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ORIGINAL ARTICLE

Motivating energy suppliers to promote energy conservation

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Abstract We examine the design of regulatory policy to induce electric utilities to deliver the surplus-maximizing level of energy efficiency services, e^*. The rebound effect (whereby increased energy efficiency stimulates the demand for energy) typically renders revenue decoupling insufficient in this regard. The additional financial incentive required to induce e^* is shown to vary with such factors as the prevailing price of energy, the magnitude of the rebound effect, the extent of observable energy efficiency investments, and the utility's objective.

Keywords Energy efficiency · Energy conservation · Incentive regulation

JEL Classification D82 · L50 · Q40

1 Introduction

Industry experts have observed that it can be more cost effective to reduce the demand for electricity than to increase its supply (Fox-Penner 2010, pp. 52–53). In response, legislators and regulators around the world have implemented policies to induce electric utilities to reduce electricity consumption by their customers. These policies include educating consumers about ways to conserve energy and encouraging expanded use of energy-efficient appliances, insulation, and weather-stripping

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(Tanaka 2011). In the US, states routinely set specific targets for reductions in electricity consumption, and twenty states have implemented explicit financial rewards to encourage electric utilities to meet these targets (Institute for Electric Efficiency 2010; Palmer et al. 2012). The explicit financial rewards often accompany or replace revenue decoupling, which insulates the utility against reductions in its revenue as its electricity sales decline (Carter 2001; Brennan 2010a).

Although regulators have been designing and implementing reward structures to encourage utilities to reduce electricity consumption by their customers for several years now,[1] they have been doing so with little formal guidance. Some authors (e.g., Moskovitz 1989; Stoft and Gilbert 1994; Eto et al. 1998) have provided useful policy discussions. However, few scholars have developed rigorous economic models that can be employed to inform the optimal design of policies to reduce electricity consumption.[2] The purpose of this research is to present one such model and to discuss its policy implications.

We analyze a setting in which the utility can deliver energy efficiency effort (e) that increases the efficacy of electricity consumption (q) in enhancing what we will call consumer "comfort," $x = X(q, e)$. For instance, e might represent energy conservation information that helps consumers to employ electricity more effectively to secure desired levels of temperature and humidity (i.e., " comfort") in their homes. The regulator in our model can observe realized electricity consumption, but she cannot measure accurately consumer comfort or the utility's supply of e.[3] Therefore, the regulator must motivate the utility to deliver e by providing explicit financial rewards for observed reductions in electricity consumption. We examine the properties of the reward structure that induces the utility to deliver the surplus-maximizing level of energy efficiency effort, e^*. Formally, e^* is the level of e that maximizes the difference between the well-being of consumers and the sum of three costs: the utility's cost of supplying electricity, its cost of delivering energy efficiency effort, and any social (e.g., environmental) cost associated with electricity consumption.

We identify conditions under which revenue decoupling provides the utility with precisely the incentive required to induce the delivery of e^*. We note, though, that these conditions are unlikely to arise in practice. Typically, revenue decoupling will provide insufficient incentive to induce the utility to deliver e^*. Revenue decoupling would provide the requisite incentive in the absence of a "rebound effect" (e.g., Wirl 1995), i.e., if consumers always secured the same level of comfort, x, even as e changes. However, consumers typically demand greater comfort as e increases, and the increased demand for comfort limits the amount by which consumers reduce their electricity consumption as e increases. In light of this induced insensitivity of

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[1] Brennan (2010b) discusses some of the reasons why policymakers do not simply rely on consumers to choose their preferred consumption of electricity and electricity conservation services.

[2] Perhaps in part because of the limited rigorous guidance at their disposal, "regulatory commissions seem to have arbitrarily selected" the financial rewards provided to utilities to encourage them to promote reduced electricity consumption (Blank and Gegax 2011, p. 34).

[3] In practice, a regulator may be able to observe whether a utility is providing energy conservation information to its customers. However, the regulator may be unable to readily assess the quality or the efficacy of the information.

observed electricity consumption (q) to e, financial rewards that are more generous than decoupling are required to induce the utility to supply e^*.

The magnitude of the requisite increase in financial reward is shown to vary with several factors, including the utility's cost of delivering energy efficiency effort (e), the rate at which e increases consumer comfort (x), and the rate at which e increases the impact of electricity consumption (q) on x. The magnitude of the requisite increase in financial reward is also shown to vary with the established price of electricity, the extent of prevailing observable energy efficiency investment (e.g., energy-saving light bulbs that the utility delivers to its customers), and the utility's objective. In particular, a public enterprise typically will deliver e^* in return for less generous compensation than its profit-maximizing counterpart.

Our analysis is most closely related to the work of Eom and Sweeney (2009), which examines the design of linear reward structures to motivate an electric utility to supply unobservable effort that reduces electricity consumption. Eom and Sweeney assume the utility receives a constant fraction of the net benefits that arise from its effort, e. These net benefits are the difference between the value of the cost savings generated by the energy conservation program and program costs. The cost savings are assumed to increase linearly with e, and the utility's unmeasured costs are assumed to be a quadratic function of e.[4] We extend Eom and Sweeney's important analysis by considering more general benefit and cost functions and nonlinear reward structures. We also explicitly model the manner in which electricity enhances consumer well-being. Our approach allows us to explain why revenue decoupling typically is insufficient to induce the surplus-maximizing level of energy efficiency effort, even when the regulator can vary a fixed retail charge for electricity to ensure the utility's financial integrity. Our approach also allows us to determine how the requisite reward varies with relevant industry parameters.

Some studies abstract from the need to motivate the utility to deliver effort that enhances program performance, focusing instead on the complications posed by asymmetric knowledge of industry conditions. For instance, Lewis and Sappington (1992) identify conditions under which a regulator's limited knowledge of consumers' preferences is not constraining, provided the regulator can observe the level of energy conservation service the utility provides. Chu and Sappington (2012) illustrate the merits of affording the utility a choice among reward structures when the utility is privately informed about its cost of supplying energy conservation services.

We abstract from asymmetric knowledge of program costs, consumer preferences, and potential program performance, focusing instead on how to motivate a utility to deliver effort that enhances the performance of programs designed to reduce electricity consumption. This motivation problem is important because, in the absence of explicit financial rewards for reduced electricity consumption, utility effort that reduces consumption often will reduce utility profit. Consequently, the utility may be reluctant to work diligently to ensure program success.

