
&+ 0.5\left(v'' + \frac{\bar{R}}{(x_2)^2}\right)\left[\frac{\bar{R}}{(x_1)^2}v''h'(\theta-\varepsilon)^2 + \left(v'' + \frac{\bar{R}}{(x_1)^2}\right)v'(X_1)(\theta-\varepsilon)h''/h'\right]. \quad (36)
\end{aligned}
$$

Note that $(x_s)(v'' + \frac{R}{(x_s)^2}) = p_s' x_s + p_s = MR_s$. Note further that 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 $x_1 > 0$).

For D_{x1}:

$$
\begin{aligned}
D_{x1} = \frac{R}{(x_2)^2}(v'')^2 hh'\theta(\theta+\varepsilon) + \left(v'' + \frac{\bar{R}}{(x_2)^2}\right)v''hq\frac{h''}{h'^2} \\
- \left(\frac{1}{2}(v_1' - v_2')\right)\left(v'' + \frac{R}{(x_2)^2}\right)(v''(\theta-\varepsilon)h')
\end{aligned}
\quad (37)
$$

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

$$
D_{x2} = \det\begin{bmatrix}
v'' + \frac{R}{(x_1)^2} & v''h(n) & v''(\theta-\varepsilon)h'(n) \\
0 & -v''h(n) & v''(\theta+\epsilon)h'(n) \\
\frac{1}{2}v''(\theta-\epsilon) & -v''h(n)\varepsilon + \frac{1}{2}[V_1' - V_2'] & v''h'(n)(\theta^2+\varepsilon^2) + \frac{q}{h'(n)^2}h''(n)
\end{bmatrix}
\quad (38)
$$

As for D_{x2}, we have

$$
\begin{aligned}
D_{x2} = -\frac{R}{(x_1)^2}(v'')^2 hh'\theta(\theta-\varepsilon) - \left(v'' + \frac{R}{(x_1)^2}\right)v''hq\frac{h''}{h'^2} \\
- \left(\frac{1}{2}(v_1' - v_2')\right)\left(v'' + \frac{R}{(x_1)^2}\right)(v''(\theta+\varepsilon)h').
\end{aligned}
\quad (39)
$$

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

$$\begin{aligned}\frac{dEU}{d\varepsilon} &= E\left[\frac{R}{x_s}\left(\frac{dx_s^u}{d\varepsilon}+\frac{d\theta_s}{d\varepsilon}h(n)\right)\right] \\ &= E\left[\frac{R}{x_s}\frac{dx_s^u}{d\varepsilon}\right]+E\left[v'(X_s)\frac{d\theta_s}{d\varepsilon}h(n)\right],\end{aligned} \tag{40}$$

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 (37) and (39) into $\frac{dx_s^u}{d\varepsilon}$:

$$\begin{aligned}E\left[\frac{R}{x_s}\frac{dx_s^u}{d\varepsilon}\right] &= \frac{\bar{R}}{2D_A x_1^u x_2^u}\left[p_2(v'')^2h'h\theta(\theta+\varepsilon)+x_2\left(v''+\frac{\bar{R}}{(x_2)^2}\right)\left(v''hq\frac{h''}{h'^2}\right)\right] \\ &+\frac{\bar{R}}{2D_A x_1^u x_2^u}\left[-\frac{1}{2}(v_1'-v_2')x_2\left(v''+\frac{\bar{R}}{(x_2)^2}\right)(v''(\theta-\varepsilon)h')\right] \\ &+\frac{\bar{R}}{2D_A x_1^u x_2^u}\left[-p_1(v'')^2h'h\theta(\theta-\varepsilon)-x_1\left(v''+\frac{\bar{R}}{(x_1)^2}\right)\left(v''hq\frac{h''}{h'^2}\right)\right] \\ &+\frac{\bar{R}}{2D_A x_1^u x_2^u}\left[-\frac{1}{2}(v_1'-v_2')x_1\left(v''+\frac{\bar{R}}{(x_1)^2}\right)(v''(\theta+\varepsilon)h')\right],\end{aligned} \tag{41}$$

