



UNIVERSITY OF ALBERTA
FACULTY OF ARTS
Department of Economics

Working Paper No. 2014-12

On the Optimal Design of Distributed Generation Policies: Is Net Metering Ever Optimal?

David Brown
University of Alberta

David Sappington
University of Florida

September 2014

Copyright to papers in this working paper series rests with the authors and their assignees. Papers may be downloaded for personal use. Downloading of papers for any other activity may not be done without the written consent of the authors.

Short excerpts of these working papers may be quoted without explicit permission provided that full credit is given to the source.

The Department of Economics, The Institute for Public Economics, and the University of Alberta accept no responsibility for the accuracy or point of view represented in this work in progress.

On the Optimal Design of Distributed Generation Policies: Is Net Metering Ever Optimal?

by

David P. Brown* and David E. M. Sappington**

Abstract

Electricity customers who install solar panels often are paid the prevailing retail price for the electricity they generate. We show that this “net metering” policy typically is not optimal. A payment for distributed generation (w) that is below the retail price of electricity (r) will induce the welfare-maximizing level of distributed generation (DG) when centralized generation and DG produce similar (pollution) externalities. However, w can optimally exceed r when DG entails a substantial reduction in externalities. We demonstrate that the optimal DG policy varies considerably as prevailing production technologies change and that a restriction to net metering policies can both reduce aggregate welfare and have substantial distributional effects.

Keywords: electricity pricing, distributed generation, net metering

JEL Codes: L11, L50, L94 Q40, Q58

October 2014

* Department of Economics, University of Alberta, Edmonton, Alberta T6G 2H4 Canada (dpbrown@ualberta.ca).

** Department of Economics, University of Florida, Gainesville, FL 32611 USA (sapping@ufl.edu).

1 Introduction

Distributed generation of electricity (i.e., the “generation of electricity from sources that are near the point of consumption, as opposed to centralized generation sources such as large utility-owned power plants”)¹ is already pervasive in many countries and is expanding rapidly throughout the world.² Distributed generation (DG) is popular in part because it can reduce electricity distribution costs (by moving generation sites closer to final consumers), improve system reliability (by ensuring multiple production sources), limit the amount of capacity required at the primary production site, and reduce generation externalities (e.g., carbon emissions).³ One popular form of DG involves the production of electricity from solar panels installed on the roofs of residential buildings.⁴ Homeowners incur the expense of the panels in order to produce electricity which they either consume or sell to the electric utility.

Forty-three of the fifty U.S. states have established policies to encourage DG in their electricity sectors.⁵ Many of the states have adopted a net metering policy, under which a household is paid the prevailing retail price of electricity for each unit of electricity it produces. Although net metering policies are popular, they are often controversial.⁶

Proponents of net metering contend that, in light of its many benefits, DG should be encouraged by providing compensation for DG that reflects at least the prevailing retail price of electricity. In contrast, critics of net metering argue that the policy provides unduly generous compensation for DG – and thereby compels customers who do not engage in DG to subsidize those who do – for at least three reasons. First, the prevailing retail price of

¹American Council for an Energy-Efficient Economy (2014).

²The World Alliance for Decentralized Energy (2014) summarizes the extent of distributed generation around the world.

³See Weissman and Johnson (2012), for example.

⁴The Solar Electric Power Association (2013) reports that “Between 2011 and 2012, the number of newly installed solar net metering systems [in the U.S.] increased from 61,400 to 89,620 – a 46% annual growth rate.”

⁵See the American Public Power Association (APPA, 2013), Linvill et al. (2013), and the Solar Electric Power Association (2013), for example.

⁶Cardwell (2012), Kind (2013), Raskin (2013), and Than (2013), among others, review the key arguments in the debate regarding the merits of net metering policies.

electricity typically exceeds the system-wide cost saving that a unit of distributed electricity generation provides. This saving is the cost the primary production source (the utility) avoids when it is not required to produce the electricity generated by the distributed source.⁷ Second, net metering does not charge customers who generate more electricity than they consume for the relevant cost of distributing the excess electricity to other consumers. Third, the electricity supply from several forms of DG (including solar and wind generation) is unreliable because the amount of electricity generated depends heavily on prevailing weather conditions.⁸

Despite the prevalence of and the controversy surrounding DG policies, the economic literature provides little guidance on the optimal design of DG policies. Several studies (e.g., Couture and Gagnon, 2010) discuss the strengths and weakness of different DG policies. Some studies (e.g., Darghouth et al., 2011, 2014; Poullikkas, 2013) simulate the effects of various DG policies. A few studies (e.g., Yamamoto, 2012) model some elements of the critical design problem but do not analyze the optimal policy.⁹

The purpose of this research is to begin to fill this void in the literature by characterizing the optimal DG policy in a simple setting where a regulator can set a retail price for electricity (r) and the compensation (w) the regulated utility must deliver to customers for each unit of electricity they generate.¹⁰ Some customers (“ D customers”) can install DG capacity at their own expense while others (“ N customers”) do not have this opportunity (perhaps because

⁷Gordon et al. (2006) observe that the proper DG “payment should be based on the wholesale power costs that the utility avoids as a result of the availability of power from the DG customer/generator” (p. 28).

⁸Consequently, such DG production may not permit the utility to reduce its generating capacity much, if at all. Furthermore, in light of DG “intermittency,” the utility may employ a technology that generates substantial externalities to address the transient excess demand for electricity that arises when DG supply falls below its expected level.

⁹Yamamoto (2012) assumes the government first chooses a retail price for electricity and then sets the DG compensation rate to ensure a specified number of customers invest in a fixed level of DG capacity. Consumers do not consider the potential reduction in their electricity bills when they decide whether to install this capacity.

¹⁰Smart meters permit the separate measurement of a customer’s consumption and generation of electricity (International Renewable Energy Agency, 2013). The Institute for Electric Efficiency (IEE, 2012) reports that 36 million smart meters had been installed as of 2012. The IEE also forecasts that 65 million U.S. households (more than half of all such households) will have smart meters by 2015.

of limited financial resources or local zoning ordinances that prohibit the installation of solar panels on residential roof tops, for example). Installed DG capacity produces a stochastic supply of electricity. The utility adjusts its electricity supply to meet market demand after observing the amount of electricity supplied via DG. The regulator chooses r and w (and the utility's base-load capacity) to maximize the welfare of all customers while ensuring non-negative (extranormal) profit for the utility. Customer welfare encompasses losses from externalities (e.g., pollution and climate change) associated with electricity production.

We find that when electricity production by the utility and by D customers generate symmetric losses from externalities, the regulator optimally sets w to ensure that the compensation D customers anticipate from installing an additional unit of DG capacity is equal to the corresponding reduction in the utility's expected variable production cost. Given the optimal level of installed capacity, this reduction in expected variable production cost is less than the utility's average cost of production. Consequently, $w < r$, so net metering is not the optimal DG policy: the optimal unit compensation for DG is less than the optimal retail price of electricity. Even at this level, though, the optimal w effectively delivers the entire expected cost savings from DG to D customers in order to induce them to install the level of DG capacity that minimizes system-wide expected production costs. The retail price of electricity is not changed by the introduction of the optimal DG program, so N customers are not harmed by its introduction in this setting with symmetric externalities. In contrast, N customers would be harmed by even an optimally-designed net metering policy.

Additional considerations and alternative conclusions can arise when different production technologies generate different losses from externalities, as they do in practice. To illustrate, consider the case where the utility employs coal-powered units to produce base-load electricity whereas D customers employ solar panels to produce electricity. Consequently, base-load production by the utility generates substantially greater losses from externalities than does production by D customers. When the regulator has the flexibility to set distinct values for w and r in this setting, she typically will set w above r to encourage D customers to expand

their investment in DG capacity that will generate “clean energy.” However, when she is constrained to implement a net metering policy, the regulator often will lower w (which must equal r) in order to avoid delivering excessive rent to the utility. The reduced compensation for DG induces under-investment in DG capacity and so net metering results in relatively large losses from externalities.

We consider several technologies (including coal, nuclear, hydro, and gas) that might be employed to generate electricity. We find that both the fully optimal, unconstrained DG policy and the optimal net metering policy can vary substantially with the prevailing production technologies. We also find that aggregate welfare can decline significantly when any DG policy that is implemented is required to entail net metering (i.e., to set $w = r$). A net metering requirement also can produce substantial distributional effects. The requirement can generate considerable gains for some customers and considerable losses for other customers. The customers that gain, and those that lose, vary with the prevailing production technologies.

We develop and explain these findings as follows. Section 2 describes our formal model. Section 3 characterizes the optimal DG policy in two benchmark settings: one where DG is not feasible and one where the regulator dictates the level of DG capacity. Section 4 identifies and explains the general properties of the optimal DG policy in the setting of primary interest where D customers choose their preferred level of DG capacity. Section 5 employs numerical solutions to illustrate how both the optimal unconstrained DG policy and the optimal net metering policy vary with the prevailing production technologies. Section 5 also explores the welfare losses and the distributional effects that arise from a restriction to implement only net metering policies. Section 6 provides conclusions and discusses directions for further research. The proofs of all formal conclusions are presented in the Appendix A. Appendix B provides details of the analyses that underlie the numerical solutions presented in section 5.

2 Model

A regulated enterprise produces and distributes electricity to its customers. This vertically-integrated producer (VIP) incurs both capacity costs and additional operating costs. We adopt a long-run perspective and assume the VIP can purchase generating capacity (K^I) at constant unit cost k_I .¹¹ The VIP incurs additional cost $\underline{v}$ for each unit of output it produces below (base-load) capacity and additional cost $\bar{v}$ ($> \underline{v}$) for each unit of output (i.e., electricity) it secures above capacity.¹² The higher unit cost for output above capacity might reflect, for example, the higher cost of operating a “peaker” gas turbine unit to supplement the electricity produced by a base-load coal generating unit. Alternatively, the relatively high value of $\bar{v}$ might reflect the premium the VIP must pay to secure electricity on the spot market during periods of peak system-wide demand. We assume $\bar{v} > \underline{v} + k_I$, so the unit cost of securing electricity in excess of base-load capacity exceeds the full unit cost of production using the base-load technology.

The VIP serves two types of consumers: those who have the potential to generate electricity and those who do not. We assume all consumers of a particular type are identical and, for expositional ease, treat the entire group of consumers of a particular type as a single consumer.¹³ Consumer N is not able to generate electricity. He simply purchases electricity from the VIP at regulated unit price r .¹⁴ Consumer D is capable of producing electricity to supplement or replace the electricity he purchases from the VIP at unit price r . The distributed generation undertaken by consumer D might reflect the electricity produced by

¹¹In the short run, capacity costs typically exhibit considerable “lumpiness,” as additional capacity is secured by incurring the substantial fixed costs associated with a new large-scale generating unit.

¹²The simplifying assumption of a constant unit cost of supplying electricity is often employed in the literature (e.g., Joskow and Tirole, 2007). For expositional ease, the ensuing discussion will refer to variable production costs, which include both generation and distribution costs. We abstract from any impact that different patterns of DG and VIP production might have on distribution congestion costs.

¹³The qualitative conclusions drawn below are not affected by this aggregation. The aggregation allows us to avoid the additional notation associated with the individual choices of multiple identical consumers.

¹⁴A customer may be unable to generate electricity for a variety of reasons, which include local zoning regulations that prohibit the installation of solar panels, residence architecture or location that is not conducive to efficient solar generation, or limited access to financing of the up-front fixed costs of installing solar panels. We do not model these fixed costs explicitly, for expositional ease.

solar panels that he installs on the roof of his home, for example. The VIP is required to pay consumer D the amount w for each unit of electricity he produces. If $w = r$, then net metering is implemented because consumer D is then paid exactly the retail price of electricity for each unit of electricity he produces.

After learning r and w , consumer D determines the level of distributed generation capacity (K^D) he will install. The cost of installing capacity K^D is $C(K^D)$, which is a strictly increasing, strictly convex function with $C'(X) = \infty$, where $X \equiv X^N + X^D$.¹⁵ This property ensures that consumer D will never install enough capacity to serve the entire market demand for electricity (X).

To capture the intermittency associated with many forms of distributed generation (DG), including solar and wind generation, we assume that a unit of DG capacity generates θ units of electricity, where $\theta \in [\underline{\theta}, 1]$ is the realization of a random variable with distribution function $G(\theta)$. The corresponding density function, $g(\theta)$, has strictly positive support on $[\underline{\theta}, 1]$ and no mass point at $\underline{\theta} < 1$. The expected value of θ is denoted θ^E .

Consumer $j \in \{D, N\}$ has a perfectly inelastic demand for X^j units of electricity and derives value $V^j(X^j)$ from these X^j units. If consumer D produces more electricity than he consumes (i.e., if $\theta K^D > X^D$), the VIP employs the excess output ($\theta K^D - X^D$) to satisfy consumer N 's demand for electricity. The VIP incurs *grid access costs* $c_a \max\{0, \theta K^D - X^D\}$ in doing so, where $c_a \in [0, \underline{v})$ is a constant.¹⁶ After observing consumer D 's output, the VIP chooses its output to equate total industry supply with the total demand for electricity (X).

The regulator must ensure nonnegative expected profit for the VIP to secure its voluntary participation. The VIP's profit when DG production state θ is realized is:

$$\pi(\theta) \equiv r X - w \theta K^D - C^I(\underline{Q}^I(\theta), \overline{Q}^I(\theta), a(\theta), K^I)$$

¹⁵The increasing marginal cost of generating capacity might reflect in part the limited surface available on a customer's roof. Less than ideal exposure to the sun reduces the electricity a solar panel generates.

¹⁶Because $c_a < \underline{v}$, it is less costly for the VIP to deliver any excess output from DG to consumer N than to both generate additional electricity itself and deliver this electricity to consumer N .

where:

$$C^I(\cdot) = F + k_I K^I + \underline{v} \underline{Q}^I(\theta) + \bar{v} \bar{Q}^I(\theta) + c_a a(\theta), \quad (1)$$

and where $a(\theta) \equiv \max\{0, \theta K^D - X^D\}$ is the amount of grid access the VIP supplies to consumer D in state θ , and $\underline{Q}^I(\theta)$ and $\bar{Q}^I(\theta)$ are, respectively, the corresponding number of units of output the VIP produces below and above its base-load capacity, K^I . $F \geq 0$ captures any relevant fixed costs of operation that the VIP might incur. The rX term in (1) represents the VIP's revenue from electricity sales. The $w\theta K^D$ term represents payments by the VIP to consumer D for the electricity he produces. The remaining terms reflect fixed, capacity, variable generation, and grid access costs.

To specify the VIP's expected profit, it is convenient to introduce the notation $\theta^I \equiv \frac{X - K^I}{K^D}$, $\hat{\theta}^I \equiv \max\{\underline{\theta}, \theta^I\}$, and $\tilde{\theta}^I \equiv \min\{\hat{\theta}^I, 1\}$. In words, $\tilde{\theta}^I$ is a critical value of θ , above (below) which the VIP produces below (above) its base-load capacity because DG output is relatively large (small). Also let $\theta^D \equiv \frac{X^D}{K^D}$, $\hat{\theta}^D \equiv \max\{\underline{\theta}, \theta^D\}$, and $\tilde{\theta}^D \equiv \min\{\hat{\theta}^D, 1\}$. In words, $\tilde{\theta}^D$ is a critical value of θ , above (below) which consumer D generates more (less) electricity than he consumes. The VIP's expected profit is:¹⁷

$$\begin{aligned} E\{\pi(\theta)\} = & rX - w\theta^E K^D - F - k_I K^I - \int_{\underline{\theta}}^{\tilde{\theta}^I} \{ \underline{v} K^I + \bar{v} [X - \theta K^D - K^I] \} dG(\theta) \\ & - \int_{\tilde{\theta}^I}^1 \underline{v} [X - \theta K^D] dG(\theta) - c_a \int_{\tilde{\theta}^D}^1 [\theta K^D - X^D] dG(\theta). \quad (2) \end{aligned}$$

The first (second) integral in (2) reflects the VIP's expected variable production costs, given that the VIP's total output exceeds (is less than) its base-load capacity. The last integral in (2) reflects the VIP's expected grid access costs.