Our analysis of this motivation problem proceeds as follows. Section 2 describes the key elements of the model. Section 3 describes the outcomes in two benchmark

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[4] Eom (2009) extends this analysis to consider piece-wise linear reward structures and to allow the utility to have superior knowledge of the impact of its conservation activities.

settings, one where the surplus-maximizing level of energy efficiency effort (e^*) can simply be dictated rather than motivated, and one where consumers always secure the same level of comfort even as e changes. Section 4 characterizes the reward structure that motivates the utility to deliver e^* and explains how industry parameters affect this reward structure. Section 5 considers extensions of the basic analysis, demonstrating how the reward structure that induces e^* is affected by the utility's objective, by energy conservation investments that the utility might provide, and by the operation of an independent energy services company. Section 6 concludes and suggests directions for future research.[5]

2 Elements of the model

The representative consumer in our model seeks to maximize her well-being. Electricity consumption enhances well-being by helping to produce "comfort," which might entail coolness in the summer and warmth in the winter, for example. Comfort might also encompass the enjoyment derived from watching movies on television or accessing online content via one's home computer. We will let q denote the amount of electricity the consumer purchases and $x = X(q, e)$ the corresponding amount of comfort she secures. The variable e denotes the effort the electric utility devotes to enhancing energy efficiency. This effort might represent information or other assistance the utility provides to customers to enhance the level of comfort they derive from electricity, for example.[6]

Energy efficiency effort (e) is assumed to increase a consumer's comfort for any given level of electricity consumption and to increase the marginal impact of electricity consumption on comfort, i.e., $X_e(q, e) > 0$ and $X_{qe}(q, e) \geq 0$ for all $q \geq 0$ and $e \geq 0$.[7] To illustrate, energy conservation information or assistance in helping consumers insulate or weather-strip their homes can enable consumers to secure more warmth or coolness from a given amount of electricity and can increase the additional warmth or coolness derived from an increase in electricity consumption. Of course, electricity consumption also increases comfort, and we presume it does so at a non-increasing rate, i.e., $X_q(q, e) > 0$ and $X_{qq}(q, e) \leq 0$ for all $q \geq 0$ and $e \geq 0$.

The utility incurs cost $K(e)$ in delivering effort e. This cost is an increasing, convex function of e, so $K'(e) > 0$ and $K''(e) \geq 0$ for all $e \geq 0$.[8] The utility's cost of supplying q units of electricity is $C(q)$, where $C'(q) > 0$ for all $q \geq 0$. The unit price of electricity is $p > 0$. Consumers also pay a fixed charge, F, for the right to purchase electricity at unit price p. This fixed charge can be viewed as including a charge to cover the relevant costs of the energy efficiency program. Given e, the representative

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[5] The proofs of formal conclusions that do not appear in the text are outlined in the Appendix. More detailed proofs are presented in Chu and Sappington (2013).

[6] For simplicity, we abstract from explicit modeling of the complementary assets (e.g., air conditioners, televisions, and computers) that consumers combine with energy to produce comfort. We also abstract from costly investments in energy efficiency that consumers might undertake. (See Brennan (2010b) for an analysis of such investments.) Section 5 considers investments by the utility.

[7] Here and throughout the ensuing analysis, subscripts on functions denote partial derivatives.

[8] We assume $K(0) = 0$ and $K'(0) = 0$ to ensure the benefit of e exceeds its cost for small levels of e.

consumer chooses q to maximize the difference between the well-being she derives from comfort, $U(x)$, and the cost of the electricity she employs to produce the comfort. Formally, the consumer chooses q to maximize $U(X(q, e)) - pq - F$, where $U(x)$ is an increasing, concave function, i.e., $U'(x) > 0$ and $U''(x) \leq 0$ for all x.[9]

In practice, the amount of electricity that consumers purchase (q) is readily measured. In contrast, the effort (e) the utility devotes to promoting energy conservation is not readily observed. Although it may be possible to determine whether a utility has established programs to promote energy conservation, it typically is difficult to measure the quality of the programs and the diligence with which the utility is acting to enhance program performance. When the utility's effort is not readily measured, the utility cannot simply be compensated according to the amount of effort it supplies. Instead, any compensation the utility is awarded must reflect an imperfect indicator of the utility's effort supply. In practice, this imperfect indicator often is the extent to which observed electricity consumption declines (Palmer et al. 2012).

We will analyze the design of programs to motivate a profit-maximizing utility to deliver energy efficiency effort by compensating the firm for observed reductions in electricity consumption (q) below some benchmark level (q_0).[10] In practice, q_0 often is the level of electricity consumption that prevails just before the implementation of the energy efficiency program. Thus, in addition to the revenue it derives from the sale of electricity ($F + pq$), the firm receives compensation $R(\Delta)$, where $\Delta \equiv q_0 - q$ is the realized reduction in electricity consumption.[11]

We focus on the properties of the pricing (p) and reward ($R(\cdot)$) structures that induce the utility to deliver the ideal levels of electricity and energy efficiency effort. These ideal levels are characterized next.

3 Benchmark settings

To identify the ideal levels of electricity consumption and energy efficiency effort, first consider the benchmark setting in which the level of effort (e) the utility supplies is readily measured. Also suppose a social planner can set a payment, P, that consumers must make to the utility in return for a specified amount of electricity (q^*) and energy efficiency effort (e^*).[12] Further suppose the social planner seeks to maximize the difference between the net well-being of the representative consumer ($U(\cdot) - P$) and the social disutility from electricity production and consumption ($D(q)$), subject to ensuring nonnegative profit for the utility. The social disutility from electricity production and consumption might reflect, for example, the associated harm to the

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[9] To ensure that consumers purchase a strictly positive and finite amount of electricity, we assume that $U'(0) = \infty$ and $U'(\infty) = 0$.

[10] Section 5 considers alternative objectives for the utility and the possibility that energy efficiency services might be provided by an independent energy services company.

[11] In principle, the utility's compensation might reflect both realized electricity consumption and the level of comfort (x) the consumer attains. At present, though, the consumer's achieved level of comfort typically is difficult to measure. Fox-Penner (2010) observes that smart meters may eventually facilitate accurate measures of comfort.

[12] The payment P incorporates all fixed and variable charges that consumers make to the utility.

environment. We assume this disutility is a nonnegative, nondecreasing function of electricity consumption, so $D(q) \geq 0$ and $D'(q) \geq 0$ for all $q \geq 0$.

The planner's formal problem in this setting, denoted [PP], is to choose q and e to maximize $U(X(q,e)) - D(q) - P$ while ensuring $P - C(q) - K(e) \geq 0$. Straightforward calculations provide the following conclusion.

Lemma 1 *The (interior) levels of electricity consumption (q^*) and energy efficiency effort (e^*) that constitute the solution to the planner's problem [PP] are given by: (i) $U'(\cdot)X_q(\cdot) = C'(q^*) + D'(q^*)$; and (ii) $U'(\cdot)X_e(\cdot) = K'(e^*)$.*

Condition (i) in Lemma 1 indicates that electricity consumption ideally is expanded to the point where the increment in well-being it provides (by increasing comfort) is equal to the corresponding full marginal cost. This full marginal cost is the sum of the utility's marginal cost of supplying electricity ($C'(\cdot)$) and the social marginal cost associated with electricity consumption ($D'(\cdot)$). Condition (ii) in Lemma 1 indicates that energy efficiency effort ideally is expanded to the point where the increment in well-being it provides (by increasing comfort) is equal to the associated marginal effort cost the utility incurs ($K'(\cdot)$).

To help understand the pricing and reward structures that will induce the utility to ensure the ideal levels of electricity consumption and energy efficiency effort, (q^*, e^*), now consider the hypothetical (and generally unrealistic) setting in which there is no rebound effect, so the representative consumer always secures a fixed level of comfort, $\overline{x}$.