where the expressions inside the square brackets are all equal to

$$[p_2(\theta+\varepsilon)-p_1(\theta-\varepsilon)]\,(v'')^2h'h\theta \tag{42}$$

$$+\left[x_2^u\left(v''+\frac{\bar{R}}{(x_2)^2}\right)-x_1^u\left(v''+\frac{\bar{R}}{(x_1)^2}\right)\right]v''hq\frac{h''}{h'^2} \tag{43}$$

$$+\left[x_2^u\left(v''+\frac{\bar{R}}{(x_2)^2}\right)(\theta-\varepsilon)+x_1^u\left(v''+\frac{\bar{R}}{(x_1)^2}\right)(\theta+\varepsilon)\right]\left(-\frac{1}{2}\right)(v_1'-v_2')v''h'. \tag{44}$$

We will show that the terms (42) - (44) 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:

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

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 (42) is positive because $p_1 < p_2$ and $\theta - \varepsilon < \theta + \varepsilon$ while term (43) implies $[v''(x_2 - x_1) + (p_2 - p_1)]v''hq\frac{h''}{h'^2} > 0$. Term (44) 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 (40).

$$\begin{aligned} E[v'\frac{d\theta_s}{d\varepsilon}h] &= \frac{1}{2}[v_1'(-h) - v_2'(h)] \\ &= \frac{1}{2}[p_2 - p_1]h > 0. \end{aligned} \tag{45}$$

Therefore, we need to evaluate the sum of the two terms in (40).

$$\frac{dEU}{d\varepsilon} = E[v'\frac{dx_s}{d\varepsilon}] + E[v'\frac{d\theta_s}{d\varepsilon}h] = E[v'\frac{dx_s}{d\varepsilon}] + D_A(x_1 - x_2)h. \tag{46}$$

We also have

$$\begin{aligned} &D_A(x_1 - x_2)h \\ &= \frac{1}{2}\left[\left(v'' + \frac{R}{(x_1^U)^2}\right)\frac{R}{(x_2^U)^2}v''h'(\theta+\varepsilon)^2 + \left(v'' + \frac{R}{(x_2^U)^2}\right)\frac{R}{(x_1^U)^2}v''h'(\theta-\varepsilon)^2\right](x_1 - x_2)h \end{aligned} \tag{47}$$

$$-\frac{1}{2}x_2\left(v'' + \frac{R}{(x_1^U)^2}\right)\left(v'' + \frac{R}{(x_2^U)^2}\right)hq\frac{h''}{h'^2} + \frac{1}{2}x_1\left(v'' + \frac{R}{(x_1^U)^2}\right)\left(v'' + \frac{R}{(x_2^U)^2}\right)hq\frac{h''}{h'^2}. \tag{48}$$

We can verify that (47) is positive. If we sum up (43) and (48), we have:

$$\begin{aligned}
\text{Eqs. (43)} + (48) &= x_2\left(v'' + \frac{R}{(x_2^U)^2}\right)hq\frac{h''}{h'^2}\left[v'' - \frac{1}{2}\left(v'' + \frac{R}{(x_1^U)^2}\right)\right] \\
&- x_1\left(v'' + \frac{R}{(x_1^U)^2}\right)hq\frac{h''}{h'^2}\left[v'' - \frac{1}{2}\left(v'' + \frac{R}{(x_2)^2}\right)\right] \\
&= \frac{1}{2}hq\frac{h''}{h'^2}\left[(v'')^2x_2 + v''\frac{R}{x_2} - v''\frac{R}{x_1} + \frac{R}{x_1x_2}\right] \\
&- \frac{1}{2}hq\frac{h''}{h'^2}\left[(v'')^2x_1 + v''\frac{R}{x_1} - v''\frac{R}{x_1} + \frac{R}{x_1x_2}\right] \\
&= \frac{1}{2}hq\frac{h''}{h'^2}\left[(v'')^2(x_2 - x_1) + v''(p_2 - p_1)\right] \\
&> 0 \qquad (49)
\end{aligned}$$

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

To show how $D_A < 0$, 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 $\frac{dx_1^u}{d_p1} = \frac{Dx_1}{Du}$, where