Consumer D 's expected utility is $E\{U^D(X^D, K^D)\} = V^D(X^D) - rX^D + w\theta^E K^D - C^D(K^D)$, which is the sum of his net utility from electricity consumption and his expected profit from DG. Consumer N 's expected utility is $E\{U^N(X^N)\} = V^N(X^N) - rX^N$. The regulator seeks to maximize the sum of the expected utilities of consumers D and N , less

¹⁷Here and throught the ensuing analysis, $E\{\cdot\}$ denotes the expectations operator.

the expected loss from externalities (e.g., pollution and climate change) associated with electricity production. $L(\underline{Q}^I, \overline{Q}^I, Q^D)$ denotes the loss from externalities that arises when the VIP produces $\underline{Q}^I$ units of output below base-load capacity and $\overline{Q}^I$ units above capacity, and when consumer D produces Q^D units of output.

Formally, the regulator's problem, denoted [RP], is:

$$\underset{r, w, K^I \geq 0}{\text{Maximize}} \quad E \left\{ U^D(\cdot) + U^N(\cdot) - L(\underline{Q}^I(\theta), \overline{Q}^I(\theta), \theta K^D) \right\} \quad (3)$$

$$\text{subject to: } E \{ \pi(\theta) \} \geq 0. \quad (4)$$

The timing in the model is as follows. First, the regulator sets r and w and directs the VIP to install base-load capacity K^I . Second, consumer D chooses K^D . Third, θ is realized and DG output θK^D is produced. Fourth, the VIP produces the output (and supplies any relevant grid access) required to equate industry supply and demand. Finally, consumers pay for the electricity they consume and the VIP pays consumer D for the electricity he generates.

3 Benchmarks

Before proceeding to characterize the solution to [RP], we briefly consider two benchmark settings. Losses from externalities are ignored in both of these settings (i.e., $L(\cdot) = 0$), so the regulator acts to maximize expected consumer welfare, subject to ensuring nonnegative expected profit for the VIP. In the benchmark *setting with no DG*, no consumer can produce electricity. Consequently, the VIP produces the entire industry demand for electricity, X . As Lemma 1 reports, the regulator optimally directs the VIP to install capacity equal to industry demand and delivers zero profit to the VIP by setting the retail price of electricity equal to the VIP's average cost of production.

Lemma 1. $K^I = X$ and $r = k_I + \underline{v} + \frac{F}{X}$ at the solution to the regulator's problem in the benchmark setting with no DG.

In the benchmark *setting with centralized choice of DG*, the regulator specifies the level of DG that consumer D must undertake. The values of capacity that are installed in this setting are characterized in Lemma 2. The lemma refers to $\tilde{\theta}^E \equiv \int_{\underline{\theta}}^{\tilde{\theta}^I} \theta dG(\theta)$, which is the expected value of θ , given that θ is sufficiently small that the VIP produces some output in excess of its base-load capacity.

Lemma 2. *In the benchmark setting with centralized choice of DG, the optimal values of K^I and K^D (denoted K^{Ic} and K^{Dc} , respectively) are determined by:*

$$[\bar{v} - \underline{v}] G(\tilde{\theta}^I) = k_I \quad \text{and} \quad \bar{v} \tilde{\theta}^E + \underline{v} [\theta^E - \tilde{\theta}^E] = C^{D'}(K^{Dc}), \quad (5)$$

$$\text{where } \tilde{\theta}^I = \frac{X - K^{Ic}}{K^{Dc}} \in (\underline{\theta}, 1) .$$

The first equality in expression (5) indicates that the VIP's base-load capacity (K^I) is optimally expanded to the point where its marginal cost (k_I) is equal to its corresponding marginal benefit. This marginal benefit is the expected marginal reduction in the VIP's variable cost of producing electricity, which is the product of: (i) $\bar{v} - \underline{v}$, the reduction in the VIP's unit variable cost as the marginal unit of output is produced below, rather than above, capacity; and (ii) $G(\tilde{\theta}^I)$, the probability that the VIP produces output in excess of its base-load capacity.

The second equality in expression (5) indicates that DG capacity (K^D) is optimally expanded to the point where its marginal cost ($C^{D'}(\cdot)$) is equal to the corresponding expected marginal benefit, given the VIP's base-load capacity. This marginal benefit is the associated marginal reduction in the VIP's expected variable cost of production. This marginal reduction is $\bar{v} \tilde{\theta}^E + \underline{v} [\theta^E - \tilde{\theta}^E]$, which is the sum of two terms. $\bar{v} \tilde{\theta}^E$ is the expected reduction in the VIP's variable cost of production from a unit increase in K^D , given that θ is sufficiently small that the VIP is producing above capacity (at unit cost $\bar{v}$).¹⁸ $\underline{v} [\theta^E - \tilde{\theta}^E]$ is the ex-

¹⁸Observe that $\tilde{\theta}^E$ is the rate at which expected DG output increases as DG capacity increases, given that θ is sufficiently small that the VIP is producing above its base-load capacity. Also recall that the VIP reduces its output at precisely the same rate that DG output increases since the VIP sets its output to equate market supply and market demand (X). Therefore, $\tilde{\theta}^E$ is the rate at which the VIP's expected

pected reduction in the VIP's variable cost of production from a unit increase in K^D , given that θ is sufficiently large that the VIP is producing below capacity (at unit cost $\underline{v}$).¹⁹

4 Primary Findings

We now proceed to characterize the optimal regulatory policy in the setting of primary interest where consumer D chooses his preferred level of capacity, facing cost $C(K^D)$, after observing r and w . We first do so in the *setting with symmetric losses from externalities*. In this setting, the rate at which the losses from externalities increase as electricity production increases is the same for all three sources of production: VIP production below base-load capacity, VIP production above capacity, and production from DG.²⁰

Proposition 1. *At the solution to [RP] in the setting with symmetric losses from externalities and no grid access costs (so $c_a = 0$):*

- (i) $K^I = K^{Ic}$ and $K^D = K^{Dc}$, so the values of VIP base-load capacity and DG capacity are precisely the corresponding values in the benchmark setting with centralized choice of DG;
- (ii) $r = \underline{v} + k_I + \frac{F}{X}$, so the retail price of electricity is precisely the corresponding price in the benchmark setting with no DG; and
- (iii) $w = \underline{v} \left[1 - \frac{\tilde{\theta}^E}{\theta^E} \right] + \bar{v} \left[\frac{\tilde{\theta}^E}{\theta^E} \right]$, so the unit payment for DG is set equal to the rate at which the VIP's expected variable production cost declines as DG capacity increases.

Conclusion (i) in Proposition 1 indicates that the regulator optimally induces consumer D to expand K^D to the point where the marginal cost of additional DG capacity ($C'(K^D)$) is equal to its social marginal benefit ($\bar{v} \tilde{\theta}^E + \underline{v} [\theta^E - \tilde{\theta}^E]$), which is the associated reduction in the VIP's expected variable cost of production. As conclusion (iii) indicates, the regulator

output declines as DG capacity increases, given that the VIP is producing above its base-load capacity.

¹⁹Observe that $\theta^E - \tilde{\theta}^E = \int_{\underline{\theta}}^1 \theta dG(\theta) - \int_{\underline{\theta}}^{\tilde{\theta}^I} \theta dG(\theta) = \int_{\tilde{\theta}^I}^1 \theta dG(\theta)$ is the rate at which expected DG output increases (and thus VIP output declines) as DG capacity increases, given that θ is sufficiently large that the VIP is producing below its base-load capacity.

²⁰Formally, $\frac{\partial L(\underline{Q}^I, \bar{Q}^I, Q^D)}{\partial \underline{Q}^I} = \frac{\partial L(\cdot)}{\partial \bar{Q}^I} = \frac{\partial L(\cdot)}{\partial Q^D}$ for all $\underline{Q}^I, \bar{Q}^I, Q^D$ in the setting with symmetric losses from externalities.

achieves this outcome by setting w to ensure that consumer D 's expected marginal financial reward from expanding K^D (i.e., $\theta^E w$) is equal to $\bar{v} \tilde{\theta}^E + \underline{v} [\theta^E - \tilde{\theta}^E]$.

This finding implies that, in contrast to policies under consideration in some jurisdictions (e.g., Minnesota – see Farrell, 2014a,b), the optimal (long run) DG payment does not include an explicit adjustment for the reduced capacity costs the VIP experiences due to DG. Instead, the optimal w reflects the rate at which the VIP's expected variable production cost declines as DG capacity increases. This level of w induces consumer D to install the level of DG capacity that minimizes expected industry costs, given the optimal level of the VIP's base-load capacity.

When the regulator sets w in the manner specified in Proposition 1, she cedes to consumer D the associated inframarginal benefit of increasing K^D , and so consumer D secures the entire incremental expected social benefit of DG. In contrast, consumer N receives exactly the same level of utility with DG that he receives in its absence. This is evident from conclusion (ii) in Proposition 1, which indicates that the optimal retail price of electricity is the same price that prevails when DG is not feasible.

In this setting, then, the optimal retail price for electricity (r) is the VIP's average cost of production in the absence of any cost reduction due to DG. Furthermore, the optimal unit price for DG (w) is a weighted average of the VIP's unit variable production costs ($\underline{v}$ and $\bar{v}$). The optimal choice of the VIP's base-load capacity ensures that the relevant weighted average of $\underline{v}$ and $\bar{v}$ is less than r , as Proposition 2 reports.

Proposition 2. *$r > w$ at the solution to $[RP]$ in the setting with symmetric losses from externalities and no grid access costs.*

Proposition 2 indicates that the regulator's ability to set a unit payment for DG (w) that differs from the retail price for electricity (r) is strictly valuable in the present setting. The regulator sets w to induce the welfare-maximizing level of DG capacity ($K^D = K^{Dc}$) and sets r at the (higher) level required to ensure zero profit ($\pi = 0$) for the VIP. In contrast, under

a net metering policy that requires the regulator to set $w = r$, the regulator effectively has a single instrument to control both K^D and π . As Proposition 3 reports, the restriction to a single instrument forces the regulator to adopt a policy that produces a lower level of aggregate consumer welfare. The regulator increases r_n , the identical unit DG payment and retail price of electricity, above the level that induces the ideal level of DG capacity (K^{Dc}). She does so because the lower level of r_n that would induce consumer D to install DG capacity K^{Dc} would generate negative profit for the VIP. The higher value of r_n required to ensure zero profit for the VIP induces consumer D to install DG capacity in excess of K^{Dc} . In this sense, an optimally designed net metering policy induces excessive investment in DG capacity in the present setting.²¹

Proposition 3. *In the setting with symmetric losses from externalities and no grid access costs: (i) $r_n > r$, i.e., the optimal retail price is higher when the regulator is constrained to implement net metering (i.e., to set $r_n = w$) than when she faces no such constraint; and (ii) $K^D > K^{Dc}$, i.e., more DG capacity is installed under the optimal net metering policy than under the optimal unconstrained regulatory policy.*

As Corollary 1 reports, the higher price for electricity that arises under the optimal net metering policy reduces consumer N 's welfare because he does not benefit from the corresponding increase in the unit payment for DG.

Corollary 1. *In the setting with symmetric losses from externalities and no grid access costs, the requirement to adopt a net metering policy strictly reduces aggregate expected consumer welfare. Furthermore, consumer N 's utility is: (i) lower in the presence of DG than in its absence under the optimal net metering policy; and (ii) the same in the presence of DG and in its absence under the optimal (unconstrained) policy.*

Corollary 1 indicates that the impact of a DG program on the welfare of electricity

²¹Formally, the regulator's optimal policy when she is required to implement net metering is the solution to [RP] with the additional constraint that $r = w$. (See the proof of Proposition 3.)

customers who do not generate any of their own electricity can depend upon the type of policies the regulator considers. If the regulator only considers net metering policies, then the optimal such policy reduces the welfare of consumers who do not undertake DG in the present setting. In contrast, if the regulator considers policies that allow the unit DG payment to differ from the retail price of electricity, then under the optimally designed policy in the present setting, the introduction of a DG program does not change the welfare of consumers who cannot undertake DG.

It remains to consider how grid access costs and differences in the externalities generated by different production technologies affect the optimal regulatory policy. To do so, it is convenient to consider the setting of Example 1, which has two key features. First, increased output from each production source increases losses from externalities at a constant rate. Second, even after accounting for relevant differences in marginal losses from externalities, the VIP's adjusted unit cost of production above base-load capacity exceeds the full adjusted unit cost of production below capacity.

Example 1. $\frac{\partial L(\underline{Q}^I, \bar{Q}^I, Q^D)}{\partial \underline{Q}^I} = \underline{e}$, $\frac{\partial L(\cdot)}{\partial \bar{Q}^I} = \bar{e}$, and $\frac{\partial L(\cdot)}{\partial Q^D} = e_D$ for all $\underline{Q}^I$, $\bar{Q}^I$, and Q^D , where $\underline{e}$, $\bar{e}$, and e_D are non-negative constants. Also, $\Delta_v \equiv \bar{v} + \bar{e} - (\underline{v} + \underline{e}) > k_I$.

Proposition 4. *At the solution to [RP] in the setting of Example 1:*

$$w = [\bar{v} + \bar{e} - e_D] \left[\frac{\tilde{\theta}^E}{\theta^E} \right] + [\underline{v} + \underline{e} - e_D] \left[1 - \frac{\tilde{\theta}^E}{\theta^E} \right] - c_a \frac{\theta^m}{\theta^E}. \quad (6)$$

Proposition 4 indicates that in the presence of grid access costs and differential losses from externalities, the regulator continues to set w to induce consumer D to expand DG capacity (K^D) to the point where its marginal cost is equal to its expected marginal social benefit. The regulator does so by setting consumer D 's expected marginal compensation from increasing K^D (i.e., $\theta^E w$) equal to the expected social marginal benefit of increasing

K^D , which is the sum of three components.

The first component, $[\bar{v} + \bar{e} - e_D] \tilde{\theta}^E$, is the expected reduction in the VIP's *adjusted* variable cost of production due to a unit increase in K^D , given that the VIP is producing above its base-load capacity. The VIP's adjusted unit variable cost of production above capacity is $\bar{v} + \bar{e} - e_D$, which is the sum of the VIP's unit variable cost of production and the difference between the rates at which VIP production above capacity and DG production generate losses from externalities. Thus, in setting w , the regulator effectively views this differential loss from externalities ($\bar{e} - e_D$) as an increment to the VIP's unit variable cost of production.

The second component, $[\underline{v} + \underline{e} - e_D][\theta^E - \tilde{\theta}^E]$, is similar. It is the expected reduction in the VIP's *adjusted* variable cost of production from a unit increase in K^D , given that the VIP is producing below capacity. This adjusted unit variable cost, $\underline{v} + \underline{e} - e_D$, is the sum of the VIP's unit variable cost of production and the difference between the rates at which VIP production below capacity and DG production generate losses from externalities.

The third component, $-c_a \theta^m$, reflects the amount by which a unit increase in K^D increases expected grid access costs. Recall that c_a is the VIP's unit grid access cost and θ^m is the expected increase in DG output as K^D increases by a unit, given that DG output exceeds consumer D 's electricity consumption.²²

We now consider how changes in model parameters affect the optimal values of w , K^D , and K^I . To do so, it is helpful to adopt parametric forms for the cost of DG capacity and the distribution of θ .

Example 2. The conditions in Example 1 hold. In addition: (i) $G(\theta) = \frac{\theta - \underline{\theta}}{1 - \underline{\theta}}$; and (ii) $C^D(K^D) = k_0 K^D + k_1 (K^D)^2$, where k_0 and k_1 are positive constants.

²²Proposition 4 implies that even when losses from externalities vary with the prevailing generation technology, the optimal (long run) DG payment (w) does not include an explicit adjustment for the reduced capacity costs the VIP experiences due to DG. The regulator directs the VIP to install the optimal level of base-load capacity and sets w as described in Proposition 4 to induce consumer D to install the optimal level of DG capacity, which accounts for reductions in the VIP's expected variable production costs and relevant differential losses from externalities.

The uniform distribution for θ in Example 2 avoids outcomes that primarily reflect large changes in the likelihood of particular DG production states. The quadratic cost of DG capacity in Example 2 permits explicit calculation of the capacity consumer D will install for any specified values of r and w .²³

Proposition 5 explains how the optimal DG payment varies as model parameters change. Proposition 6 reports the corresponding changes in the optimal VIP base-load capacity and equilibrium DG capacity.