Lemma 2 *In the benchmark setting where the consumer always secures a fixed level of comfort, (q^*, e^*) will arise if social marginal cost pricing ($p = C'(q^*) + D'(q^*)$) is implemented and $R'(\Delta) = D'(q^*) + p$.*

Lemma 2 reflects in part the well-known fact that consumers will purchase the ideal level of electricity (q^*) when the unit price they pay for electricity reflects its full marginal cost ($C'(q^*) + D'(q^*)$). Lemma 2 also identifies a potential merit of revenue decoupling in the absence of any social disutility from electricity consumption (i.e., when $D'(q) = 0$ for all $q \geq 0$). Revenue decoupling arises when the utility's revenue ($F + pq$) does not vary with the amount of electricity it sells.[13] Revenue decoupling is implemented when the utility's reward for realized reductions in electricity consumption (q) increases at precisely the rate its revenue from sales declines as q declines, i.e., when $R'(\Delta) = p$. Lemma 2 reflects the fact that when revenue decoupling is implemented and consumers always secure the same level of comfort, $\overline{x}$, the utility will select e to minimize the cost of delivering $U(\overline{x})$ to consumers. The social planner selects e in precisely the same manner in the absence of any social disutility from electricity consumption.[14] In the presence of such disutility, the incremental reward for reduced electricity consumption is increased (so $R'(\Delta) = D'(q^*) + p > p$) in order to induce the utility to internalize the social value of reduced electricity consumption.

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[13] Palmer et al. (2012, p. 23) report that ten states allow their electric utilities to apply for revenue decoupling. Brennan (2010a) provides an analysis of profit decoupling, under which the utility's profit does not vary with the realized level of electricity sales.

[14] This conclusion is demonstrated formally in the proof of Lemma 2.

4 Main findings

In practice, of course, consumers will vary the level of comfort they secure as the price of electricity changes and as the level of energy efficiency effort the utility supplies varies. We now examine how the reward structure that induces (q^*, e^*) departs from revenue decoupling in this more realistic setting.

To begin, recall that the representative consumer chooses her preferred level of electricity consumption (q) given e and p to maximize her net well-being. Formally, the consumer chooses q to maximize $U(X(q,e)) - pq - F$. The consumer will expand her consumption of electricity to the point where the marginal increase in well-being it provides by increasing comfort is equal to the unit price of electricity, i.e.:

$$U'(\cdot)X_q(\cdot) = p. \tag{1}$$

Differentiating equation (1) provides the rate at which electricity consumption changes as e increases, holding p constant, i.e.,

$$\frac{dq}{de} = -\frac{U'(\cdot)X_{qe}(\cdot) + U''(\cdot)X_q(\cdot)X_e(\cdot)}{U'(\cdot)X_{qq}(\cdot) + U''(\cdot)\left[X_q(\cdot)\right]^2}. \tag{2}$$

Now consider the utility's choice of e. Given the prevailing price and reward structure, the utility will choose e to maximize $F + pq - C(q) + R(q_0 - q) - K(e)$. Differentiating this expression reveals that the utility's profit-maximizing choice of e is given by:

$$R'(\Delta)\left[-\frac{dq}{de}\right] = K'(e) + \left[p - C'(\cdot)\right]\left[-\frac{dq}{de}\right] \Leftrightarrow R'(\Delta) = p - C'(\cdot) - K'(e)\frac{de}{dq}. \tag{3}$$

The first equality in expression (3) indicates that the utility will expand e to the point where its marginal benefit to the utility is equal to its full private marginal cost. This marginal benefit of e is the marginal increase in the utility's direct payment due to the reduction in electricity consumption caused by the increase in e $(R'(\Delta)\frac{dq}{de})$. The full private marginal cost of e is the sum of: (i) the utility's marginal cost of providing e $(K'(e))$; and (ii) the reduction in profit from reduced electricity sales the utility experiences as e increases $\left(\left[p - C'(\cdot)\right]\left[-\frac{dq}{de}\right]\right)$.

The second equality in expression (3) helps to prove the following key finding.

Proposition 1 *(q^*, e^*) will arise if the regulator sets $p = C'(q^*) + D'(q^*)$ and:*

$$R'(\Delta) = D'(q) + p\left[\frac{\left.\frac{dq}{de}\right|_{dx=0}}{\frac{dq}{de}}\right] = D'(q) + p\left[\frac{\frac{X_{qq}(\cdot)}{X_q(\cdot)} - \left|\frac{U''(\cdot)}{U'(\cdot)}\right| X_q(\cdot)}{\frac{X_{qe}(\cdot)}{X_e(\cdot)} - \left|\frac{U''(\cdot)}{U'(\cdot)}\right| X_q(\cdot)}\right]. \tag{4}$$

Proof Lemma 1 and expression (3) imply that realized electricity consumption will be q^* if the regulator sets $p = C'(q^*) + D'(q^*)$. Lemma 1 and expression (3) then imply that the firm will deliver e^* if the regulator sets $R'(\Delta) = D'(q) + U'(\cdot)X_q(\cdot)\frac{X_e(\cdot)}{X_q(\cdot)}\Big/\left[-\frac{dq}{de}\right]$. Since $\left.\frac{dq}{de}\right|_{dx=0} = -\frac{X_e(\cdot)}{X_q(\cdot)}$, Eqs. (1) and (2) imply that Eq. (4) holds. □

Corollary 1 *Suppose* $\frac{dq}{de} < 0$ *for all* $x \geq 0$, $q \geq 0$, *and* $e \geq 0$. *Then the reward function that induces* (q^*, e^*) *never provides the firm with less direct compensation than revenue decoupling provides, i.e.,* $R'(\Delta) \geq p = C'(q^*) + D'(q^*)$.

The following lemmas help to explain Proposition 1 and Corollary 1.

Lemma 3 $\frac{dx}{de} \geq 0$ *(so the consumer's consumption of comfort (weakly) increases as the utility's energy efficiency effort increases), with strict inequality if* $X_{qq}(\cdot) < 0$ *or* $X_{qe}(\cdot) > 0$.

Proof Equation (2) implies $\frac{dx}{de} = \frac{X_e(\cdot)U'(\cdot)X_{qq}(\cdot) - X_q(\cdot)U'(\cdot)X_{qe}(\cdot)}{U'(\cdot)X_{qq}(\cdot) + U''(\cdot)[X_q(\cdot)]^2} \geq 0$. This inequality holds strictly if $X_{qq}(\cdot) < 0$ or $X_{qe}(\cdot) > 0$. □

Lemma 4 *Suppose* $\frac{dq}{de} < 0$. *Then* $\left|\frac{dq}{de}\right| \leq \left|\frac{dq}{de}\right|_{dx=0}$, *with strict inequality if* $X_{qq}(\cdot) < 0$ *or* $X_{qe}(\cdot) > 0$.