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

and

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

Solving for Dx_1 yields:

$$Dx_1 = v''\left[v''h'(\theta^2+\varepsilon^2)+q\frac{h''}{(h')^2}\right]-\frac{1}{2}(v'')^2(\theta+\varepsilon)^2h'. \tag{50}$$

As for Du, we have

$$\begin{aligned} Du &= (v'')^2\left[v''h'(\theta^2+\varepsilon^2)+q\frac{h''}{(h')^2}\right]-\frac{1}{2}(v'')^3(\theta-\varepsilon)^2h'-\frac{1}{2}(v'')^3(\theta+\varepsilon)^2h' \\ &= (v'')^2q\frac{h''}{(h')^2}. \end{aligned} \tag{51}$$

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

$$\frac{dx_1^u}{dp_1} = \frac{v''\left[v''h'(\theta^2+\varepsilon^2)+q\frac{h''}{(h')^2}\right]-\frac{1}{2}(v'')^2(\theta+\varepsilon)^2h'}{(v'')^2q\frac{h''}{(h')^2}} = \frac{\frac{1}{2}h'(\theta-\varepsilon)^2}{q\frac{h''}{(h')^2}}+\frac{1}{v''}. \tag{52}$$

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;

$$\frac{dx_1^u}{dp_1}\frac{p_1}{x_1^u} = \frac{p_1}{x_1^u}\left[\frac{\frac{1}{2}h'(\theta-\varepsilon)^2}{q\frac{h''}{(h')^2}}+\frac{1}{v''}\right] > -1 \Leftrightarrow \frac{p_1}{x_1^u}\left[\frac{v''\frac{1}{2}h'(\theta-\varepsilon)^2+q\frac{h''}{(h')^2}}{v''x_1^uq\frac{h''}{(h')^2}}\right] > -1. \tag{53}$$

Because $v''x_1^uq\frac{h''}{(h')^2}>0$, it follows from (53) that

$$p_1v''\frac{1}{2}h'(\theta-\varepsilon)^2+p_1q\frac{h''}{(h')^2} > -v''x_1^uq\frac{h''}{(h')^2}. \tag{54}$$

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

$$
\begin{aligned}
-\frac{dx_1^u}{dp_1}\frac{p_1}{x_1^u} < 1 &\Leftrightarrow \frac{v'(X_1)}{x_1^u}v''\frac{1}{2}h'(\theta-\varepsilon)^2 + \frac{v'(X_1)}{x_1^u}q\frac{h''}{(h')^2} + v''q\frac{h''}{(h')^2} > 0 \\
&\Leftrightarrow \frac{R}{(x_1^u)^2}v''\frac{1}{2}h'(\theta-\varepsilon)^2 + \left(\frac{R}{x_1^u} + v''\right)q\frac{h''}{(h')^2} > 0. \qquad (55)
\end{aligned}
$$

Similarly, we can have

$$
\begin{aligned}
-\frac{dx_2^u}{dp_2}\frac{p_2}{x_2^u} < 1 &\Leftrightarrow \frac{v'(X_2)}{x_2^u}v''\frac{1}{2}h'(\theta+\varepsilon)^2 + \frac{v'(X_2)}{x_2^u}q\frac{h''}{(h')^2} + v''q\frac{h''}{(h')^2} > 0 \\
&\Leftrightarrow \frac{R}{(x_2^u)^2}v''\frac{1}{2}h'(\theta+\varepsilon)^2 + \left(\frac{R}{x_2^u} + v''\right)q\frac{h''}{(h')^2} > 0. \qquad (56)
\end{aligned}
$$

Recall that:

$$
\begin{aligned}
D_A = &\left(v'' + \frac{\bar{R}}{(x_1)^2}\right)\left[0.5\frac{\bar{R}}{(x_2)^2}v''h'(\theta+\varepsilon)^2 + 0.5\left(v'' + \frac{\bar{R}}{(x_2)^2}\right)q\frac{h''}{(h')^2}\right] \\
&+ \left(v'' + \frac{\bar{R}}{(x_2)^2}\right)\left[0.5\frac{\bar{R}}{(x_1)^2}v''h'(\theta-\varepsilon)^2 + 0.5\left(v'' + \frac{\bar{R}}{(x_1)^2}\right)q\frac{h''}{(h')^2}\right]. \qquad (57)
\end{aligned}
$$