Proposition 5. *At the solution to [RP] in the setting of Example 2, the optimal DG payment (w) increases as: (i) the VIP's variable cost of producing below capacity ($\underline{v}$) increases; (ii) the VIP's variable cost of producing above capacity ($\bar{v}$) declines; (iii) the incumbent's cost of capacity (k_I) increases; (iv) the extent of DG intermittency declines (so $\underline{\theta}$ increases); (v) the loss from externalities generated by VIP production below capacity ($\underline{e}$) increases; (vi) the loss from externalities generated by VIP production above capacity ($\bar{e}$) decreases; and (vii) the loss from externalities generated by DG production (e_D) declines. The optimal DG payment does not vary with the VIP's fixed cost, F . Furthermore, when $K^D > X^D$, w increases as the VIP's unit cost of providing access (c_a) declines or as DG capacity costs (k_0 and/or k_1) increase. When $K^D \leq X^D$, w does not change as k_0 , k_1 , or c_a changes.*

Proposition 6. *At the solution to [RP] in the setting of Example 2:*

$$K^D = \frac{1}{2k_1} [w\theta^E - k_0] \quad \text{and} \quad K^I = X - K^D \left[\underline{\theta} + k_I \left(\frac{1 - \underline{\theta}}{\Delta_v} \right) \right]. \quad (7)$$

Consequently, K^D increases and K^I decreases as: (i) $\underline{\theta}$, $\underline{v}$, k_I , or $\underline{e}$ increases; or (ii) $\bar{v}$, e_D , or $\bar{e}$ decreases. Furthermore, K^D and K^I do not change as F changes. If $K^D \leq X^D$, then: (i) K^D increases and K^I decreases as k_0 or k_1 decreases; and (ii) K^D and K^I do not change as c_a changes. If $K^D > X^D$, then K^D increases and K^I decreases as c_a declines.

²³As noted above, the increasing marginal cost implied by this quadratic cost function might reflect, for example, the constraints imposed by limited rooftop space with ideal exposure to the sun.

Propositions 5 and 6 reflect the following considerations. As the VIP's unit variable cost of production below capacity ($\underline{v}$) increases, the VIP's capacity effectively becomes less valuable and so less is secured. Instead, increased DG capacity is induced by increasing w . Similarly, as the VIP's unit variable cost of production above base-load capacity ($\bar{v}$) increases, VIP capacity is increased in order to reduce the incidence of the higher costs that arise when VIP production exceeds capacity. Consequently, the expected social value of DG capacity declines, and so w is reduced to reduce investment in DG capacity.

As the VIP's unit cost of capacity (k_I) increases, VIP capacity declines and w is increased to induce increased investment in DG capacity. In contrast, as the extent of DG intermittency increases (so $\underline{\theta}$ declines), VIP capacity is increased and w is reduced to induce less investment in DG capacity.²⁴

As the loss from externalities generated by VIP production below capacity ($\underline{e}$) increases, the value of VIP capacity effectively declines. Consequently, less VIP capacity is installed, and w is increased to induce increased investment in DG capacity. In contrast, as the loss from externalities generated by VIP production above capacity ($\bar{e}$) increases, such production effectively becomes more costly. Consequently, more VIP capacity is installed, and w is lowered to reduce investment in DG capacity. As the loss from pollution externalities generated by DG production (e_D) increases, VIP capacity is increased and w is reduced to limit investment in DG capacity.²⁵

When $K^D \leq X^D$, the VIP never supplies grid access. Therefore, w does not change as the VIP's cost of supplying grid access (c_a) changes.²⁶ Furthermore, consumer D fully

²⁴Observe that as $\underline{\theta}$ declines, intermittency increases in the sense that the range of possible DG production increases for any specified level of DG capacity, $K^D > 0$. In addition, the expected level of DG output declines for any specified $K^D > 0$ as $\underline{\theta}$ declines. Both effects promote reduced investment in DG capacity.

²⁵Recall from Proposition 2 that r exceeds w at the solution to [RP] in the presence of symmetric losses from externalities across generation technologies and in the absence of grid access costs. It can be shown that r also exceeds w under the optimal DG policy in the setting of Example 2 when the losses from externalities associated with the VIP's base-load production are not too much larger than the corresponding losses under DG production. Thus, as illustrated in section 5 below, w is optimally increased above r only when grid access costs are sufficiently small and electricity production from DG is substantially "cleaner" than production by the VIP's base-load technology.

²⁶ w also does not change as F changes. This is the case because w is set to implement the desired mix of

internalizes the relevant benefits and costs of DG capacity investment in this case, given the optimal value of w . Consequently, increases in k_0 and k_1 reduce DG capacity to the optimal extent directly, and no additional change in w is required to ensure the optimal level of K^D .

When $K^D > X^D$, the VIP may supply some grid access. As the VIP's cost of supplying this access declines, DG becomes more economical. Consequently, K^I is reduced and w is increased to stimulate expanded DG capacity. When k_0 or k_1 increases, consumer D reduces his investment in DG capacity because of its increased cost. Consumer D would reduce K^D below the welfare-maximizing level if w were unchanged because consumer D does not bear the entire expected increase in industry costs (which include grid access costs) as K^D declines. Therefore, the regulator increases w to induce increased investment in DG capacity.

5 The Range of Optimal DG Policies

It remains to illustrate how the optimal DG policy varies with the prevailing technologies employed to generate electricity and to assess the magnitudes of the welfare losses and the distributional effects that can arise from implementing the optimal net metering policy rather than the optimal unconstrained regulatory policy. To do so, we begin by identifying representative values for the model parameters.

For simplicity, we abstract from grid access costs and fixed production costs (so $c_a = F = 0$) and assume the DG production state (θ) is uniformly distributed on $[0, 1]$.²⁷ We employ data from the U.S. Energy Information Administration (EIA) to approximate the VIP's unit cost of production below capacity ($\underline{v}$) and the corresponding unit cost of capacity (k_I). Specifically, we assume: (i) $\underline{v} = 23.9$ (dollars per MWh) and $k_I = 73.0$ for coal generation; (ii) $\underline{v} = 9.4$ and $k_I = 106.6$ for nuclear generation; and (iii) $\underline{v} = 7.0$ and $k_I = 109.2$ for hydro generation. We further assume that output above capacity is produced at unit cost $\bar{v} = 124.0$ using generation units powered by natural gas.²⁸

VIP capacity and DG capacity. The relative merits of the two types of capacity do not change on the margin as F changes.

²⁷Setting $\underline{\theta} = 0$ accounts for the possibility that a solar panel might produce no electricity during periods of exceptionally heavy cloud cover, for example.

²⁸The identified values of $\underline{v}$, $\bar{v}$, and k_I reflect the EIA estimates for 2016 (EIA, 2010). The value of $\bar{v}$

We adopt a simple, linear representation of the value that consumers derive from electricity by assuming $V^j(X^j) = 200 X^j$ for $j = D, N$, where 200 represents an estimate of the average value of lost load (VOLL) for residential electricity customers.²⁹ We further assume that total electricity consumption (X) is 8,500 (MWh),³⁰ and consumer N accounts for 97 percent of this total (so $X^N = 8,245$ and $X^D = 255$).³¹ (Solar) distributed generation and hydro base-load generation are assumed to produce no losses from externalities (so $e_D = 0$ and $\underline{e} = 0$ under hydro generation). The unit losses from externalities are taken to be 40.17, 22.69, and 4.71 when electricity is produced using the coal, natural gas, and nuclear technology, respectively.³²

For simplicity, we assume the cost of DG capacity is quadratic, so $C^D(K^D) = k_0 K^D + k_1(K^D)^2$. As explained further in Appendix B, our estimates of k_0 and k_1 arise from fitting the equation that determines consumer D 's choice of DG capacity (i.e., $C^{D'}(K^D) = w \theta^E$) to data on DG payments and investment in solar panels in the U.S. in 2013.³³ The resulting

represents the sum of the unit production cost ($\underline{v} = 82.9$) and the unit capacity cost ($k_I = 41.1$) using the natural gas generation technology. The values of k_I are levelized cost estimates that reflect the present value of the total cost of building and operating a plant over its expected life, amortized by the expected lifetime output of the plant.

²⁹Estimates of the VOLL for residential customers vary widely. To illustrate, Sullivan et al. (2009) estimate VOLL to be approximately \$107. London Economics International (2013) reports estimates of VOLL in the U.S. that typically are between \$0 and \$1,735. Appendix B illustrates how the findings below change as the estimate of VOLL changes.

³⁰Total electricity consumption in the U.S. was 3,695,346 thousand megawatt hours in 2012 (EIA, 2012). Dividing this number by the product of 8,766 (hours per year) and 50 (states) provides an estimate of the average state-level hourly electricity consumption (8,431 megawatts) in 2012. Accounting for the 0.9% average annual growth in electricity consumption in the U.S. in recent years (EIA, 2013a), we assume total demand for electricity is $X = 8,500$. Appendix B illustrates how the findings below change as the presumed value of X changes.

³¹In 2012, 10.6% of residential customers in Hawaii had solar panels on their premises and operated under net metering. The corresponding percentages in California and Arizona were 2.0 and 1.6, respectively (EIA, 2014c). Several states, including California, have seen rapid growth in solar panel installation in recent years, and corresponding future growth is anticipated (Schneider and Sargent, 2014). To account for this growth, we assume consumer D accounts for 3 percent of aggregate electricity consumption in the ensuing analysis. Appendix B illustrates how the findings below change as X^D/X , the presumed fraction of total electricity consumption accounted for by consumer D , changes.

³²These values reflect the carbon dioxide (CO₂) emissions produced under each generation technology and the estimated social cost of CO₂ emissions. Appendix B explains the underlying calculation in more detail and illustrates how the findings below change as the estimated social cost of CO₂ emissions changes.

³³We also implement adjustments to ensure positive levels of equilibrium investment in DG capacity. See Appendix B for details.

estimates are $k_0 = 47.42$ and $k_1 = 0.00149$.

Using these parameter values, we solve numerically for the values of r , w , and K^I (and the associated equilibrium value of K^D) that solve [RP].³⁴ These values and the associated expected utilities of consumer N and consumer D ($E\{U^N\}$ and $E\{U^D\}$, respectively) are reported in Table 1. Table 1 also reports the corresponding level of expected welfare ($E\{W\} = E\{U^N\} + E\{U^D\} - E\{L(\cdot)\}$).

Base Unit	r	w	K^I	K^D	$E\{U^N\}$	$E\{U^D\}$	$E\{W\}$
Coal	105.2	129.5	6,226.5	2,556.3	781,916.6	46,354.9	552,486.9
Nuclear	115.7	99.8	7,828.0	835.7	695,382.4	22,547.4	675,005.7
Hydro	116.2	92.4	8,500.0	0.0	690,931.0	21,369.0	712,300.0

Table 1. Outcomes Under the Optimal DG Policy.

Table 2 reports the corresponding values that arise under the optimal net metering policy, which constrains the regulator to set the unit compensation for DG equal to the unit retail price of electricity (r_n). Table 2 also reports the change in welfare ($\Delta E\{W\}$) that arises when the regulator is constrained to implement net metering rather than the optimal unconstrained DG policy.

Base Unit	r_n	K^I	K^D	$E\{U^N\}$	$E\{U^D\}$	$E\{W\}$	$\Delta E\{W\}$
Coal	96.8	8,367.2	144.5	850,874.9	26,386.6	539,785.5	−2.3%
Nuclear	127.8	3,815.6	5,534.4	595,082.9	64,042.6	596,478.8	−11.6%
Hydro	129.7	3,560.3	5,848.5	579,648.2	68,892.5	601,207.7	−15.6%

Table 2. Outcomes Under the Optimal Net Metering Policy.

Three elements of Table 1 warrant emphasis. First, the optimal unconstrained DG policy varies considerably according to the prevailing base-load generation technology. Notice, for

³⁴The solutions were generated using *Mathematica*, as explained more fully in Appendix B.

instance, that the optimal unit DG payment (w) is 40% higher when the base-load generation technology is coal than when it is hydro. Second, w can differ substantially from r (the optimal retail price for electricity) under the optimal regulatory policy. To illustrate, w is 23% higher than r when the base-load generation technology is coal.

Third, the optimal w can be either greater than or less than the optimal r . A relatively high value of w induces considerable investment in DG capacity in order to limit losses from externalities under base-load coal generation. A relatively small value of w avoids excessive investment in DG capacity when the prevailing base-load technology is one of the “cleaner” technologies (i.e., nuclear or hydro).³⁵

Tables 1 and 2 together provide three additional findings that warrant emphasis. First, even when prevailing losses from externalities are accounted for, a restriction to net metering policies can produce higher retail prices and substantial over-investment in DG capacity relative to the optimal unconstrained DG policy.³⁶ These outcomes arise in the present setting when the base-load generation technology is either nuclear or hydro. For both technologies, a restriction to net metering policies results in DG capacity that is many times its optimal value and base-load capacity that is less than half its optimal value.

Second, a restriction to net metering policies also can induce under-investment in DG capacity. When the base-load generation technology is coal in the present setting, a net metering policy prevents the regulator from setting w well above r in order to encourage investment in DG capacity and thereby limit losses from externalities without ceding substantial rent to the VIP. The optimal r_n under net metering induces investment in DG capacity that is less than 6% of the level that is induced under the optimal unconstrained DG policy in the present setting.

Third, a restriction to net metering can have substantial distributional effects. Notice, for

³⁵The present formulation does not explicitly account for potential safety concerns under base-load nuclear generation. A full accounting for these concerns could produce a w that exceeds r at the solution to [RP].

³⁶Recall the corresponding conclusion in Proposition 3 for the setting where the losses from externalities do not vary with the prevailing generation technology.

instance, that when the base-load generation technology is nuclear or hydro, the expected utility of consumer D more than doubles whereas the utility of consumer N declines by roughly 15% when the regulator is constrained to implement a net metering policy. Consumer N is harmed by the higher retail price that arises under net metering whereas consumer D benefits from the higher payment for DG.³⁷

In part because of the presumed inelastic demand for electricity, a restriction to net metering does not produce dramatic reductions in aggregate expected welfare in the present setting. The largest percentage reductions in welfare arise when the base-load technology is either nuclear or hydro. In these cases, the loss that consumer N suffers (due to the higher retail price of electricity) under net metering outweighs consumer D 's gain (from the increased compensation for DG) because of consumer N 's relatively pronounced consumption of electricity. The reduction in aggregate welfare that arises under net metering is substantially smaller when the base-load generation technology is coal in this setting. Consumer N 's gain (from the reduced retail price of electricity) exceeds consumer D 's loss (from the reduced compensation for DG) in this case.³⁸ However, the increased expected losses from externalities under net metering counterbalance the net increase in expected consumer utility, resulting in a relatively modest net reduction in aggregate expected welfare.³⁹

Parameter values other than those considered here may well be plausible in relevant settings. (See Appendix B.) Consequently, the entries in Tables 1 and 2 are only illustrative. Nevertheless, these entries allow us to conclude that the optimal unconstrained DG policy can vary substantially according to the prevailing base-load generation technology.⁴⁰ The

³⁷Different distributional effects arise in the present setting when the base-load technology is coal. The lower retail price that arises under net metering increases consumer N 's utility (by 9%), whereas the smaller payment for DG reduces consumer D 's expected utility (by 43%).

³⁸The relatively large gain for consumer N reflects in part his presumed relatively large demand for electricity. Appendix B illustrates the changes that arise as X and X^D/X (and thus X^N/X) change.

³⁹This percentage welfare loss varies inversely with the estimated VOLL because a larger VOLL gives rise to larger *levels* of expected utility and associated smaller *percentage* changes as w and r vary. See Appendix B.

⁴⁰The optimal unconstrained DG policy also can vary substantially as the technology employed to generate electricity in excess of base-load capacity changes.

entries also demonstrate that a requirement to implement a net metering policy can entail substantial distributional effects and non-trivial reductions in aggregate expected welfare.

6 Conclusions

We have analyzed the optimal design of policies to promote the distributed generation (DG) of electricity. We found that the optimal DG policy typically does not entail net metering, so the optimal payment for electricity produced via DG (w) typically differs from the optimal retail price of electricity (r). When the losses from externalities produced by different generation technologies are symmetric, w is optimally set below r . More generally, though, w can exceed r , as it often does when the utility employs coal-powered units to produce base-load electricity and DG of electricity entails solar generation, for example. In this case, a relatively high value for w induces substantial investment in the generation of “clean energy” and thereby limits losses from externalities.