Proof From Eq. (2), when $\frac{dq}{de} < 0$:

$$\left|\frac{dq}{de}\right| = \frac{\left|\frac{U''(\cdot)}{U'(\cdot)}\right| X_q(\cdot)X_e(\cdot) - X_{qe}(\cdot)}{U'(\cdot)\left|X_{qq}(\cdot)\right| + \left|\frac{U''(\cdot)}{U'(\cdot)}\right| \left[X_q(\cdot)\right]^2} \leq \frac{\left|\frac{U''(\cdot)}{U'(\cdot)}\right| X_q(\cdot)X_e(\cdot)}{\left|\frac{U''(\cdot)}{U'(\cdot)}\right| \left[X_q(\cdot)\right]^2} = \left|\frac{dq}{de}\right|_{dx=0}.$$

This inequality holds strictly if $X_{qe}(\cdot) > 0$ or if $X_{qq}(\cdot) < 0$. □

Because of the rebound effect identified in Lemma 3, i.e., because she typically secures greater comfort as e increases, the consumer reduces her electricity consumption (q) less rapidly as e increases than she would in the absence of a rebound effect (Lemma 4). The diminished response of q to e implies that the utility must receive more generous compensation than revenue decoupling provides to induce the utility to deliver e^* since revenue decoupling only provides the requisite incentive in the absence of a rebound effect (Lemma 2).

It is important to emphasize that the conclusion in Corollary 1 does not reflect a need to ensure nonnegative profit for the utility. The regulator could increase the fixed charge, F, if reduced electricity sales caused by an increase in e threatened the financial viability of the utility. The need to provide compensation that is more generous than the compensation delivered under revenue decoupling simply reflects the fact that electricity consumption declines less rapidly as e increases than it would decline in the absence of a rebound effect.

Corollary 2 identifies one special setting in which revenue decoupling will induce (q^*, e^*).

Corollary 2 *Revenue decoupling and marginal cost pricing* ($R'(\Delta) = p = C'(q)$ *) will induce* (q^*, e^*) *if* $D'(q) = 0$ *and* $X_{qq}(\cdot) = X_{qe}(\cdot) = 0$ *for all* $q \geq 0$ *and* $e \geq 0$.

Proof The proof follows immediately from Eq. (4). □

There is no rebound effect, i.e., the consumer does not alter the level of comfort she secures as e changes, when $X_{qq}(\cdot) = X_{qe}(\cdot) = 0$ (so the marginal product of electricity in enhancing comfort does not vary as q changes or as e changes). This is the case because the two effects of an increase in e offset each other exactly in this special setting. Holding electricity consumption (q) constant, an increase in e increases the comfort (x) the consumer secures at the rate $X_e(\cdot)$. However, the increase in e also reduces q at the rate $\frac{dq}{de} = -\frac{X_e(\cdot)}{X_q(\cdot)}$,[15] and the corresponding impact on x is $X_q(\cdot)\frac{dq}{de} = -X_e(\cdot)$. When x does not change as e increases (so there is no rebound effect), revenue decoupling induces the utility to deliver e^*. (Recall Lemma 2.)

Although revenue decoupling will induce the utility to deliver e^* under the special conditions identified in Corollary 2, revenue decoupling often will provide the utility with inadequate incentive to deliver e^*. As Proposition 1 reveals, the precise nature of the additional incentive required to induce e^* depends upon both the manner in which electricity consumption and energy efficiency effort combine to generate comfort and the manner in which comfort affects the consumer's well-being. To gain further insight into the factors that influence the nature of the reward structure that induces the utility to deliver e^*, consider the setting of Example 1. This setting has six key features. First, electricity consumption generates no social disutility, so $D(q) = 0$ for all $q \geq 0$. Second, electricity is produced at constant marginal cost, so $C'(q) = c > 0$ for all $q \geq 0$. Third, the representative consumer exhibits constant absolute risk aversion, so $U(x) = -\exp(-rx)$, which implies that $\left|\frac{U''(\cdot)}{U'(\cdot)}\right| = r > 0$, a constant, for all $x \geq 0$. Fourth, the utility's cost of delivering energy efficiency effort e increases linearly with e, so $K'(e) = k > 0$ for all $e \geq 0$. Fifth, the utility's energy efficiency effort reduces electricity consumption, so $\frac{dq}{de} < 0$ for all $e \geq 0$ and $q \geq 0$. Sixth, $X(q, e) = \alpha_1 q + \alpha_2 e + \alpha_0 eq$, where α_0, α_1, and α_2 are strictly positive constants.

Proposition 2 *In the setting of Example 1, the slope of the reward function* ($R'(\Delta)$) *that induces the utility to secure* (q^*, e^*)*: (i) declines as* α_1, α_2, *or* r *increases; and (ii) increases as* k *or* α_0 *increases.*

To understand the conclusion in Proposition 2, observe that when r increases, the consumer's marginal valuation of comfort ($U'(x)$) declines more rapidly as comfort (x) increases. The reduced marginal valuation of comfort reduces the marginal value the consumer derives from electricity consumption (q). Consequently, q declines relatively rapidly as e increases, and so less pronounced marginal compensation is required to induce the utility to deliver e^*, *ceteris paribus*.

When α_1 increases, comfort (x) increases more rapidly with electricity consumption (q). Consequently, the social planner prefers more electricity consumption (i.e., q^* increases). The desired increase in q is achieved by providing the utility with less marginal compensation for reducing q. When α_2 increases, comfort (x) increases

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[15] This conclusion is apparent from expression (2).

more rapidly, and so $U'(x)$ declines more rapidly, as e increases. The associated reduction in the consumer's marginal valuation of q causes q to decline relatively rapidly with e. Consequently, the marginal compensation required to induce the utility to deliver e^* declines.

When k increases, e becomes more costly for the utility to deliver. Consequently, more generous compensation for observed reductions in q is required to induce the firm to deliver any desired level of e. When α_0 increases, the marginal product of q in enhancing comfort increases. Consequently, the consumer will reduce q relatively slowly as e increases, necessitating a relatively large marginal reward for realized reductions in q to induce the utility to deliver any desired level of e.[16]

To consider the practical implications of Proposition 2, consider a setting in which effective home energy audits are relatively costly to deliver (due to training, equipment, and personnel costs), whereas a bill insert that provides some energy savings tips is relatively inexpensive to design and disseminate. Proposition 2 indicates that if the two programs were equally effective in generating consumer comfort from electricity consumption, more substantial compensation for the home energy audit program would be required to induce the utility to deliver the surplus-maximizing level of energy efficiency effort (e^*) in both programs.

Somewhat less obviously, Proposition 2 indicates that more generous rewards often will be required to induce e^* when consumers increase the level of comfort they consume relatively rapidly as e increases (perhaps because $r = -\frac{U''(x)}{U'(x)}$ is relatively small). For instance, residential customers may be more likely than industrial customers to demand greater comfort (e.g., cooler indoor temperatures in the summer or increased services from appliances) in response to an enhanced ability to employ electricity to increase comfort (due to the installation of more effective insulation or more energy-efficient appliances, for example). The increased demand for comfort will limit the associated reduction in electricity consumption. Consequently, abstracting from differences in the costs of serving residential and industrial customers, relatively generous compensation for realized reductions in electricity consumption by residential customers would be required to induce the utility to deliver e^*.