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

$$
\left(v'' + \frac{\bar{R}}{(x_s)^2}\right) < 0, \forall s \in S \qquad (58)
$$

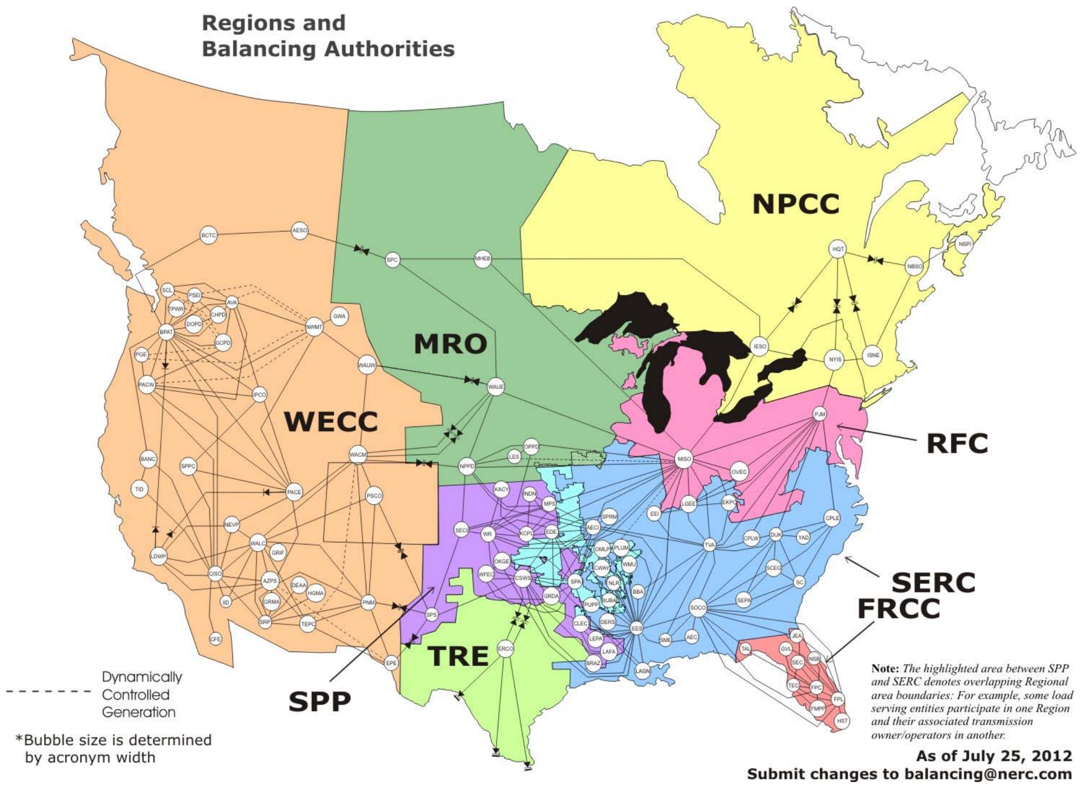
$$
\left[0.5\frac{\bar{R}}{(x_1)^2}v''h'(\theta-\varepsilon)^2 + \left(v'' + \frac{\bar{R}}{(x_1)^2}\right)q\frac{h''}{(h')^2}\right] > 0 \qquad (59)
$$

$$
\left[0.5\frac{\bar{R}}{(x_2)^2}v''h'(\theta+\varepsilon)^2 + \left(v'' + \frac{\bar{R}}{(x_2)^2}\right)q\frac{h''}{(h')^2}\right] > 0. \qquad (60)
$$

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

Figure A.1: NERC Regions and Balancing Authorities, as of 2012

Page 1 of 1



http://www.nerc.com/fileUploads/File/AboutNERC/maps/BubbleDiagram_072512.jpg 11/6/2012

Table A.9: 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	