We found that aggregate welfare can decline considerably when DG policies are required to implement net metering. A net metering requirement also can produce substantial distributional effects, and it can harm either customers that undertake DG or those that are unable to do so. In addition, both the fully optimal, unconstrained DG policy and the optimal net metering policy can vary substantially with the prevailing production technologies. Consequently, there is no single DG policy that is optimal in all settings.

Net metering policies can enhance welfare in settings where it is not possible to monitor a customer’s production and consumption of electricity separately. However, as smart meters are deployed more ubiquitously, DG policies other than net metering can be widely deployed to enhance welfare even further. The “value of solar” program that has been proposed in Minnesota (Farrell, 2014a,b) is one potential departure from net metering. Under this program, the DG payment would reflect estimates of the associated environmental benefits and reductions in the variable costs of base-load generation of electricity, as our analysis prescribes. However, in contrast to the prescriptions of our model, the DG payment also would

include an estimate of the associated reduction in base-load capacity costs.⁴¹ Furthermore, customers would not be compensated for electricity generated in excess of consumption. Our analysis suggests that these particular elements of the “value of solar” program may warrant further consideration. However, our analysis also suggests that the basic thrust of the program reflects sound economic principles.

In concluding, we note two directions in which our analysis might be fruitfully extended. First, alternative DG technologies should be considered. The amount of electricity produced by a non-solar DG source typically is not entirely beyond the producer’s control. The ability to control DG output can engender contracting opportunities that facilitate a utility’s load management activities. Because the nature and extent of DG intermittency varies by production technology, the presence of multiple distinct DG technologies may also facilitate load management. Just as the optimal DG policy varies with the characteristics of the single DG source in our model, more generally the optimal DG policy will vary with (and help to determine) the entire range of DG technologies that are employed.⁴²

Second, additional policy instruments warrant consideration. The regulator may be able to secure a higher level of welfare if, for example, she can compensate consumers directly for the DG capacity they install. Nonlinear and time-varying prices also could enhance welfare, particularly in settings where consumer demand for electricity varies over time and is price sensitive.⁴³ More generally, the optimal design of a DG policy is best viewed as an element of a broader exercise that includes, for example, the optimal design of demand-response, energy conservation, and renewable energy portfolio policies. The optimal coordination of these policies awaits formal investigation.

⁴¹Our analysis is a long run analysis in which the VIP’s base-load capacity is chosen optimally. The design of short-term DG policies during the transition to the optimal long run policy merits further study.

⁴²A characterization of the optimal payments to a utility for the DG capacity it installs also merits investigation, as does competition in the electricity sector.

⁴³Alternative regulatory objectives also merit consideration. In practice, political pressures can compel regulators to value differently the welfare of different constituents (e.g., those who can readily install DG capacity and those who cannot). (See Cardwell (2012), for example.) Such differential welfare considerations can lead a regulator to induce levels of DG investment that do not minimize expected industry production costs.

Appendix A. Proofs of the Formal Conclusions

Proof of Lemma 1.

The regulator's problem in this setting is:

$$\underset{r, K^I, \underline{Q}^I, \overline{Q}^I}{\text{Maximize}} \quad V^D(X^D) - r X^D + V^N(X^N) - r X^N$$

subject to:

$$r X - k_I K^I - \underline{v} \underline{Q}^I - \overline{v} \overline{Q}^I - F \geq 0; \quad (8)$$

$$\underline{Q}^I \leq K^I; \quad \text{and} \quad \underline{Q}^I + \overline{Q}^I \geq X. \quad (9)$$

Let λ_B denote the Lagrange multiplier associated with constraint (8) and let γ_o and γ_k , respectively, denote the Lagrange multipliers associated with the first and second constraints in (9). Then the necessary conditions for a solution to [RP] include:

$$r : \quad X [-1 + \lambda_B] = 0; \quad (10)$$

$$K^I : \quad -\lambda_B k_I + \gamma_o \leq 0; \quad K^I [\cdot] = 0; \quad (11)$$

$$\underline{Q}^I : \quad -\underline{v} \lambda_B - \gamma_o + \gamma_k \leq 0; \quad \underline{Q}^I [\cdot] = 0; \quad (12)$$

$$\overline{Q}^I : \quad -\overline{v} \lambda_B + \gamma_k \leq 0; \quad \overline{Q}^I [\cdot] = 0. \quad (13)$$

$\lambda_B = 1$, from (10). Suppose $K^I = 0$. Then $\underline{Q}^I = 0$ from (9) and so $\overline{Q}^I \geq X$ from (9). Therefore, $\gamma_k = \overline{v}$ from (13). Consequently, $\gamma_o \geq \overline{v} - \underline{v}$ from (12), and so $k_I \geq \gamma_o \geq \overline{v} - \underline{v}$ from (11). But this conclusion violates the maintained assumption that $k_I < \overline{v} - \underline{v}$. Therefore, by contradiction, $K^I > 0$.

Consequently, $\gamma_o = k_I > 0$ from (11), and so $\underline{Q}^I = K^I$. If $\overline{Q}^I > 0$, then $\gamma_k = \overline{v}$ from (13). Therefore, $\gamma_o = k_I = \overline{v} - \underline{v}$ from (12). But this conclusion violates the maintained assumption that $k_I < \overline{v} - \underline{v}$. Therefore, $\overline{Q}^I = 0$.

Since $\underline{Q}^I > 0$, $\gamma_k = \underline{v} + \gamma_o > 0$ from (12). Therefore, $\underline{Q}^I = K^I = X$. Finally, since $\lambda_B > 0$, (8) implies:

$$r X = k_I X + \underline{v} X + F \Rightarrow r = k_I + \underline{v} + \frac{F}{X}. \quad \blacksquare$$

Proof of Lemma 2.

From (2), the regulator's problem in this setting is:

$$\begin{aligned}
 & \underset{r, w, K^I, K^D}{\text{Maximize}} \quad V^D(X^D) - r X^D + w \theta^E K^D - C(K^D) + V^N(X^N) - r X^N \\
 & \text{subject to:} \\
 & r X - w \theta^E K^D - F - k_I K^I - \int_{\underline{\theta}}^{\tilde{\theta}^I} \{ \underline{v} K^I + \bar{v} [X - \theta K^D - K^I] \} dG(\theta) \\
 & \quad - \int_{\tilde{\theta}^I}^1 \underline{v} [X - \theta K^D] dG(\theta) \geq 0. \tag{14}
 \end{aligned}$$

Let λ_b denote the Lagrange multiplier associated with constraint (14). Then the necessary conditions for a solution to this problem include:

$$r : \quad X [-1 + \lambda_b] = 0; \tag{15}$$

$$w : \quad \theta^E K^D [1 - \lambda_b] = 0; \tag{16}$$

$$\begin{aligned}
 K^I : \quad & -\lambda_b \left\{ k_I - \int_{\underline{\theta}}^{\tilde{\theta}^I} [\bar{v} - \underline{v}] dG(\theta) \right. \\
 & \left. + \left[\underline{v} K^I + \bar{v} (X - \tilde{\theta}^I K^D - K^I) - \underline{v} (X - \tilde{\theta}^I K^D) \right] g(\tilde{\theta}^I) \frac{d\tilde{\theta}^I}{dK^I} \right\} \leq 0. \tag{17}
 \end{aligned}$$

$$\begin{aligned}
 K^D : \quad & w \theta^E - C^{D'}(K^D) - \lambda_b w \theta^E + \lambda_b \int_{\underline{\theta}}^{\tilde{\theta}^I} \bar{v} \theta dG(\theta) + \lambda_b \int_{\tilde{\theta}^I}^1 \underline{v} \theta dG(\theta) \\
 & + \left[\underline{v} K^I + \bar{v} (X - \tilde{\theta}^I K^D - K^I) - \underline{v} (X - \tilde{\theta}^I K^D) \right] g(\tilde{\theta}^I) \frac{d\tilde{\theta}^I}{dK^D} \Big\} \leq 0. \tag{18}
 \end{aligned}$$

$\lambda_b = 1$, from (15). Also, using the techniques employed to prove Lemma A1 (below), it can be shown that $K^I > 0$, $K^D > 0$, and $\tilde{\theta}^I = \theta^I = \frac{X - K^I}{K^D}$. Therefore, $X - \tilde{\theta}^I K^D = X - (X - K^I) = K^I$ and so (17) and (18) can be written as:

$$\begin{aligned}
 & -k_I + [\bar{v} - \underline{v}] G(\theta^I) = 0; \\
 & -C^{D'}(K^D) + \bar{v} \tilde{\theta}^E + \underline{v} [\theta^E - \tilde{\theta}^E] = 0. \quad \blacksquare
 \end{aligned}$$

Proof of Proposition 1.

Let $\lambda \geq 0$ denote the Lagrange multiplier associated with constraint (4). Using (1) – (3), the necessary conditions for a solution to [RP] include:

$$r : \quad -X^D - X^N + \lambda [X^N + X^D] = 0. \quad (19)$$

$$w : \quad w \theta^E \frac{\partial K^D}{\partial w} + \theta^E K^D - C^{D'}(K^D) \frac{\partial K^D}{\partial w} - \frac{dE\{L(\cdot)\}}{dK^D} \frac{dK^D}{dw} \\ \lambda \left[-w \theta^E \frac{\partial K^D}{\partial w} - \theta^E K^D - \frac{dE\{C^I(\cdot)\}}{dK^D} \frac{dK^D}{dw} \right] = 0. \quad (20)$$

$$K^I : \quad -\frac{dE\{L(\cdot)\}}{dK^I} - \lambda \frac{dE\{C^I(\cdot)\}}{dK^I} \leq 0. \quad (21)$$

Observe that:

$$\underline{Q}^I(\theta) = \begin{cases} X - \theta K^D & \text{if } X - \theta K^D \leq K^I \\ K^I & \text{if } X - \theta K^D > K^I \end{cases}$$

and

$$\overline{Q}^I(\theta) = \begin{cases} 0 & \text{if } X - \theta K^D \leq K^I \\ X - \theta K^D - K^I & \text{if } X - \theta K^D > K^I. \end{cases} \quad (22)$$

$$\text{Let } \delta_o \equiv \begin{cases} 1 & \text{if } X - \theta K^D \leq K^I \\ 0 & \text{if } X - \theta K^D > K^I \end{cases} \quad \text{and} \quad \delta_D \equiv \begin{cases} 1 & \text{if } \theta K^D \geq X^D \\ 0 & \text{if } \theta K^D < X^D. \end{cases} \quad (23)$$

Then

$$\frac{\partial \underline{Q}^I(\theta)}{\partial K^D} = -\delta_o \theta; \quad \frac{\partial \overline{Q}^I(\theta)}{\partial K^I} = -[1 - \delta_o] \theta; \quad \frac{\partial a(\theta)}{\partial K^D} = \delta_D \theta; \\ \frac{\partial \underline{Q}^I(\theta)}{\partial K^I} = 1 - \delta_o; \quad \text{and} \quad \frac{\partial \overline{Q}^I(\theta)}{\partial K^I} = -[1 - \delta_o]. \quad (24)$$

Consumer D 's choice of K^I is determined by:

$$w \theta^E = C^{D'}(K^D) \Rightarrow \frac{dK^D}{dw} = \frac{\theta^E}{C^{D''}(K^D)} > 0. \quad (25)$$

Recall $\theta^I \equiv \frac{X - K^I}{K^D}$, $\hat{\theta}^I \equiv \max\{\underline{\theta}, \theta^I\}$, and $\tilde{\theta}^I \equiv \min\{\hat{\theta}^I, 1\}$. Let $Q^D(\theta) \equiv \theta K^D$.

Then (1), (2), (23), (24), and (25) imply that (20) can be written as:

$$\begin{aligned}
& \theta^E K^D + E \left\{ \theta \left[\delta_o \frac{\partial L(\cdot)}{\partial \underline{Q}^I} + (1 - \delta_o) \frac{\partial L(\cdot)}{\partial \overline{Q}^I} - \frac{\partial L(\cdot)}{\partial Q^D} \right] \right\} \frac{\partial K^D}{\partial w} \\
& - \lambda w \theta^E \frac{\partial K^D}{\partial w} - \lambda \theta^E K^D - \lambda \frac{\partial K^D}{\partial w} \left[\bar{v} \int_{\underline{\theta}}^{\tilde{\theta}^I} \theta dG(\theta) + \underline{v} \int_{\tilde{\theta}^I}^1 \theta dG(\theta) + c_a \int_{\tilde{\theta}^I}^1 \theta dG(\theta) \right] \\
& - \lambda \frac{\partial K^D}{\partial w} \left[\underline{v} K^I + \bar{v} (X - \tilde{\theta}^I K^D - K^I) - \underline{v} (X - \tilde{\theta}^I K^D) \right] g(\tilde{\theta}^I) \frac{d\tilde{\theta}^I}{dK^D} = 0. \quad (26)
\end{aligned}$$

Similarly, (21) can be written as:

$$\begin{aligned}
& - E \left\{ [1 - \delta_o] \left[\frac{\partial L(\cdot)}{\partial \underline{Q}^I} - \frac{\partial L(\cdot)}{\partial \overline{Q}^I} \right] \right\} - \lambda \left\{ k_I - \int_{\underline{\theta}}^{\tilde{\theta}^I} [\bar{v} - \underline{v}] dG(\theta) \right. \\
& \left. + [\underline{v} K^I + \bar{v} (X - \tilde{\theta}^I K^D - K^I) - \underline{v} (X - \tilde{\theta}^I K^D)] g(\tilde{\theta}^I) \frac{d\tilde{\theta}^I}{dK^I} \right\} \leq 0. \quad (27)
\end{aligned}$$

Observe that:

$$\begin{aligned}
& \underline{v} K^I + \bar{v} [X - \tilde{\theta}^I K^D - K^I] - \underline{v} [X - \tilde{\theta}^I K^D] \\
& = [\bar{v} - \underline{v}] [X - \tilde{\theta}^I K^D - K^I] = 0 \text{ if } \tilde{\theta}^I \in (\underline{\theta}, 1); \text{ and} \\
& \frac{d\tilde{\theta}^I}{dK^I} = \frac{d\tilde{\theta}^I}{dK^D} = 0 \text{ if } \tilde{\theta}^I \in \{\underline{\theta}, 1\}. \quad (28)
\end{aligned}$$

(28) implies that (26) and (27) can be written as:

$$\begin{aligned}
& \theta^E K^D + E \left\{ \theta \left[\delta_o \frac{\partial L(\cdot)}{\partial \underline{Q}^I} + (1 - \delta_o) \frac{\partial L(\cdot)}{\partial \overline{Q}^I} - \frac{\partial L(\cdot)}{\partial Q^D} \right] \right\} \frac{\partial K^D}{\partial w} - \lambda w \theta^E \frac{\partial K^D}{\partial w} \\
& - \lambda \theta^E K^D - \lambda \frac{\partial K^D}{\partial w} \left[\bar{v} \int_{\underline{\theta}}^{\tilde{\theta}^I} \theta dG(\theta) + \underline{v} \int_{\tilde{\theta}^I}^1 \theta dG(\theta) + c_a \int_{\tilde{\theta}^I}^1 \theta dG(\theta) \right] = 0; \quad (29)
\end{aligned}$$

and

$$-E \left\{ [1 - \delta_o] \left[\frac{\partial L(\cdot)}{\partial \underline{Q}^I} - \frac{\partial L(\cdot)}{\partial \overline{Q}^I} \right] \right\} - \lambda \left[k_I - \int_{\underline{\theta}}^{\tilde{\theta}^I} [\bar{v} - \underline{v}] dG(\theta) \right] \leq 0. \quad (30)$$

(19) implies that $\lambda = 1$. Therefore, from (1):

$$r = \frac{1}{X} \left[w \theta^E K^D + E \left\{ C^I(\underline{Q}^I(\theta), \overline{Q}^I(\theta), a(\theta), K^I) \right\} \right]. \quad (31)$$

Assumption 1. $-k_I < E \left\{ [1 - \delta_o] \left[\frac{\partial L(\cdot)}{\partial \underline{Q}^I} - \frac{\partial L(\cdot)}{\partial \overline{Q}^I} \right] \right\} < \bar{v} - \underline{v} - k_I,$

where δ_o is defined in (23).