Proposition 2 also indicates that, even among programs designed exclusively for residential customers, different marginal rewards may be appropriate for programs that are offered to customers with different characteristics. For instance, utilities often conduct special programs for low-income customers. If these customers are systematically less (or more) likely than their higher-income counterparts to increase the amount of comfort they secure as e increases, then less (or more) pronounced financial rewards to the utility for fostering reductions in electricity consumption by low-income residential customers will be required to induce the utility to deliver e^*.[17]

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[16] $X_{qq}(\cdot) = 0$ in the setting of Example 1. More generally, as $\left|X_{qq}(\cdot)\right|$ increases, $X_q(\cdot)$ increases more rapidly as q declines. This relatively rapid increase in the marginal product of electricity consumption in enhancing comfort limits the magnitude of the rebound effect. Consequently, the slope of the reward function that induces the utility to secure $\left(q^*, e^*\right)$ increases as $\left|X_{qq}(\cdot)\right|$ increases, *ceteris paribus*.

[17] In practice, income distribution considerations can lead policymakers to implement policies that particularly promote the delivery of energy efficiency services to low-income customers.

Customers also differ according to the age of their homes. Homes of different vintages often are constructed using different materials and conform to different building codes. To the extent that newer materials and more modern codes reduce the potential impact of a utility's effort to reduce electricity consumption (by conducting home energy audits, for example), the marginal rewards for realized reductions in electricity consumption will need to be increased to induce a given level of energy efficiency effort.

Before proceeding to consider extensions of this basic model, we note that the reward structure that induces e^* does not necessarily reward the utility for realized reductions in electricity consumption. If $X_{qe}(\cdot) > \left|\frac{U''(\cdot)}{U'(\cdot)}\right| X_q(\cdot)X_e(\cdot)$, an increase in e increases the marginal product of q in enhancing comfort sufficiently rapidly that the consumer increases her electricity consumption as e increases.[18] In this case, the utility must be rewarded when q increases, rather than decreases, in order to induce e^*.[19]

5 Additional findings

5.1 Exogenous price, p_0

In practice, regulators do not always have unlimited flexibility to set the unit price of electricity equal to the social marginal cost of producing electricity. When faced with limited pricing flexibility, regulators typically will be unable to secure the level of electricity consumption preferred by a social planner (q^*). However, a regulator still can design a reward structure to induce the utility to deliver the energy efficiency effort most preferred by the social planner, given an exogenous unit price for electricity, p_0. Formally, this effort, $e^*(p_0)$, is the value of e that maximizes $U(X(q, e)) - D(q) - p_0 q - F$, subject to ensuring nonnegative profit for the utility, where the consumer's choice of q is determined by $U'(\cdot)X_q(\cdot) = p_0$. Proposition 3 describes the reward structure that will induce the utility to deliver $e^*(p_0)$.

Proposition 3 *The reward structure that will induce the profit-maximizing electricity supplier to deliver $e^*(p_0)$ when the (exogenous) unit price of electricity is p_0 is of the form* $R'(\Delta) = D'(q) + p_0 \left[\frac{\left.\frac{dq}{de}\right|_{dx=0}}{\frac{dq}{de}}\right]$.

Proposition 3 implies that the reward structure that induces $e^*(p_0)$, given p_0, has the same functional form as the reward structure that induces (e^*, q^*) when the regulator can choose both e and p. Despite having the same functional form, the two reward structures differ when $p_0 \neq C'(q) + D'(q)$. In particular, if $p_0 > C'(q) + D'(q)$, then the reward structure that induces $e^*(p_0)$ provides higher marginal rewards than the structure that induces (e^*, q^*), *ceteris paribus*.[20] The higher marginal rewards

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[18] Notice from Eq. (2) that $\frac{dq}{de} > 0$ when $X_{qe}(\cdot) > \left|\frac{U''(\cdot)}{U'(\cdot)}\right| X_q(\cdot)X_e(\cdot)$. Thus, an increase in electricity consumption induced by an increase in energy efficiency effort reflects a relatively large rebound effect.

[19] This conclusion follows directly from Eq. (4).

[20] *Ceteris paribus* here means that the value of the expression in square brackets in the expression for $R'(\Delta)$ in Proposition 3 does not change.

arise because the rewards are designed in part to compensate the utility for the profit it foregoes when its supply of e reduces electricity sales. As is well known (e.g., Tschirhart 1995; Brennan 2010a), the larger is p_0, the greater the loss in profit the utility suffers as electricity consumption declines, and thus the larger is the marginal reward that must be promised to the utility to induce it to deliver $e^*(p_0)$.

5.2 Observable and unobservable investments

Now suppose the utility can undertake an observable energy efficiency investment (I) at cost $K_o(I)$ in addition to supplying unobservable energy efficiency effort (e) at cost $K(e)$. The observable investment might reflect, for example, energy-saving appliances (e.g., compact fluorescent light bulbs) that the utility provides to consumers. We will denote by $x = X(q, e, I)$ the level of comfort the representative consumer enjoys when she consumes q units of electricity and the utility delivers I units of the observable investment and e units of energy efficiency effort. The observable investment, like unobservable energy efficiency effort, increases both comfort and the marginal product of electricity in enhancing comfort, so $X_I(\cdot) > 0$ and $X_{qI}(\cdot) \geq 0$.[21]

Let (q^*, e^*, I^*) denote the values of q, e, and I that maximize $U(X(q, e, I)) - D(q) - P$, subject to ensuring nonnegative profit ($P - C(q) - K(e) - K_o(I) \geq 0$) for the utility.[22] Proposition 4 identifies the nature of the reward structure that will secure (q^*, e^*, I^*) in this setting.

Proposition 4 (q^*, e^*, I^*) *will arise in this setting with observable investment if the regulator directs the firm to set* $I = I^*$, *while setting* $p = C'(q^*) + D'(q^*)$ *and* $R'(\Delta) = D'(q) + pH$, *where* $H \equiv \dfrac{\frac{X_{qq}(\cdot)}{X_q(\cdot)} - \left|\frac{U''(\cdot)}{U'(\cdot)}\right| X_q(\cdot)}{\frac{X_{qe}(\cdot)}{X_e(\cdot)} - \left|\frac{U''(\cdot)}{U'(\cdot)}\right| X_q(\cdot)}$.

Proposition 4 implies that the reward structure that induces (q^*, e^*, I^*) has the same functional form as the structure that induces (q^*, e^*) in the absence of any observable investment. However, this does not imply that the two structures are identical. Notice, for instance, that $R'(\Delta)$ declines as I increases if $\frac{dH}{dI} < 0$.

A change in I can alter H both directly (i.e., holding e and q constant) and indirectly by changing e and q. The following proposition considers the direct effect of a change in I on H, and thus on $R'(\Delta)$.

Proposition 5 *Suppose:* (i) $X_{eI}(\cdot) \geq 0$; (ii) $X_{qeI}(\cdot) \leq 0$; *(iii)* $X_{qqI}(\cdot) \geq 0$; *(iv)* $r \equiv \frac{|U''(x)|}{U'(x)}$ *does not vary with x; and (v)* $\frac{dq}{de} < 0$. *Then* $\frac{dH}{dI}\big|_{de=dq=0} < 0$, *so the direct effect of an increase in I on the reward structure that induces* (q^*, e^*, I^*) *is to reduce the rate at which the reward increases as q declines, holding p constant.*

When $X_{eI}(\cdot) \geq 0$ and $X_{qeI}(\cdot) \leq 0$, an increase in the observable investment I limits the rebound effect, i.e., reduces the rate at which an increase in e increases the marginal impact of q in enhancing comfort (x) without reducing the marginal impact

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[21] We continue to assume that $X_q(\cdot) > 0$, $X_e(\cdot) > 0$, $X_{qq}(\cdot) \leq 0$, and $X_{qe}(\cdot) \geq 0$.

[22] Recall that P denotes the total payment from consumers to the utility.

of e on x. The increase in I thereby increases the rate at which an increase in e reduces q. Consequently, less direct marginal compensation for observed reductions in q is needed to induce the firm to deliver any specified level of e, *ceteris paribus*. Similarly, when $X_{eI}(\cdot) \geq 0$ and $X_{qqI}(\cdot) \geq 0 \Leftrightarrow \frac{\partial}{\partial I}\left|X_{qq}(\cdot)\right| \leq 0$, an increase in the observable investment I reduces $\left|X_{qq}(\cdot)\right|$ without reducing the marginal impact of e on x. The reduction in $\left|X_{qq}(\cdot)\right|$ diminishes the rate at which $X_q(\cdot)$ increases as q declines due to expanded e. Consequently, as I increases, q tends to decline more rapidly as e increases, and so less marginal compensation is required to induce the firm to deliver e^*.

In summary, when $X_{eI}(\cdot) \geq 0$, $X_{qeI}(\cdot) \leq 0$, and $X_{qqI}(\cdot) \geq 0$, an increase in I increases the sensitivity of q to e without diminishing the impact of e on x, and so a utility that is rewarded as q declines anticipates a larger return from increasing e. Consequently, the marginal reward required to induce the utility to deliver e^* declines, *ceteris paribus.*

The requisite marginal reward can decline as I increases under plausible conditions even when all relevant direct and indirect effects are fully accounted for. To illustrate this conclusion, consider the setting of Example 2, which shares the first four features of the setting of Example 1 (i.e., $D(q) = 0$ for all $q \geq 0$; $C'(q) = c > 0$ for all $q \geq 0$; $U(x) = -\exp(-rx)$, so $\left|\frac{U''(\cdot)}{U'(\cdot)}\right| = r > 0$, a constant, for all $x \geq 0$; and $K'(e) = k > 0$ for all $e \geq 0$). In addition, $X(q, e, I) = \alpha_1 q + \alpha_2 eI + \alpha_0 eq$, where α_0, α_1, and α_2 are strictly positive constants. Notice that the observable investment in this setting increases both comfort and the marginal impact of e in enhancing comfort without altering the effect of e on the marginal impact of electricity consumption on comfort (i.e., $X_I(\cdot) = \alpha_2 e \geq 0, X_{eI}(\cdot) = \alpha_2 > 0$, and $X_{Iqe}(\cdot) = 0$). When α_0 is sufficiently small in this setting, the primary effect of an increase in I is to increase the marginal impact of e in enhancing comfort (x), even after accounting for induced changes in e and q. When x increases rapidly with e, the associated relatively rapid reduction in the marginal value of comfort (reflecting the concavity of $U(\cdot)$) ensures that q declines relatively rapidly as e increases. Consequently, less pronounced financial reward is required to induce the utility to ensure (q^*, e^*, I^*) as I^* increases, as Proposition 6 reports.

Proposition 6 $\frac{dH}{dI} < 0$ *when* α_0 *is sufficiently small in the setting of Example 2, so an increase in* I *reduces the rate at which payment to the utility increases as* q *declines under the reward structure that induces* (q^*, e^*).

5.3 Operation by a public enterprise

We now return to the setting with no observable energy efficiency investment, but allow for the possibility that the utility may not seek solely to maximize profit. In particular, suppose the utility is a public enterprise that seeks to maximize the sum of profit and the fraction $\gamma \in [0, 1]$ of the representative consumer's well-being. Proposition 7 identifies the nature of the reward structure that will secure (q^*, e^*) in this setting.

Proposition 7 (q^*, e^*) *will arise in this setting with a public enterprise if the regulator sets* $p = C'(q^*) + D'(q^*)$ *and* $R'(\Delta) = D'(q) + p\left[\gamma + (1-\gamma)\left(\frac{\left.\frac{dq}{de}\right|_{dx=0}}{\frac{dq}{de}}\right)\right]$.

Recall from Lemma 4 that $\frac{dq}{de}\Big|_{dx=0} \leq \frac{dq}{de}$ when $\frac{dq}{de} < 0$. Consequently, in this case, Proposition 7 implies that the marginal reward for reducing electricity consumption that induces e^* is (weakly) smaller for a public enterprise than for a profit-maximizing utility. This conclusion reflects the fact that a public enterprise derives value from increasing e simply because the increase in e increases comfort and thereby increases consumer well-being. In light of this intrinsic motivation for increasing e, less direct financial reward is required to induce a public enterprise to deliver e^*.

5.4 Energy efficiency effort provided by an ESCO

Now suppose the regulator procures energy efficiency effort (e) from an independent energy service company (ESCO) rather than from the utility that sells electricity. To account for the possibility that the ESCO might be a public enterprise, suppose the ESCO chooses e to maximize the sum of the profit it earns and the fraction $\gamma \in [0, 1]$ of the representative consumer's well-being, $U(\cdot)$. The ESCO's profit is the difference between $R(\Delta)$, the financial reward it receives from the regulator for reduced electricity consumption, and $K(e)$, its cost of supplying e. Proposition 8 identifies the nature of the reward structure that will secure (q^*, e^*) in this setting.

Proposition 8 (q^*, e^*) *will arise in the setting where an ESCO supplies e and the utility supplies electricity if the regulator sets* $p = C'(q^*) + D'(q^*)$ *and* $R'(\Delta) = p\left[\gamma + (1-\gamma)\left(\frac{\frac{dq}{de}\big|_{dx=0}}{\frac{dq}{de}}\right)\right]$.

Propositions 7 and 8 imply that the marginal compensation for reducing electricity consumption that is required to induce an ESCO to deliver e^* is less than the corresponding compensation for the energy supplier by $D'(q) = p - C'(q)$. This difference represents the profit margin the utility (but not the ESCO) foregoes as an increase in e reduces electricity consumption.