Lemma A1. Suppose Assumption 1 holds (as it does under the maintained conditions). Then $0 < X - K^D < K^I < X - \underline{\theta} K^D$ and so $\tilde{\theta}^I = \hat{\theta}^I = \theta^I = \frac{X - K^I}{K^D} \in (\underline{\theta}, 1)$ at the solution to [RP].

Proof. Suppose $K^I = 0$. Then $\theta^I = \frac{X}{K^D} > 1$ since $X > K^D$, by assumption. Therefore, $\tilde{\theta}^I \equiv \min \{ \max \{ \underline{\theta}, \theta^I \}, 1 \} = 1$. Consequently, since $\lambda = 1$, (30) implies:

$$\bar{v} - \underline{v} - k_I \leq E \left\{ [1 - \delta_o] \left[\frac{\partial L(\cdot)}{\partial \underline{Q}^I} - \frac{\partial L(\cdot)}{\partial \overline{Q}^I} \right] \right\}. \quad (32)$$

This inequality contradicts Assumption 1, so $K^I > 0$.

Since $K^I > 0$ and $\lambda = 1$, (30) implies:

$$[\bar{v} - \underline{v}] G(\tilde{\theta}^I) - k_I - E \left\{ [1 - \delta_o] \left[\frac{\partial L(\cdot)}{\partial \underline{Q}^I} - \frac{\partial L(\cdot)}{\partial \overline{Q}^I} \right] \right\} = 0. \quad (33)$$

If $K^I \leq X - K^D$, then $\theta^I = \frac{X - K^I}{K^D} \geq \frac{X - (X - K^D)}{K^D} = 1$. Therefore, $G(\tilde{\theta}^I) = 1$ because $\tilde{\theta}^I \equiv \min \{ \max \{ \underline{\theta}, \theta^I \}, 1 \} = 1$. Then (33) implies $\bar{v} - \underline{v} - k_I = E \left\{ [1 - \delta_o] \left[\frac{\partial L(\cdot)}{\partial \underline{Q}^I} - \frac{\partial L(\cdot)}{\partial \overline{Q}^I} \right] \right\}$, which contradicts Assumption 1. Therefore, $K^I > X - K^D$.

If $K^I \geq X - \underline{\theta} K^D$, then $\theta^I = \frac{X - K^I}{K^D} \leq \frac{X - (X - \underline{\theta} K^D)}{K^D} = \underline{\theta}$. Therefore, $G(\tilde{\theta}^I) = 0$ because $\tilde{\theta}^I \equiv \min \{ \max \{ \underline{\theta}, \theta^I \}, 1 \} = \underline{\theta}$. Then (33) implies $-k_I = E \left\{ [1 - \delta_o] \left[\frac{\partial L(\cdot)}{\partial \underline{Q}^I} - \frac{\partial L(\cdot)}{\partial \overline{Q}^I} \right] \right\}$, which contradicts Assumption 1. Therefore, $K^I < X - \underline{\theta} K^D$.

Observe that:

$$\begin{aligned}
X - K^D < K^I &\Rightarrow X - K^I < K^D \Rightarrow \theta^I \equiv \frac{X - K^I}{K^D} < 1, \text{ and} \\
K^I < X - \underline{\theta} K^D &\Rightarrow X - K^I > \underline{\theta} K^D \Rightarrow \theta^I \equiv \frac{X - K^I}{K^D} > \underline{\theta}.
\end{aligned}$$

Therefore, $\widehat{\theta}^I \equiv \max\{\underline{\theta}, \theta^I\} = \theta^I$ and $\widetilde{\theta}^I \equiv \min\{\widehat{\theta}^I, 1\} = \min\{\theta^I, 1\} = \theta^I$. ■

Since $\lambda = 1$, (25) and (29) imply that when $c_a = 0$ and $\frac{\partial L(\cdot)}{\partial \underline{Q}^I} = \frac{\partial L(\cdot)}{\partial \overline{Q}^I} = \frac{\partial L(\cdot)}{\partial Q^D}$ for all $\underline{Q}^I, \overline{Q}^I, Q^D$:

$$w \theta^E = \bar{v} \widetilde{\theta}^E + \underline{v} [\theta^E - \widetilde{\theta}^E]. \quad (34)$$

(5), (33), and (34) imply that $K^I = K^{Ic}$ and $K^D = K^{Dc}$ under the specified conditions.

From (1) and (2), the VIP's expected cost is:

$$\begin{aligned}
E\{C^I(\cdot)\} &= F + k_I K^I + \int_{\underline{\theta}}^{\widetilde{\theta}^I} [\underline{v} K^I + \bar{v} (X - \theta K^D - K^I)] dG(\theta) \\
&\quad + \int_{\widetilde{\theta}^I}^1 \underline{v} [X - \theta K^D] dG(\theta). \quad (35)
\end{aligned}$$

From (31) and (35):

$$\begin{aligned}
r &= \frac{1}{X} \{ w \theta^E K^D + F + k_I K^I + \int_{\underline{\theta}}^{\widetilde{\theta}^I} [\underline{v} K^I + \bar{v} (X - \theta K^D - K^I)] dG(\theta) \\
&\quad + \int_{\widetilde{\theta}^I}^1 \underline{v} [X - \theta K^D] dG(\theta) \}. \quad (36)
\end{aligned}$$

Observe that:

$$\begin{aligned}
&\int_{\underline{\theta}}^{\widetilde{\theta}^I} [\underline{v} K^I + \bar{v} (X - \theta K^D - K^I)] dG(\theta) + \int_{\widetilde{\theta}^I}^1 \underline{v} [X - \theta K^D] dG(\theta) \\
&= \underline{v} K^I G(\widetilde{\theta}^I) + \bar{v} [X - K^I] G(\widetilde{\theta}^I) - \bar{v} K^D \int_{\underline{\theta}}^{\widetilde{\theta}^I} \theta dG(\theta) \\
&\quad + \underline{v} X [1 - G(\widetilde{\theta}^I)] - \underline{v} K^D \int_{\widetilde{\theta}^I}^1 \theta dG(\theta) \\
&= \underline{v} X - K^D [\bar{v} \widetilde{\theta}^E + \underline{v} (\theta^E - \widetilde{\theta}^E)] + \bar{v} [X - K^I] G(\widetilde{\theta}^I) - \underline{v} X G(\widetilde{\theta}^I) + \underline{v} K^I G(\widetilde{\theta}^I) \\
&= \underline{v} X - K^D [\bar{v} \widetilde{\theta}^E + \underline{v} (\theta^E - \widetilde{\theta}^E)] + [\bar{v} - \underline{v}] [X - K^I] G(\widetilde{\theta}^I). \quad (37)
\end{aligned}$$

(36) and (37) imply:

$$\begin{aligned}
r = \underline{v} + \frac{F + k_I K^I}{X} + \frac{\theta^E K^D}{X} \left[w - \bar{v} \frac{\tilde{\theta}^E}{\theta^E} - \underline{v} \left(1 - \frac{\tilde{\theta}^E}{\theta^E} \right) \right] \\
+ \frac{1}{X} [\bar{v} - \underline{v}] [X - K^I] G(\tilde{\theta}^I). \quad (38)
\end{aligned}$$

(34) and (38) imply:

$$r = \underline{v} + \frac{F + k_I K^I}{X} + \frac{1}{X} [\bar{v} - \underline{v}] [X - K^I] G(\tilde{\theta}^I). \quad (39)$$

(33) and (39) imply:

$$r = \underline{v} + \frac{F}{X} + \frac{k_I}{X} K^I + \frac{k_I}{X} [X - K^I] = \underline{v} + k_I + \frac{F}{X}. \quad \blacksquare \quad (40)$$

Proof of Proposition 2.

From (34) and (40):

$$r = \underline{v} + k_I + \frac{F}{X} \quad \text{and} \quad w = \underline{v} + [\bar{v} - \underline{v}] \frac{\tilde{\theta}^E}{\theta^E}. \quad (41)$$

(33) and (41) imply:

$$r > w \Leftrightarrow k_I + \frac{F}{X} > [\bar{v} - \underline{v}] \frac{\tilde{\theta}^E}{\theta^E} \Leftrightarrow \frac{F}{X} + k_I > \frac{k_I}{G(\theta^I)} \frac{\tilde{\theta}^E}{\theta^E}. \quad (42)$$

Since $F \geq 0$, the last inequality in (42) holds if:

$$\begin{aligned}
\theta^E G(\theta^I) > \tilde{\theta}^E &\Leftrightarrow \theta^E \int_{\underline{\theta}}^{\theta^I} dG(\theta) > \int_{\underline{\theta}}^{\theta^I} \theta dG(\theta) \\
&\Leftrightarrow \int_{\underline{\theta}}^{\theta^I} [\theta^E - \theta] dG(\theta) > 0. \quad (43)
\end{aligned}$$

First suppose $\theta^I < \theta^E$. Then $\theta < \theta^E$ for all $\theta \in [\underline{\theta}, \theta^I]$. Therefore, the inequality in (43) holds.

Now suppose $\theta^I \geq \theta^E$. Then the inequality in (43) holds if:

$$\int_{\underline{\theta}}^{\theta^E} [\theta^E - \theta] dG(\theta) > \int_{\theta^E}^{\theta^I} [\theta - \theta^E] dG(\theta). \quad (44)$$

Since $\theta^I < 1$ from Lemma A1, the inequality in (44) holds if:

$$\int_{\underline{\theta}}^{\theta^E} [\theta^E - \theta] dG(\theta) \geq \int_{\theta^E}^1 [\theta - \theta^E] dG(\theta)$$

$$\Leftrightarrow \int_{\underline{\theta}}^1 [\theta^E - \theta] dG(\theta) \geq 0 \Leftrightarrow \theta^E - \theta^E \geq 0. \quad \blacksquare$$

Proof of Proposition 3.

The regulator's problem in this setting, denoted [RP-2], is:

$$\begin{aligned} \underset{r_n = w, K^I \geq 0}{\text{Maximize}} \quad & E\{V^N(X^N) - r_n X^N + V^D(X^D) - r_n [X^D - \theta^E K^D] - C^D(K^D) \\ & - L(\underline{Q}^I(\theta), \overline{Q}^I(\theta), \theta K^D)\} \end{aligned} \quad (45)$$

$$\text{subject to: } E\{r_n [X - \theta K^D] - C^I(\underline{Q}^I(\theta), \overline{Q}^I(\theta), a(\theta), K^I)\} \geq 0, \quad (46)$$

where consumer D 's choice of K^D is given by:

$$r_n \theta^E = C^{D'}(K^D) \Rightarrow \frac{\partial K^D}{\partial r_n} = \frac{\theta^E}{C^{D''}(K^D)} > 0 \quad \text{and} \quad \frac{\partial K^D}{\partial K^I} = 0. \quad (47)$$

Let $\lambda_n \geq 0$ denote the Lagrange multiplier associated with constraint (46). Then the necessary conditions for a solution to [RP-2] include:

$$\begin{aligned} r_n : \quad & -(X - \theta^E K^D) + r_n \theta^E \frac{\partial K^D}{\partial r_n} - C^{D'}(K^D) \frac{\partial K^D}{\partial r_n} - \frac{dE\{L(\cdot)\}}{dK^D} \frac{\partial K^D}{\partial r_n} \\ & + \lambda_n \left[X - \theta^E K^D - r_n \theta^E \frac{\partial K^D}{\partial r_n} - \frac{dE\{C^I(\cdot)\}}{dK^D} \frac{\partial K^D}{\partial r_n} \right] = 0. \end{aligned} \quad (48)$$

$$K^I : \quad - \frac{dE\{L(\cdot)\}}{dK^I} - \lambda_n \frac{dE\{C^I(\cdot)\}}{dK^I} \leq 0. \quad (49)$$

Recall $\theta^I \equiv \frac{X - K^I}{K^D}$, $\widehat{\theta}^I \equiv \max\{\underline{\theta}, \theta^I\}$, and $\widetilde{\theta}^I \equiv \min\{\widehat{\theta}^I, 1\}$. Also, $Q^D(\theta) \equiv \theta K^D$.

Then (1), (2), (24), (28), and (47) imply that (48) and (49) can be written as:

$$[\lambda_n - 1] [X - \theta^E K^D] + E \left\{ \theta \left[\delta_o \frac{\partial L(\cdot)}{\partial \underline{Q}^I} + (1 - \delta_o) \frac{\partial L(\cdot)}{\partial \overline{Q}^I} - \frac{\partial L(\cdot)}{\partial Q^D} \right] \right\} \frac{\partial K^D}{\partial r_n}$$

$$- \lambda_n r_n \theta^E \frac{\partial K^D}{\partial r_n} + \lambda_n \frac{\partial K^D}{\partial r_n} \left[\bar{v} \int_{\underline{\theta}}^{\tilde{\theta}^I} \theta dG(\theta) + \underline{v} \int_{\tilde{\theta}^I}^1 \theta dG(\theta) - c_a \int_{\tilde{\theta}}^1 \theta dG(\theta) \right] = 0 \quad (50)$$

and

$$- E \left\{ [1 - \delta_o] \left[\frac{\partial L(\cdot)}{\partial \underline{Q}^I} - \frac{\partial L(\cdot)}{\partial \bar{Q}^I} \right] \right\} - \lambda_n \left[k_I - \int_{\underline{\theta}}^{\tilde{\theta}^I} [\bar{v} - \underline{v}] dG(\theta) \right] \leq 0. \quad (51)$$

When $c_a = 0$ and $\frac{\partial L(\cdot)}{\partial \underline{Q}^I} = \frac{\partial L(\cdot)}{\partial \bar{Q}^I}$ for all $\underline{Q}^I$, $\bar{Q}^I$, and Q^D , (50) and (51) can be written as:

$$\begin{aligned} & [\lambda_n - 1] [X - \theta^E K^D] - \lambda_n r_n \theta^E \frac{\partial K^D}{\partial r_n} \\ & + \lambda_n \frac{\partial K^D}{\partial r_n} \left[\bar{v} \int_{\underline{\theta}}^{\tilde{\theta}^I} \theta dG(\theta) + \underline{v} \int_{\tilde{\theta}^I}^1 \theta dG(\theta) \right] = 0 \end{aligned} \quad (52)$$

and

$$- \lambda_n \left[k_I - \int_{\underline{\theta}}^{\tilde{\theta}^I} [\bar{v} - \underline{v}] dG(\theta) \right] \leq 0. \quad (53)$$

If $\lambda_n = 0$, then (52) implies $X - \theta^E K^D = 0$. This is a contradiction because $X > \theta^E K^D$ by assumption. Therefore, $\lambda_n > 0$ and so:

$$r_n = \frac{E \left\{ C^I(\underline{Q}^I(\theta), \bar{Q}^I(\theta), a(\theta), K^I) \right\}}{X - \theta^E K^D}. \quad (54)$$

Following the proof of Lemma A1, it is readily verified that $0 < X - K^D < K^I < X - \underline{\theta} K^D$ and so $\tilde{\theta}^I = \hat{\theta}^I = \theta^I = \frac{X - K^I}{K^D} \in (\underline{\theta}, 1)$. Therefore, (33) and (54) imply:

$$\begin{aligned} r_n &= \frac{1}{X - \theta^E K^D} [F + k_I K^I + \int_{\underline{\theta}}^{\tilde{\theta}^I} [\underline{v} K^I + \bar{v} (X - \theta K^D - K^I)] dG(\theta) \\ &\quad + \int_{\tilde{\theta}^I}^1 \underline{v} [X - \theta K^D] dG(\theta)] \\ &= \frac{1}{X - \theta^E K^D} [F + k_I K^I + \underline{v} X - K^D (\bar{v} \tilde{\theta}^E + \underline{v} [\theta^E - \tilde{\theta}^E]) \\ &\quad + (\bar{v} - \underline{v}) (X - K^I) G(\tilde{\theta}^I)] \end{aligned}$$

$$\begin{aligned}
&= \frac{1}{X - \theta^E K^D} [F + k_I K^I + \underline{v} X - K^D (\bar{v} \tilde{\theta}^E + \underline{v} [\theta^E - \tilde{\theta}^E])] + k_I [X - K^I] \\
&= \frac{1}{X - \theta^E K^D} [F + k_I X + \underline{v} X - K^D (\bar{v} \tilde{\theta}^E + \underline{v} [\theta^E - \tilde{\theta}^E])]. \tag{55}
\end{aligned}$$

Recall r denotes the retail price of electricity at the solution to [RP]. (40) and (55) provide:

$$\begin{aligned}
&r_n - r > 0 \\
&\Leftrightarrow \frac{1}{X - \theta^E K^D} [F + k_I X + \underline{v} X - K^D (\bar{v} \tilde{\theta}^E + \underline{v} [\theta^E - \tilde{\theta}^E])] - \underline{v} - k_I - \frac{F}{X} > 0 \\
&\Leftrightarrow F + k_I X + \underline{v} X - K^D [\bar{v} \tilde{\theta}^E + \underline{v} (\theta^E - \tilde{\theta}^E)] - [\underline{v} + k_I + \frac{F}{X}] [X - \theta^E K^D] > 0 \\
&\Leftrightarrow F \left[1 - \frac{X - \theta^E K^D}{X} \right] + \theta^E K^D \left[\underline{v} + k_I - \bar{v} \frac{\tilde{\theta}^E}{\theta^E} - \underline{v} \left(1 - \frac{\tilde{\theta}^E}{\theta^E} \right) \right] > 0 \\
&\Leftrightarrow \theta^E K^D \left[\frac{F}{X} + k_I - (\bar{v} - \underline{v}) \frac{\tilde{\theta}^E}{\theta^E} \right] > 0 \\
&\Leftrightarrow \theta^E K^D \left[\frac{F}{X} + k_I - \frac{k_I}{G(\tilde{\theta}^I)} \frac{\tilde{\theta}^E}{\theta^E} \right] > 0. \tag{56}
\end{aligned}$$

The last inequality in (56) holds because $F \geq 0$ and $\theta^E G(\tilde{\theta}^I) > \tilde{\theta}^E$, from the proof of Proposition 2.

Recall that $r > w$ at the solution to [RP], from Proposition 2. Therefore, since $r_n > r$, it follows that $r_n > w$. Consequently, K^D is higher at the solution to [RP-2] than at the solution to [RP] because K^D is an increasing function of the unit DG payment, from (25) and (47). ■

Proof of Corollary 1.

Aggregate expected consumer welfare is strictly lower at the solution to [RP-2] than at the solution to [RP] because the $(r_n, w = r_n, K^I)$ values that solve [RP-2] constitute a feasible solution to [RP], but are not the solution to [RP].

The remaining conclusions in the corollary follow immediately from Propositions 1 and 3, since consumer N 's expected welfare is strictly decreasing in the retail price of electricity and independent of the level of compensation for DG. ■

Proof of Proposition 4.

Recall $\theta^D \equiv \frac{X^D}{K^D}$, $\widehat{\theta}^D \equiv \max\{\theta, \theta^D\}$, and $\widetilde{\theta}^D \equiv \min\{\widehat{\theta}^D, 1\}$. Since $\lambda = 1$ at the solution to [RP], (24) and (29) imply:

$$\begin{aligned} \int_{\underline{\theta}}^1 \theta [\delta_o \underline{e} + (1 - \delta_o) \bar{e} - e_D] dG(\theta) \\ - w \theta^E + \int_{\underline{\theta}}^1 \theta [\delta_o \underline{v} + (1 - \delta_o) \bar{v} - \delta_D c_a] dG(\theta) = 0. \end{aligned} \quad (57)$$

Observe that:

$$\begin{aligned} \int_{\underline{\theta}}^1 \theta [\delta_o \underline{e} + (1 - \delta_o) \bar{e} - e_D] dG(\theta) &= \int_{\underline{\theta}}^{\widetilde{\theta}^I} \bar{e} \theta dG(\theta) + \int_{\widetilde{\theta}^I}^1 \underline{e} \theta dG(\theta) - e_D \int_{\underline{\theta}}^1 \theta dG(\theta) \\ &= \bar{e} \widetilde{\theta}^E + \underline{e} \left[\int_{\underline{\theta}}^1 \theta dG(\theta) - \int_{\underline{\theta}}^{\widetilde{\theta}^I} \theta dG(\theta) \right] - e_D \theta^E = \bar{e} \widetilde{\theta}^E + \underline{e} [\theta^E - \widetilde{\theta}^E] - e_D \theta^E. \end{aligned} \quad (58)$$

Also observe that:

$$\begin{aligned} \int_{\underline{\theta}}^1 \theta [\delta_o \underline{v} + (1 - \delta_o) \bar{v} - \delta_D c_a] dG(\theta) &= \int_{\underline{\theta}}^{\widetilde{\theta}^I} \bar{v} \theta dG(\theta) + \int_{\widetilde{\theta}^I}^1 \underline{v} \theta dG(\theta) - c_a \int_{\underline{\theta}}^1 \theta dG(\theta) \\ &= \bar{v} \widetilde{\theta}^E + \underline{v} \left[\int_{\underline{\theta}}^1 \theta dG(\theta) - \int_{\underline{\theta}}^{\widetilde{\theta}^I} \theta dG(\theta) \right] - c_a \theta^m \\ &= \bar{v} \widetilde{\theta}^E + \underline{v} [\theta^E - \widetilde{\theta}^E] - c_a \theta^m, \quad \text{where } \theta^m \equiv \int_{\widetilde{\theta}}^1 \theta dG(\theta). \end{aligned} \quad (59)$$

(57), (58), and (59) provide:

$$\bar{e} \widetilde{\theta}^E + \underline{e} [\theta^E - \widetilde{\theta}^E] - e_D \theta^E - w \theta^E + \bar{v} \widetilde{\theta}^E + \underline{v} [\theta^E - \widetilde{\theta}^E] - c_a \theta^m = 0$$

$$\Rightarrow w = [\underline{v} + \underline{e} - e_D] \left[1 - \frac{\tilde{\theta}^E}{\theta^E} \right] + [\bar{v} + \bar{e} - e_D] \left[\frac{\tilde{\theta}^E}{\theta^E} \right] - c_a \frac{\theta^m}{\theta^E}. \quad \blacksquare \quad (60)$$

Proof of Proposition 5.

(23) and Lemma A1 imply that in the setting of Example 2:

$$\begin{aligned} E \left\{ [1 - \delta_o] \left[\frac{\partial L(\cdot)}{\partial \underline{Q}^I} - \frac{\partial L(\cdot)}{\partial \bar{Q}^I} \right] \right\} &= E[(1 - \delta_o)(\underline{e} - \bar{e})] \\ &= [\underline{e} - \bar{e}] \int_{\underline{\theta}}^{\theta^I} dG(\theta) = [\underline{e} - \bar{e}] G(\theta^I). \end{aligned} \quad (61)$$

Since $\lambda = 1$ and since $K^I > 0$ from Lemma A1, (33) and (61) imply:

$$\begin{aligned} [\bar{v} - \underline{v}] \left[\frac{\theta^I - \underline{\theta}}{1 - \underline{\theta}} \right] - [\underline{e} - \bar{e}] \left[\frac{\theta^I - \underline{\theta}}{1 - \underline{\theta}} \right] &= k_I \\ \Rightarrow \theta^I &= \underline{\theta} + k_I \left[\frac{1 - \underline{\theta}}{\bar{v} + \bar{e} - (\underline{v} + \underline{e})} \right] = \underline{\theta} + k_I \left[\frac{1 - \underline{\theta}}{\Delta_v} \right]. \end{aligned} \quad (62)$$

(62) implies:

$$\begin{aligned} \tilde{\theta}^E &= \int_{\underline{\theta}}^{\theta^I} \theta dG(\theta) = \left[\frac{1}{1 - \underline{\theta}} \right] \frac{1}{2} [(\theta^I)^2 - (\underline{\theta})^2] = \frac{\left(\underline{\theta} + k_I \left[\frac{1 - \underline{\theta}}{\Delta_v} \right] \right)^2 - (\underline{\theta})^2}{2[1 - \underline{\theta}]} \\ &= \frac{2\underline{\theta} k_I \left[\frac{1 - \underline{\theta}}{\Delta_v} \right] + (k_I)^2 \left[\frac{1 - \underline{\theta}}{\Delta_v} \right]^2}{2[1 - \underline{\theta}]} = \frac{2\underline{\theta} k_I \Delta_v + (k_I)^2 [1 - \underline{\theta}]}{2[\Delta_v]^2} \\ \Rightarrow \frac{\tilde{\theta}^E}{\theta^E} &= \frac{2\underline{\theta} k_I \Delta_v + (k_I)^2 [1 - \underline{\theta}]}{[1 + \underline{\theta}][\Delta_v]^2} \in (0, 1). \end{aligned} \quad (63)$$

(60) and (63) provide:

$$\begin{aligned} w &= \underline{v} + [\bar{v} - \underline{v}] \frac{\tilde{\theta}^E}{\theta^E} + \underline{e} + [\bar{e} - \underline{e}] \frac{\tilde{\theta}^E}{\theta^E} - e_D - c_a \frac{\theta^m}{\theta^E} \\ &= \underline{v} + \underline{e} - e_D - c_a \frac{\theta^m}{\theta^E} + [\bar{v} + \bar{e} - (\underline{v} + \underline{e})] \frac{\tilde{\theta}^E}{\theta^E} \\ &= \underline{v} + \underline{e} - e_D - c_a \left[\frac{2\theta^m}{1 + \underline{\theta}} \right] + B, \end{aligned} \quad (64)$$

where:

$$B \equiv \frac{2\underline{\theta} k_I \Delta_v + (k_I)^2 [1 - \underline{\theta}]}{[1 + \underline{\theta}] \Delta_v}. \quad (65)$$

Case 1. $K^D \leq X^D$.

$\tilde{\theta}^D = 1$ and so $\theta^m = 0$ in this case. Therefore, since $\frac{\tilde{\theta}^E}{\theta^E} \in (0, 1)$ and B does not vary with e_D , k_0 , k_1 , F , or c_a , (64) implies:

$$\frac{dw}{de_D} = -1 \quad \text{and} \quad \frac{dw}{dk_0} = \frac{dw}{dk_1} = \frac{dw}{dF} = \frac{dw}{dc_a} = 0. \quad (66)$$

Let $G \equiv [1 + \underline{\theta}] \Delta_v$. From (64) and (65):

$$\begin{aligned} \frac{dw}{d\bar{e}} &= \frac{dB}{d\bar{e}} = \frac{1}{G^2} \{ [1 + \underline{\theta}] \Delta_v 2\underline{\theta} k_I - 2\underline{\theta} k_I [1 + \underline{\theta}] \Delta_v - (k_I)^2 [1 + \underline{\theta}] [1 - \underline{\theta}] \} \\ &= - \frac{(k_I)^2 [1 - (\underline{\theta})^2]}{G^2} \equiv Z_{\bar{e}} < 0. \end{aligned}$$

From (65):

$$\begin{aligned} \frac{dB}{d\bar{e}} &= \frac{1}{G^2} \{ -[1 + \underline{\theta}] \Delta_v 2\underline{\theta} k_I + 2\underline{\theta} k_I [1 + \underline{\theta}] \Delta_v + (k_I)^2 [1 + \underline{\theta}] [1 - \underline{\theta}] \} \\ &= \frac{(k_I)^2 [1 - (\underline{\theta})^2]}{G^2} > 0. \end{aligned} \quad (67)$$

(64) and (67) provide:

$$\frac{dw}{d\bar{e}} = 1 + \frac{dB}{d\bar{e}} \equiv Z_{\bar{e}} > 0.$$

From (65):

$$\begin{aligned} \frac{dB}{d\bar{v}} &= \frac{1}{G^2} \{ -[1 + \underline{\theta}] \Delta_v 2\underline{\theta} k_I + 2\underline{\theta} k_I [1 + \underline{\theta}] \Delta_v + (k_I)^2 [1 + \underline{\theta}] [1 - \underline{\theta}] \} \\ &= \frac{(k_I)^2 [1 - (\underline{\theta})^2]}{G^2} \equiv Z_{\bar{v}} > 0. \end{aligned} \quad (68)$$

From (64) and (68):

$$\frac{dw}{d\bar{v}} = 1 + \frac{dB}{d\bar{v}} = Z_{\bar{v}} > 0. \quad (69)$$

From (64) and (65):

$$\frac{dw}{d\bar{v}} = \frac{dB}{d\bar{v}} = \frac{1}{G^2} \{ [1 + \underline{\theta}] \Delta_v 2\underline{\theta} k_I - 2\underline{\theta} k_I [1 + \underline{\theta}] \Delta_v - (k_I)^2 [1 + \underline{\theta}] [1 - \underline{\theta}] \}$$

$$= -\frac{(k_I)^2 [1 - (\underline{\theta})^2]}{G^2} \equiv Z_{\bar{v}} < 0. \quad (70)$$

From (64) and (65):

$$\frac{dw}{dk_I} = \frac{dB}{dk_I} = \frac{2}{G} [\underline{\theta} \Delta_v + k_I (1 - \underline{\theta})] \equiv Z_{k_I} > 0. \quad (71)$$

From (64) and (65):

$$\begin{aligned} \frac{dw}{d\underline{\theta}} &= \frac{dB}{d\underline{\theta}} = \frac{1}{\Delta_v} \frac{1}{[1 + \underline{\theta}]^2} \{ [1 + \underline{\theta}] [2 k_I \Delta_v - (k_I)^2] - 2 \underline{\theta} k_I \Delta_v - (k_I)^2 (1 - \underline{\theta}) \} \\ &= \frac{1}{\Delta_v} \left[\frac{2 k_I \Delta_v - 2 (k_I)^2}{(1 + \underline{\theta})^2} \right] = \frac{2 k_I [\Delta_v - k_I]}{[1 + \underline{\theta}]^2 \Delta_v} \equiv Z_{\underline{\theta}} > 0. \end{aligned} \quad (72)$$

Case 2. $K^D < X^D$.