6 Conclusions

We have analyzed a streamlined formal model of a setting in which a utility can deliver energy efficiency effort (e) that reduces electricity consumption by its customers. We have employed the model to characterize the financial rewards required to induce the utility to deliver the surplus-maximizing level of energy efficiency effort, e^*. We identified some restrictive conditions under which revenue decoupling will induce e^*. More generally, financial rewards in excess of those provided by revenue decoupling are required to induce the utility to deliver e^*. The requisite rewards tend to be more pronounced when e is more costly for the utility to deliver, when the rebound effect is pronounced so higher levels of e encourage consumers to demand substantially higher levels of comfort, and when the unit price of electricity exceeds its marginal cost of supply, so the utility's profit from the sale of electricity declines as e diminishes electricity consumption.[23]

Our analysis reveals that there is no simple, standard reward structure that will induce the desired level of energy efficiency effort in all settings. The most appropriate reward structure typically will vary across regulatory jurisdictions. It can also vary within a regulatory jurisdiction when multiple programs to reduce electricity consumption are implemented.[24] The properties of the ideal reward structure(s) vary with a variety of industry conditions, including consumer preferences, the impact of electricity consumption and energy efficiency effort on consumer comfort, and the magnitude of both measured and unmeasured costs of delivering energy efficiency services.

We have analyzed the special setting in which the regulator and the utility are perfectly informed about all relevant industry conditions. In practice, regulators and utilities are less omniscient. Although the energy conservation programs that are being implemented around the world will provide valuable information to regulators and utilities alike, imperfect knowledge undoubtedly will persist. Future research should analyze the design of energy conservation policies when both the regulator and the utility have limited knowledge of relevant industry conditions.[25] Further study of policy design in settings where the utility has better information than the regulator about these conditions would be useful. The optimal policy in such settings typically will afford the utility a choice among reward structures and induce the utility to choose a reward structure that reflects the prevailing conditions.[26]

In closing, we note four additional directions in which our streamlined analysis should be extended. First, energy efficiency investments by consumers should be modeled explicitly, particularly in settings where the utility's effort (e) entails informing consumers about how to increase the comfort they derive from consuming energy most effectively. Any constraints that consumers face in determining and implementing desirable energy efficiency investments should be modeled explicitly.[27]

Second, competition among suppliers of energy efficiency services might be considered. We have focused on a setting in which the utility is the sole supplier of energy

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[23] For expositional simplicity, we have abstracted from the fixed costs of program implementation. Of course, if these fixed costs (and/or the accompanying variable costs) are so large that the costs of a program exceed its benefits, then the program should not be pursued.

[24] In practice, a single energy conservation program typically is implemented for an entire population of consumers even though subgroups within the population reduce their energy consumption at different rates in response to energy efficiency effort delivered by the utility. Under these conditions, a profit-maximizing utility can be expected to direct its effort (e) primarily to the subgroups that will reduce their energy consumption most rapidly as e increases. Such targeting of e will secure the greatest profit for the utility when the costs of delivering e to the different subgroups are sufficiently similar.

[25] The complications that arise when consumers have limited knowledge of the value of energy efficiency services (e.g., Brennan 2010b) also merit further study.

[26] Chu and Sappington (2012) analyze a model with asymmetric knowledge of industry conditions, but do not allow the utility to deliver unobservable effort. Eom (2009) analyzes a model with both asymmetric information and unobservable effort, but does not allow the regulator to offer the utility a choice among reward structures.

[27] These constraints might include financing and information constraints (Wirl 1995). Brennan (2010b) suggests one tractable approach to modeling consumer information constraints.

efficiency services. This may effectively be the case in settings where consumers perceive much higher transaction costs of securing services from a non-utility supplier (Tschirhart 1995). In other settings, though, when energy efficiency investments are contractible (as in the setting of Sect. 5.2) and the utility charges explicitly for these investments, consumers can decide whether to secure investments from the utility or from a competing supplier. The relevant comfort production function ($X(\cdot)$) in this case would need to account for the investments purchased from all suppliers.

Third, in practice, regulators often raise the unit price of electricity to generate the funds that are awarded to the utility to induce it to promote reduced electricity consumption. When the unit price of electricity serves both to influence consumers' consumption of electricity given e and to finance rewards that induce the utility to increase its supply of e, the specification of the appropriate unit price of electricity and the corresponding reward structure can entail additional subtleties.

Fourth, different types of reward structures merit further study. We have considered financial rewards that vary with the magnitude of the observed reduction in electricity consumption. In cases where the expenditures that utilities make to discourage electricity consumption are readily observed, reward structures might explicitly reflect both these costs and realized reductions in electricity consumption. Of course, reward structures that reimburse a utility for some or all of its observed expenditures can be problematic in settings where it is difficult to identify the efficacy and the purpose of all of the utility's expenditures.

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Appendix

This appendix outlines the proofs of formal conclusions that are not proved in the text. Detailed proofs of these conclusions are available in Chu and Sappington (2013).

Proof of Lemma 2 The social problem in this benchmark setting is to choose q and e to maximize $U(X(e,q)) - C(q) - D(q) - K(e)$ subject to ensuring $X(e,q) = \overline{x}$. At an interior solution to this problem, $\left.\frac{X_q(\cdot)}{X_e(\cdot)}\right|_{x=\overline{x}} = \frac{C'(q)+D'(q)}{K'(e)}$. Therefore, from (3), the utility will deliver the socially preferred level of e if:

$$R'(\Delta) = p - C'(\cdot) + K'(e)\left[\frac{C'(q) + D'(q)}{K'(e)}\right] = D'(q) + p.$$

□

Proof of Corollary 1 The proof follows directly from Lemma 4. □

Proof of Proposition 2 (1) and Lemma 1 imply that $p = c$ under the reward function that induces the firm to secure (q^*, e^*) in the setting of Example 1. (4) implies that this reward function is of the form:

$$R'(\Delta) = c\left[\frac{1}{1-z}\right] \quad \text{where } z \equiv \frac{\alpha_0}{r\,[\alpha_1+\alpha_0 e]\,[\alpha_2+\alpha_0 q]}$$
$$\Rightarrow \frac{dR'(\Delta)}{dr} \overset{s}{=} \frac{dz}{dr} \overset{s}{=} -\left[1+\frac{r\alpha_0}{\alpha_2+\alpha_0 q}\left(\frac{dq}{dr}\right)+\frac{r\alpha_0}{\alpha_1+\alpha_0 e}\left(\frac{de}{dr}\right)\right]. \tag{5}$$

Lemma 1 implies:

$$f(q,e,\cdot) \equiv r\,[\alpha_1 q+\alpha_2 e+\alpha_0 eq] - \ln\left(\frac{r}{c}\,[\alpha_1+\alpha_0 e]\right) = 0, \quad \text{and}$$
$$g(q,e,\cdot) \equiv r\,[\alpha_1 q+\alpha_2 e+\alpha_0 eq] - \ln\left(\frac{r}{k}\,[\alpha_2+\alpha_0 q]\right) = 0.$$

It is readily verified that $|M| = 2r\alpha_0 - \frac{(\alpha_0)^2}{[\alpha_1+\alpha_0 e][\alpha_2+\alpha_0 q]} > 0$, where $M \equiv \begin{bmatrix} f_q & f_e \\ g_q & g_e \end{bmatrix}$. Cramer's Rule provides $\frac{dq}{dr} = -\frac{\alpha_0\left[\alpha_1 q+\alpha_2 e+\alpha_0 eq-\frac{1}{r}\right]}{|M|[\alpha_1+\alpha_0 e]}$ and $\frac{de}{dr} = \frac{[\alpha_1+\alpha_0 e]}{[\alpha_2+\alpha_0 q]}\left[\frac{dq}{dr}\right]$. Therefore, from (5), $\frac{dR'(\Delta)}{dr} \overset{s}{=} \frac{dz}{dr} \overset{s}{=} \frac{-[\alpha_0+2r\alpha_1\alpha_2]}{2r[\alpha_1+\alpha_0 e][\alpha_2+\alpha_0 q]-\alpha_0} < 0$.