In this case, $\tilde{\theta} = \tilde{\theta}^D = \frac{X^D}{K^D} < 1$, and so $\theta^m \in (0, 1)$. Therefore, $\frac{d\tilde{\theta}}{dz} = -\frac{X^D}{(K^D)^2} \frac{dK^D}{dz}$ for $z \in \{\underline{v}, \bar{v}, \bar{e}, \underline{e}, e_D, \alpha^N, \underline{\theta}, F, k_I, c_a, k_0, k_1\}$. Consequently:

$$\frac{d\theta^m}{dz} = \frac{d}{dz} \int_{\tilde{\theta}}^1 \theta dG(\theta) = -\tilde{\theta} g(\tilde{\theta}) \left[-\frac{X^D}{(K^D)^2} \frac{dK^D}{dz} \right] = \frac{\tilde{\theta} g(\tilde{\theta}) X^D}{(K^D)^2} \frac{dK^D}{dz}. \quad (73)$$

From (25), $\frac{dK^D}{dz} = \frac{\theta^E}{2k_1} \frac{dw}{dz}$ for $z \in \{\underline{v}, \bar{v}, \bar{e}, \underline{e}, e_D, \alpha^N, \underline{\theta}, F, k_I, c_a, k_0, k_1\}$. Therefore, (73) implies:

$$\begin{aligned} \frac{d\theta^m}{dz} &= h \frac{dw}{dz} \text{ for } z \in \{\underline{v}, \bar{v}, \bar{e}, \underline{e}, e_D, \alpha^N, \underline{\theta}, F, k_I, c_a, k_0, k_1\} \\ \text{where } h &\equiv \frac{\tilde{\theta} g(\tilde{\theta}) \theta^E X^D}{2k_1 (K^D)^2} > 0. \end{aligned} \quad (74)$$

(64), (66), (69), (70), (71), (72), and (74) imply:

$$\frac{dw}{d\underline{v}} = Z_{\underline{v}} - \left[\frac{2c_a}{1 + \underline{\theta}} \right] h \frac{dw}{d\underline{v}} \Rightarrow \frac{dw}{d\underline{v}} = \frac{Z_{\underline{v}}}{1 + \frac{2c_a h}{1 + \underline{\theta}}} > 0;$$

$$\frac{dw}{d\bar{v}} = Z_{\bar{v}} - \left[\frac{2c_a}{1 + \underline{\theta}} \right] h \frac{dw}{d\underline{v}} \Rightarrow \frac{dw}{d\bar{v}} = \frac{Z_{\bar{v}}}{1 + \frac{2c_a h}{1 + \underline{\theta}}} < 0;$$

$$\frac{dw}{d\bar{e}} = Z_{\bar{e}} - \left[\frac{2c_a}{1+\underline{\theta}} \right] h \frac{dw}{de} \Rightarrow \frac{dw}{de} = \frac{Z_{\bar{e}}}{\theta^E \left[1 + \frac{2c_a h}{1+\underline{\theta}} \right]} > 0;$$

$$\frac{dw}{d\bar{e}} = Z_{\bar{e}} - \left[\frac{2c_a}{1+\underline{\theta}} \right] h \frac{dw}{de} \Rightarrow \frac{dw}{de} = \frac{Z_{\bar{e}}}{1 + \frac{2c_a h}{1+\underline{\theta}}} > 0;$$

$$\frac{dw}{de_D} = -1 - \left[\frac{2c_a}{1+\underline{\theta}} \right] h \frac{dw}{de} \Rightarrow \frac{dw}{de_D} = -\frac{1}{1 + \frac{2c_a h}{1+\underline{\theta}}} < 0;$$

$$\frac{dw}{dF} = - \left[\frac{2c_a}{1+\underline{\theta}} \right] h \frac{dw}{dF} \Rightarrow \frac{dw}{dF} = 0;$$

$$\frac{dw}{d\underline{\theta}} = Z_{\underline{\theta}} + \frac{2c_a \theta^m}{[1+\underline{\theta}]^2} - \left[\frac{2c_a}{1+\underline{\theta}} \right] h \frac{dw}{d\underline{\theta}} \Rightarrow \frac{dw}{d\underline{\theta}} = \frac{1}{1 + \frac{2c_a h}{1+\underline{\theta}}} \left[Z_{\underline{\theta}} + \frac{2c_a \theta^m}{[1+\underline{\theta}]^2} \right] > 0;$$

$$\frac{dw}{dk_I} = Z_{k_I} - \left[\frac{2c_a}{1+\underline{\theta}} \right] h \frac{dw}{dk_I} \Rightarrow \frac{dw}{dk_I} = \frac{Z_{k_I}}{1 + \frac{2c_a h}{1+\underline{\theta}}} > 0; \quad \text{and}$$

$$\frac{dw}{dc_a} = -\frac{2\theta^m}{1+\underline{\theta}} - \left[\frac{2c_a}{1+\underline{\theta}} \right] h \frac{dw}{dc_a} \Rightarrow \frac{dw}{dc_a} = -\frac{2\theta^m}{1+\underline{\theta}} \left[\frac{1}{1 + \frac{2c_a h}{1+\underline{\theta}}} \right] < 0.$$

From (25), $\frac{dK^D}{dk_0} = -\frac{1}{2k_1} + \frac{\theta^E}{2k_1} \frac{dw}{dk_0}$. Therefore, from (73):

$$\frac{d\theta^m}{dk_0} = \frac{\tilde{\theta} g(\tilde{\theta}) X^D}{(K^D)^2} \left[-\frac{1}{2k_1} + \frac{\theta^E}{2k_1} \frac{dw}{dk_0} \right] = \frac{\tilde{\theta} g(\tilde{\theta}) \theta^E X^D}{2k_1 (K^D)^2} \frac{dw}{dk_0} - \frac{\tilde{\theta} g(\tilde{\theta}) X^D}{2k_1 (K^D)^2}. \quad (75)$$

(64) and (75) imply:

$$\begin{aligned} \frac{dw}{dk_0} &= -\frac{2c_a}{1+\underline{\theta}} \left[h \frac{dw}{dk_0} - \frac{\tilde{\theta} g(\tilde{\theta}) X^D}{2k_1 (K^D)^2} \right] \\ \Rightarrow \frac{dw}{dk_0} &= \frac{1}{1 + \frac{2c_a h}{1+\underline{\theta}}} \left[\frac{c_a \tilde{\theta} g(\tilde{\theta}) X^D}{k_1 (K^D)^2 (1+\underline{\theta})} \right] > 0. \end{aligned}$$

From (25), $\frac{dK^D}{dk_1} = \frac{k_1 \theta^E \frac{dw}{dk_1} - (w \theta^E - k_0)}{2(k_1)^2}$. Therefore, from (73):

$$\frac{d\theta^m}{dk_1} = \frac{\tilde{\theta} g(\tilde{\theta}) X^D}{(K^D)^2} \left[\frac{k_1 \theta^E \frac{dw}{dk_1} - (w \theta^E - k_0)}{2(k_1)^2} \right]$$

$$= h \frac{dw}{dk_1} - \frac{[w \theta^E - k_0] \tilde{\theta} g(\tilde{\theta}) X^D}{2 (k_1)^2 (K^D)^2}. \quad (76)$$

(64) and (76) imply:

$$\begin{aligned} \frac{dw}{dk_1} &= -\frac{2c_a}{1+\underline{\theta}} \left[h \frac{dw}{dk_1} - \frac{[w \theta^E - k_0] \tilde{\theta} g(\tilde{\theta}) X^D}{2 (k_1)^2 (K^D)^2} \right] \\ \Rightarrow \frac{dw}{dk_1} &= \frac{1}{1 + \frac{2c_a h}{1+\underline{\theta}}} \left[\frac{c_a \tilde{\theta} g(\tilde{\theta}) X^D (w \theta^E - k_0)}{(1+\underline{\theta}) (k_1)^2 (K^D)^2} \right] > 0. \end{aligned} \quad (77)$$

The inequality in (77) holds because, from (25), $w \theta^E - k_0 = 2 k_1 K^D > 0$. ■

Proof of Proposition 6.

The expression for K^D in (7) reflects (25). From (62):

$$\theta^I = \frac{X - K^I}{K^D} = \underline{\theta} + k_I \left[\frac{1 - \underline{\theta}}{\Delta_v} \right] \Rightarrow K^I = X - K^D \left[\underline{\theta} + k_I \left(\frac{1 - \underline{\theta}}{\Delta_v} \right) \right].$$

$\frac{dw}{dF} = 0$, from Proposition 5. Therefore, (7) implies that $\frac{dK^D}{dF} = \frac{dK^I}{dF} = 0$.

If $K^D \leq X^D$, then $\frac{dw}{dk_0} = \frac{dw}{dk_1} = \frac{dw}{dc_a} = 0$, from Proposition 5. Therefore, (7) implies that $\frac{dK^D}{dk_0} < 0$, $\frac{dK^D}{dk_1} < 0$, and $\frac{dK^D}{dc_a} = 0$, and so $\frac{dK^I}{dk_0} > 0$, $\frac{dK^I}{dk_1} > 0$, and $\frac{dK^I}{dc_a} = 0$ when $K^D \leq X^D$.

If $K^D > X^D$, then $\frac{dw}{dc_a} < 0$, from Proposition 5. Therefore, (7) implies that $\frac{dK^D}{dc_a} < 0$ and so $\frac{dK^I}{dc_a} > 0$ when $K^D > X^D$.

$\frac{dw}{d\underline{\theta}} > 0$, from Proposition 5. Therefore, (7) implies that $\frac{dK^D}{d\underline{\theta}} > 0$ since $\frac{d\theta^E}{d\underline{\theta}} > 0$. Furthermore, $\frac{d}{d\underline{\theta}} \left(\underline{\theta} + k_I \left[\frac{1 - \underline{\theta}}{\Delta_v} \right] \right) = 1 - \frac{k_I}{\Delta_v} > 0$ since $k_I < \Delta_v$, by assumption. Consequently, $\frac{dK^I}{d\underline{\theta}} < 0$, from (7).

$\frac{dw}{d\bar{v}} < 0$, from Proposition 5. Therefore, (7) implies that $\frac{dK^D}{d\bar{v}} < 0$. Furthermore, $\frac{d}{d\bar{v}} \left(\underline{\theta} + k_I \left[\frac{1 - \underline{\theta}}{\Delta_v} \right] \right) < 0$. Consequently, $\frac{dK^I}{d\bar{v}} > 0$, from (7).

$\frac{dw}{d\underline{v}} > 0$, from Proposition 5. Therefore, (7) implies that $\frac{dK^D}{d\underline{v}} > 0$. Furthermore, $\frac{d}{d\underline{v}} \left(\underline{\theta} + k_I \left[\frac{1 - \underline{\theta}}{\Delta_v} \right] \right) > 0$. Consequently, $\frac{dK^I}{d\underline{v}} < 0$, from (7).

$\frac{dw}{dk_I} > 0$, from Proposition 5. Therefore, (7) implies that $\frac{dK^D}{dk_I} > 0$. Furthermore,

$\frac{d}{dk_I} \left(\underline{\theta} + k_I \left[\frac{1-\underline{\theta}}{\Delta_v} \right] \right) > 0$. Consequently, $\frac{dK^I}{dk_I} < 0$, from (7).

$\frac{dw}{d\underline{e}} > 0$, from Proposition 5. Therefore, $\frac{dK^D}{d\underline{e}} > 0$ and so $\frac{dK^I}{d\underline{e}} < 0$, from (7).

$\frac{dw}{d\bar{e}} < 0$, from Proposition 5. Therefore, $\frac{dK^D}{d\bar{e}} < 0$ and so $\frac{dK^I}{d\bar{e}} > 0$, from (7).

$\frac{dw}{de_D} < 0$, from Proposition 5. Therefore, $\frac{dK^D}{de_D} < 0$ and so $\frac{dK^I}{de_D} > 0$, from (7). ■

Appendix B. Elements of the Numerical Solutions

This Appendix: (1) further explains the choice of parameter values employed in section 5 and the methodology employed in the associated numerical solutions; and (2) illustrates how the estimates reported in section 5 change as parameter values change.

1. Further Explanation of Parameter Choices and Solution Methodology.

Unit Losses from Externalities ($\underline{e}$)

For each generation technology, the value of $\underline{e}$ is the product of: (i) the metric tons of CO₂ emissions that arise from the production of a KWh of electricity; and (ii) the estimated social cost of a metric ton of CO₂ emissions. The U.S. Environmental Protection Agency (EPA) estimates that the social cost of CO₂ emissions varies between \$13 and \$62 per metric ton (EPA, 2013), depending upon the relevant discount rate. Employing the intermediate 3 percent discount rate cited by the EPA, the estimated social cost of CO₂ emissions is \$41 per metric ton.

The amount of CO₂ emissions a technology produces per KWh of electricity is taken to be one one-thousandth of the product of: (i) the CO₂ emissions factor for the relevant fuel (EIA, 2011); and (ii) the heat rate for the technology (EIA, 2013a).⁴⁴ The emissions estimates are provided in (EIA, 2014b), which employs data from (EIA, 2011) and (EIA, 2013a).

DG Capacity Costs (k_0, k_1)

We assume the cost of DG capacity is $C^D(K^D) = k_0 K^D + k_1 (K^D)^2$. Given this cost function and the retail price of electricity (r_n), consumer D 's (interior) choice of K^D under a net metering policy is determined by:

$$r_n \theta^E = k_0 + 2 k_1 K^D. \quad (78)$$

To derive values for k_0 and k_1 , define $y \equiv r_n \theta^E$ and $x \equiv 2 K^D$ to rewrite equation (78)

⁴⁴The heat rate measures the amount of fuel required to generate a unit of electricity.

as:

$$y = b_0 + b_1 x. \quad (79)$$

We employ ordinary least squares (OLS) to estimate equation (79). The resulting coefficient estimates, $\hat{b}_0$ and $\hat{b}_1$, provide our estimates for k_0 and k_1 , respectively. The data for the explanatory variable x reflects the installed solar capacity in U.S. states with net metering plans in 2013 (SEIA, 2014). The data for the dependent variable y reflects the prevailing retail price of electricity in these states (EIA, 2013b).

The OLS regression produces coefficient estimates $\hat{b}_0 = k_0 = 52.8$ and $\hat{b}_1 = k_1 = 0.00149$. Given these values for k_0 and k_1 , K^D is often 0 in the numerical solutions, which can cause technical problems under the methodology employed to solve for the optimal net metering policy.⁴⁵ To avoid these technical problems, we approximate the substantially reduced costs of solar panels that are expected in the near future (APPA, 2013) by reducing k_0 to 47.42. This is the largest value for k_0 that ensures K^D is always strictly positive under the optimal net metering policy for the parameter values we consider.

Solution Methodology

To characterize the solution to [RP] in the setting of Example 2, we employ *Mathematica* to solve simultaneously the necessary conditions for an optimum identified in the proof of Proposition 1.

We also employ *Mathematica* to solve the system of nonlinear equations that constitute the necessary conditions for a solution to [RP-2], as identified in the proof of Proposition 3. The Newton-Raphson Iteration Method is employed to determine the values of r_n , K^I , and K^D that satisfy the equations, given the identified parameter values.

⁴⁵This methodology is described briefly below.

2. Sensitivity Analysis.

To illustrate how the findings in section 5 change as key parameter values change, we consider changes in the consumers' value of lost load (VOLL) (Table B1), the total demand for electricity (Table B2), the fraction of total demand accounted for by consumer D (Table B3), and the social cost of externalities from electricity production (Table B4). In each case, we assume that parameters other than the one being changed are fixed at the levels identified in section 5.

VOLL	Base Unit	r	w	K^I	K^D	$E \{U^N\}$	$E \{U^D\}$	$E \{W\}$
175	Coal	105.2	129.5	6,226.5	2,556.3	575,791.6	39,979.9	339,986.9
175	Nuclear	115.7	99.8	7,828.0	835.7	489,257.4	16,172.4	462,505.7
175	Hydro	116.2	92.4	8,500.0	0.0	484,806.0	14,994.0	499,800.0
500	Coal	105.2	129.5	6,226.5	2,556.3	3,255,416.6	122,854.9	3,102,486.9
500	Nuclear	115.7	99.8	7,828.0	835.7	3,168,882.4	99,047.4	3,225,005.7
500	Hydro	116.2	92.4	8,500.0	0.0	3,164,431.0	97,869.0	3,262,300.0
1,000	Coal	105.2	129.5	6,226.5	2,556.3	7,377,916.6	250,354.9	7,352,486.9
1,000	Nuclear	115.7	99.8	7,828.0	835.7	7,291,382.4	226,547.4	7,475,005.7
1,000	Hydro	116.2	92.4	8,500.0	0.0	7,286,931.0	225,369.0	7,512,300.0

Table B1(a). Outcomes Under the Optimal DG Policy when the VOLL Differs from 200.

VOLL	Base Unit	r_n	K^I	K^D	$E\{U^N\}$	$E\{U^D\}$	$E\{W\}$	$\Delta E\{W\}$
175	Coal	96.8	8,367.2	144.5	644,749.9	20,011.6	327,285.5	−3.7%
175	Nuclear	127.8	3,815.6	5,534.4	388,957.9	57,667.6	383,978.8	−17.0%
175	Hydro	129.7	3,560.3	5,848.5	373,523.2	62,517.5	388,707.7	−22.2%
500	Coal	96.8	8,367.2	144.5	3,324,374.9	102,886.6	3,089,785.5	−0.4%
500	Nuclear	127.8	3,815.6	5,534.4	3,068,582.9	140,542.6	3,146,478.8	−2.4%
500	Hydro	129.7	3,560.3	5,848.5	3,053,148.2	145,392.5	3,151,207.7	−3.4%
1,000	Coal	96.8	8,367.2	144.5	7,446,874.9	230,386.6	7,339,785.5	−0.2%
1,000	Nuclear	127.8	3,815.6	5,534.4	7,191,082.9	268,042.6	7,396,478.8	−1.1%
1,000	Hydro	129.7	3,560.3	5,848.5	7,175,648.2	272,892.5	7,401,207.7	−1.5%

**Table B1(b). Outcomes Under the Optimal Net Metering Policy
when the VOLL Differs from 200.**

X	Base Unit	r	w	K^I	K^D	$E\{U^N\}$	$E\{U^D\}$	$E\{W\}$
7,000	Coal	106.9	129.5	4,726.5	2,556.3	631,906.1	41,715.4	458,901.9
7,000	Nuclear	115.6	99.8	6,328.0	835.7	573,162.4	18,767.4	556,070.7
7,000	Hydro	116.2	92.4	7,000.0	0.0	569,002.0	17,598.0	586,600.0
10,000	Coal	103.9	129.5	7,726.5	2,556.3	931,927.1	50,994.4	646,071.9
10,000	Nuclear	115.7	99.8	9,328.0	835.7	817,602.4	26,327.4	793,940.7
10,000	Hydro	116.2	92.4	10,000.0	0.0	812,860.0	25,140.0	838,000.0

Table B2(a). Outcomes Under the Optimal DG Policy when X Differs from 8,500.

X	Base Unit	r_n	K^I	K^D	$E\{U^N\}$	$E\{U^D\}$	$E\{W\}$	$\Delta E\{W\}$
7,000	Coal	96.8	6,868.3	141.5	700,996.2	21,748.2	445,467.4	− 2.9%
7,000	Nuclear	131.1	1,702.9	6,081.0	467,946.4	69,571.4	477,386.5	− 14.2%
7,000	Hydro	132.4	1,495.1	6,296.9	459,207.7	73,283.7	477,893.1	− 18.5%
10,000	Coal	96.8	9,866.7	146.2	1,000,803.3	31,025.2	634,128.5	− 1.9%
10,000	Nuclear	125.2	5,752.9	5,093.2	725,608.5	61,091.9	719,756.5	− 9.3%
10,000	Hydro	126.9	5,546.7	5,382.6	708,876.0	65,092.1	732,168.5	− 12.6%

Table B2(b). Outcomes Under the Optimal Net Metering Policy when X Differs from 8,500.

X^D/X	Base Unit	r	w	K^I	K^D	$E\{U^N\}$	$E\{U^D\}$	$E\{W\}$
0.01	Coal	105.2	129.5	6,226.5	2,556.3	798,038.6	30,232.9	552,486.9
0.01	Nuclear	115.7	99.8	7,828.0	835.7	709,720.2	8,209.6	675,005.7
0.01	Hydro	116.2	92.4	8,500.0	0.0	705,177.0	7,123.0	712,300.0
0.05	Coal	105.2	129.5	6,226.5	2,556.3	765,794.6	62,476.9	552,486.9
0.05	Nuclear	115.7	99.8	7,828.0	835.7	681,044.6	36,885.1	675,005.7
0.05	Hydro	116.2	92.4	8,500.0	0.0	676,685.0	35,615.0	712,300.0

Table B3(a). Outcomes Under the Optimal DG Policy
when X^D/X Differs from 0.03.

X^D/X	Base Unit	r_n	K^I	K^D	$E\{U^N\}$	$E\{U^D\}$	$E\{W\}$	$\Delta E\{W\}$
0.01	Coal	96.8	8,367.2	144.5	868,418.7	8,842.8	539,785.5	− 2.3%
0.01	Nuclear	127.8	3,815.6	5,534.4	607,352.6	51,772.9	596,478.8	− 11.6%
0.01	Hydro	129.70	3,560.3	5,848.5	591,599.8	56,941.0	601,207.7	− 15.6%
0.05	Coal	96.8	8,367.2	144.5	833,331.1	43,930.4	539,785.5	− 2.3%
0.05	Nuclear	127.8	3,815.6	5,534.4	582,813.1	76,312.4	596,478.8	− 11.6%
0.05	Hydro	129.7	3,560.3	5,848.5	567,696.7	80,844.0	601,207.7	− 15.6%

Table B3(b). Outcomes Under the Optimal Net Metering Policy
when X^D/X Differs from 0.03.

Cost	Base Unit	r	w	K^I	K^D	$E\{U^N\}$	$E\{U^D\}$	$E\{W\}$
\$25	Coal	98.7	108.0	7,709.2	968.8	835,207.7	29,015.6	671,284.5
\$25	Nuclear	115.6	102.8	7,370.0	1,331.0	695,827.1	24,160.2	692,244.8
\$25	Hydro	115.9	98.2	8,037.0	554.7	693,523.2	21,907.7	712,758.5
\$50	Coal	109.3	138.7	5,544.0	3,230.5	748,212.0	58,552.3	503,846.7
\$50	Nuclear	115.7	98.4	8,037.4	592.5	694,772.2	22,010.9	665,733.1
\$50	Hydro	116.2	89.4	8,500.0	0.0	690,931.0	21,369.0	712,300.0

Table B4(a). Outcomes Under the Optimal DG Policy when the Social Cost of CO₂ Emissions Differs from \$41 per Metric Ton.

Cost	Base Unit	r_n	K^I	K^D	$E\{U^N\}$	$E\{U^D\}$	$E\{W\}$	$\Delta E\{W\}$
\$25	Coal	97.0	8,372.3	155.5	849,648.9	26,359.8	670,222.7	−0.2%
\$25	Nuclear	124.1	4,235.9	4,901.9	626,166.5	55,167.8	618,687.7	−10.6%
\$25	Hydro	125.6	4,038.8	5,152.7	613,840.3	58,544.5	645,676.1	−9.4%
\$50	Coal	96.7	8,364.9	137.9	851,611.2	26,403.0	474,752.2	−5.8%
\$50	Nuclear	129.9	3,578.5	5,877.5	578,221.9	69,355.5	584,930.7	−12.1%
\$50	Hydro	131.7	3,315.5	6,190.1	562,861.4	74,500.9	577,286.7	−19.0%

Table B4(b). Outcomes Under the Optimal Net Metering Policy when the Social Cost of CO₂ Emissions Differs from \$41 per Metric Ton.

References

American Council for an Energy-Efficient Economy, *Distributed Generation* (<http://www.aceee.org/topics/distributed-generation>), visited September 21, 2014.

American Public Power Association, *Distributed Generation: An Overview of Recent Policy and Market Developments*, Washington, DC: APPA, November 2013 (<http://www.publicpower.org/files/PDFs/Distributed%20Generation-Nov2013.pdf>).

Cardwell, Diane, “Solar Panel Payments Set Off a Fairness Debate,” *The New York Times*, June 4, 2012 (http://www.nytimes.com/2012/06/05/business/solar-payments-set-off-a-fairness-debate.html?_r=0).

Couture, Toby and Yves Gagnon, “An Analysis of Feed-in Tariff Remuneration Models: Implications for Renewable Energy Investment,” *Energy Policy*, 38(3), February 2010, 955-965.

Darghouth, Naïm, Galen Barbose, and Ryan Wiser, “The Impact of Rate Design and Net Metering on the Bill Savings from Distributed PV for Residential Customers in California,” *Energy Policy*, 39(9), September 2011, 5243-5253.

Darghouth, Naïm, Galen Barbose, and Ryan Wiser, “Customer-Economics of Residential Photovoltaic Systems (Part 1): The Impact of High Renewable Energy Penetrations on Electricity Bill Savings with Net Metering,” *Energy Policy*, 67(4), April 2014, 290-300.

Farrell, John, “Could Minnesota’s “Value of Solar” Make Everyone a Winner?” *Renewable Energy World.Com*, March 22, 2014a (<http://www.renewableenergyworld.com/rea/blog/post/2014/03/could-minnesotas-value-of-solar-make-everyone-a-winner>).

Farrell, John, “Minnesota’s Value of Solar: Can a Northern State’s New Solar Policy Defuse Distributed Generation Battles?” Institute for Local Self-Reliance Report, April 2014b, (<http://www.ilsr.org/wp-content/uploads/2014/04/MN-Value-of-Solar-from-ILSR.pdf>).

Gordon, Kenneth, Wayne Olson, and Amparo Nieto, “Responding to EPA 2005: Looking at Smart Meters for Electricity, Time-Based Rate Structures, and Net Metering,” Report prepared for the Edison Electric Institute, May 2006 (http://sites.energetics.com/MADRI/pdfs/responding_to_epact.pdf).

Institute for Electric Efficiency, *Utility-Scale Smart Meter Deployments, Plans, & Proposals*, May 2012 (http://www.edisonfoundation.net/iee/documents/iee_smartmeterrollouts.0512.pdf).

International Renewable Energy Agency, *Smart Grids and Renewables: A Guide for Effective Deployment*, November 2013 (http://www.irena.org/DocumentDownloads/Publications/smart_grids.pdf).

Joskow, Paul and Jean Tirole, “Reliability and Competitive Electricity Markets,” *Rand Journal of Economics*, 38(1), Spring 2007, 60-84.

Kind, Peter, “Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business,” Report prepared for the Edison Electric Institute, January 2013 (<http://www.eei.org/ourissues/finance/Documents/disruptivechallenges.pdf>).

Linville, Carl, John Shenot, and Jim Lazar, *Designing Distributed Generation Tariffs Well: Fair Compensation in a Time of Transition*, The Regulatory Assistance Project, November 2013 (www.raponline.org).

London Economics International, “Estimating the Value of Lost Load,” Briefing Paper prepared for the Electric Reliability Council of Texas, June 17, 2013, (http://www.ercot.com/content/gridinfo/resource/2014/mktanalysis/ERCOT_ValueofLostLoad_LiteratureReviewandMacroeconomic.pdf).

Poullikkas, Andreas, “A Comparative Assessment of Net Metering and Feed in Tariff Schemes for Residential PV Systems,” *Sustainable Energy Technologies and Assessments*, 3, September 2013, 1-8.

Raskin, David, “The Regulatory Challenge of Distributed Generation,” *Harvard Business Law Review Online*, 4, 2013, 38-51.

Schneider, Jordan and Rob Sargent, “Lighting the Way: The Top Ten States that Helped Drive America’s Solar Energy Boom in 2013,” PennEnvironment Research & Policy Center Report, August 2014 (http://environmentamericacenter.org/sites/environment/files/reports/EA_Lightingtheway_scrn.pdf).

Solar Electric Power Association, *Ratemaking, Solar Value, and Solar Net Energy Metering – A Primer*, July 2013 (<http://www.solarelectricpower.org/media/51299/sepa-nem-report-0713-print.pdf>).

Solar Energy Industries Association (SEIA), Solar Net Metering by State, November 16, 2012 (http://www.seia.org/sites/default/files/resources/Net-Metering-by-State_0.pdf).

Solar Energy Industries Association (SEIA), *Solar State by State* (<http://www.seia.org/policy/state-solar-policy>), visited September 21, 2014.

Sullivan, Michael, Matthew Mercurio, and Josh Schellenberg, “Estimated Value of Service Reliability for Electric Utility Customers in the United States,” Earnest Orlando Lawrence Berkeley National Laboratory Report LBNL-2132E, June 2009 (<http://certs.lbl.gov/pdf/lbnl-2132e.pdf>).

Than, Ker, “As Solar Power Grows, Dispute Flares Over U.S. Utility Bills,” *National Geographic Daily News*, December 24, 2013 (<http://news.nationalgeographic.com/news/energy/2013/12/131226-utilities-dispute-net-metering-for-solar/>).

U.S. Energy Information Administration, *2016 Levelized Cost of New Generation Resources from the Annual Energy Outlook*, 2010 (http://www.eia.gov/oiaf/aeo/pdf/2016levelized_costs_aeo2010.pdf).

U.S. Energy Information Administration, *Reporting of Greenhouse Gases Program, Table of Fuel and Energy Source: Codes and Emission Coefficients*, 2011 (<http://www.eia.gov/oiaf/1605/coefficients.html>).

U.S. Energy Information Administration, *Electricity Consumption Estimates, 2012*, State Energy Data System, Table F21 (http://www.eia.gov/state/seds/sep_fuel/html/pdf/fuel_use_es.pdf), visited September 21, 2014.

U.S. Energy Information Administration, *Form EIA-860, Annual Electric Generator Report*, 2013a (<http://www.eia.gov/electricity/data/eia860/>).

U.S. Energy Information Administration, *2012 Total Electric Industry - Average Retail Price*, Released November 2013b (http://www.eia.gov/electricity/sales_revenue_price/pdf/table4.pdf).

U.S. Energy Information Administration, *Annual Energy Outlook*, Released May 7, 2014a (http://www.eia.gov/forecasts/aeo/MT_electric.cfm).

U.S. Energy Information Administration, *How Much Carbon Dioxide is Produced per Kilo-watthour when Generating Electricity with Fossil Fuels?* (<http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11>). visited September 21, 2014b.

U.S. Energy Information Administration, *Form 826*, 2014c (<http://www.eia.gov/electricity/data/eia826/>).

U.S. Environmental Protection Agency, *Regulatory Impact Analysis for the Proposed Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units*, EPA-452/R-13-003, September 2013 (<http://www2.epa.gov/sites/production/files/2013-09/documents/20130920proposalria.pdf>).

Weissman, Steven and Nathaniel Johnson, *The Statewide Benefits of Net-Metering in California & the Consequences of Changes to the Program*, Center for Law, Energy & the Environment, University of California, 2012 (http://www.law.berkeley.edu/files/The_Statewide_Benefits_of_Net-Metering_in_CA_Weissman_and_Johnson.pdf).

World Alliance for Decentralized Energy, *Where Can DE be Used?* (http://www.localpower.org/deb_where.html), visited September 21, 2014.

Yamamoto, Yoshihiro, "Pricing Electricity from Residential Photovoltaic Systems: A Comparison of Feed-in Tariffs, Net Metering, and Net Purchase and Sale," *Solar Energy*, 86(9), September 2012, 2678-2685.

Department of Economics, University of Alberta Working Paper Series

2014-11: Output Growth and Commodity Prices in Latin America: What Has Changed? – Fossati, S.
2014-10: A Survey of the Economics of Patent Systems and Procedures – Eckert, A., Langinier, C.
2014-09: Using Bayesian Imputation to Assess Racial and Ethnic Disparities in Pediatric Performance Measures – Brown, D., Knapp, C., Baker, K., Kaufmann, M.
2014-08: Effects of an Integrated Care System on Children with Special Health Care Needs' Medicaid Expenditures – Marcu, M., Knapp, C., Madden, V., Brown, D., Wang, H., Sloyer, P.
2014-07: The Effect of Subsidized Entry on Capacity Auctions and the Long-Run Resource Adequacy of Electricity Markets – Brown, D.
2014-06: The Impact of Place-Based Employment Tax Credits on Local Labor: Evidence from Tax Data – Tong, P., Zhou, L.
2014-05: The Louis-Schmelling Paradox and the League Standing Effect Reconsidered – Humphreys, B., Zhou, L.
2014-04: Urban Casinos and Local Housing Markets: Evidence from the US - Huang, H., Humphreys, B., Zhou, L.
2014-03: Loss Aversion, Team Relocations, and Major League Expansion –Humphreys, B., Zhou, L.
2014-02: Do Urban Casinos Affect Nearby Neighborhoods? Evidence from Canada – Huang, H., Humphreys, B., Zhou, L.
2014-01: Rule-Based Resource Revenue Stabilization Funds: A Welfare Comparison – Landon, S., Smith, C.
2013-13: The Distributional Impacts of an Energy Boom in Western Canada – Marchand, J.
2013-12: Privatization in China: Technology and Gender in the Manufacturing Sector – Dammert, Ana C., Ural-Marchand, B.
2013-11: Market Structure, Imperfect Tariff Pass-Through, and Household Welfare in Urban China – Han, J., Runjuan L., Ural-Marchand, B., Zhang, J.
2013-10: Shotgun Mechanisms for Common-Value Partnerships: The Unassigned-Offeror Problem – Landeo, C., Spier, K.
2013-09: Irreconcilable Differences: Judicial Resoluton of Business Deadlock – Landeo, C., Spier, K.
2013-08: The Effects of Exchange Rates on Employment in Canada – Huang, H., Pang, K., Tang, Y.
2013-07: How Did Exchange Rates Affect Employment in US Cities? – Huang, H., Tang, Y.
2013-06: The Impact of Resale on Entry in Second Price Auctions – Che, X., Lee, P., Yang, Y.
2013-05: Shotguns and Deadlocks – Landeo, C., Spier, K.
2013-04: Sports Facilities, Agglomeration, and Urban Redevelopment – Humphreys, B., Zhou, L.
2013-03: Forecasting U.S. Recessions with Macro Factors – Fossati, S.
2013-02: Strategic Investments under Open Access: Theory and Evidence – Klumpp, T., Su, X.
2013-01: Gender Wage-Productivity Differentials and Global Integration in China – Dammert, Ural-Marchand, B., Wan
2012-25: College Expansion and Curriculum Choice – Su, X., Kaganovich, Schiopu