The proofs of the other conclusions are analogous, and so are omitted. □

Proof of Proposition 3 The social planner's problem is this setting, [PP1], is to choose e to maximize $U(X(q,e)) - D(q) - p_0 q - F$, subject to $F + p_0 q - C(q) - K(e) \geq 0$, where $U'(\cdot)X_q(\cdot) = p_0$. At the solution to [PP1]:

$$U'(\cdot)X_e(\cdot) - K'(e) + \left[p_0 - C'(q) - D'(q)\right]\frac{dq}{de} = 0. \tag{6}$$

(2), (3), and (6) imply that the reward structure that will induce the utility to deliver $e^*(p_0)$ (the value of e that solves [PP1]) when the prevailing price of electricity is p_0 is of the form specified in the Proposition. □

Proof of Proposition 4 (1) and Lemma 1 imply that $p = C'(q^*) + D'(q^*)$ under the reward function that induces the firm to secure (q^*, e^*). (3) implies that the reward structure that will induce the firm to deliver (q^*, e^*) when it has implemented I^* and when $p = C'(q^*) + D'(q^*)$ is of the form $R'(\Delta) = D'(q) - U'(\cdot)X_e(\cdot)\frac{de}{dq}$. Straightforward substitution using (2) completes the proof. □

Proof of Proposition 5 Straightforward calculations reveal:

$$\begin{aligned}\left.\frac{dH}{dI}\right|_{de=dq=0} \overset{s}{=}\; & \left[rX_qX_e - X_{qe}\right]\left[X_eX_{qq}X_{qI} - X_qX_eX_{qqI}\right] \\ & + X_qX_{qq}X_{qe}X_{eI} - X_qX_eX_{qq}X_{qeI} \\ & + rX_qX_e\left[X_eX_{qq}X_{qI} + \left(X_q\right)^2 X_{qeI} - X_qX_{qe}X_{qI}\right] \\ & - r\left(X_q\right)^3 X_{qe}X_{eI} < 0.\end{aligned}$$

This inequality holds because $X_{eI}(\cdot) \geq 0$, $X_{qeI}(\cdot) \leq 0$, $X_{qqI}(\cdot) \geq 0$, and, from (2), $\frac{dq}{de} < 0 \Leftrightarrow rX_q X_e - X_{qe} > 0$.

Proof of Proposition 6 Proposition 5 implies that under the reward structure that induces the utility to secure (q^*, e^*, I^*) in the setting of Example 2:

$$R'(\Delta) = c\left[\frac{1}{1-h}\right] \text{ where } h \equiv \frac{\alpha_0}{r\left[\alpha_1 + \alpha_0 e\right]\left[\alpha_2 I + \alpha_0 q\right]}$$
$$\Rightarrow \frac{dR'(\Delta)}{dI} = -\frac{\alpha_0 c\left\{\left[\alpha_1 + \alpha_0 e\right]\left[\alpha_2 + \alpha_0 \frac{dq}{dI}\right] + \left[\alpha_2 I + \alpha_0 q\right]\alpha_0 \frac{de}{dI}\right\}}{\left[1-h\right]^2 r\left[\alpha_1 + \alpha_0 e\right]^2\left[\alpha_2 I + \alpha_0 q\right]^2}. \quad (7)$$

From (1) and Lemma 1, q^* and e^* are determined by:

$$G(q, e, I) \equiv r\exp\left(-r\left[\alpha_1 q + \alpha_2 eI + \alpha_0 eq\right]\right)\left[\alpha_1 + \alpha_0 e\right] - c = 0, \quad \text{and}$$
$$J(q, e, I) \equiv \alpha_2 I + \alpha_0 q - \frac{k}{c}\left[\alpha_1 + \alpha_0 e\right] = 0.$$

Let $V \equiv \frac{k}{c} r\left[\alpha_1 + \alpha_0 e\right]^2 - \alpha_0 + r\left[\alpha_1 + \alpha_0 e\right]\left[\alpha_2 I + \alpha_0 q\right]$. Cramer's Rule reveals $\left[\alpha_1 + \alpha_0 e\right]\left[\alpha_2 + \alpha_0 \frac{dq}{dI}\right] = \frac{k}{cV}\alpha_1\alpha_2 r\left[\alpha_1 + \alpha_0 e\right]^2$ and $\left[\alpha_2 I + \alpha_0 q\right]\alpha_0 \frac{de}{dI} = \frac{\alpha_1\alpha_2 r}{V}\left[\alpha_1 + \alpha_0 e\right]\left[\alpha_2 I + \alpha_0 q\right]$. Therefore, $\frac{dR'(\Delta)}{dI} < 0$ if $h \neq 1$ and $V > 0$. Observe that $h \neq 1$ if $\alpha_0 \neq r\left[\alpha_1 + \alpha_0 e\right]\left[\alpha_2 I + \alpha_0 q\right]$, and $V > 0$ if $\alpha_0 < r\left[\alpha_1 + \alpha_0 e\right]\left[\alpha_2 I + \alpha_0 q\right] + \frac{k}{c} r\left[\alpha_1 + \alpha_0 e\right]^2$. Therefore, $\frac{dR'(\Delta)}{dI} < 0$ if α_0 is sufficiently close to 0. □

Proof of Proposition 7 By assumption, the public enterprise seeks to maximize $pq - C(q) + R(q_0 - q) - K(e) + \gamma\, U\left(X(q, e)\right)$. The interior value of e that maximizes this expression is given by:

$$R'(\Delta) = p - C'(\cdot) + \gamma\, U'(\cdot)X_q(\cdot) - \left[K'(e) - \gamma\, U'(\cdot)X_e(\cdot)\right]\frac{de}{dq}.$$

Therefore, from (1) and Lemma 1, (q^*, e^*) will arise under the conditions specified in the Proposition. □

Proof of Proposition 8 By assumption, the ESCO seeks to maximize $R(q_0 - q) - K(e) + \gamma U(\cdot)$. The interior value of e that maximizes this expression is given by:

$$R'(\Delta) = \gamma U'(\cdot)X_q(\cdot) + \gamma U'(\cdot)X_e(\cdot)\left[\frac{1}{\frac{dq}{de}}\right] - \left[\frac{K'(e)}{\frac{dq}{de}}\right].$$

Therefore, from (1) and Lemma 1, (q^*, e^*) will arise under the conditions specified in the Proposition. □

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