Consumers' Preferences for Green Electricity and Regulatory Incentives

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Abstract

This paper develops a theoretical model to investigate the impact of consumers' preference for green energy on the regulatory incentives faced by a monopolist who supplies both brown and green electricity. In our model, the market is fully covered (i.e., every consumer is served) and consumers differ in their willingness to pay for green electricity. The monopolist chooses whether or not to undertake an investment in green electricity, which is not observable by the regulator. We show that a regulatory regime which imposes a cap on the price of both green electricity and brown electricity leads to socially optimal investment in green electricity. By contrast, a price cap regulatory regime which imposes a price ceiling on green electricity only induces over-investment in green electricity. The socially efficient level of expected welfare is not reachable by either form of price cap regulation. In some circumstances, an unregulated monopoly dominates price cap regulation from the perspective of expected welfare.

Keywords: Consumers' environmental concerns, Green electricity, Price-cap regulation, Incentives

1 Introduction

A number of surveys and choice experiments (e.g., Mozumder et al., 2011; Gracia et al., 2012; Kaenzig et al., 2013) have shown that consumers prefer electricity generated from green sources to that generated from brown sources. This is despite the fact that consumers cannot distinguish green from brown electricity as electricity is a homogenous good. In real economy, many consumers actually chose to pay higher prices through participating in green electricity programs, although individuals may overstate their willingness to choose green electricity in surveys (Menges et al., 2005; Diaz-Rainey and Tzavara, 2012).[1] For instance, 4.9 million German residential customers purchased green electricity in 2012, accounting for 12.5% of all private households in Germany. In 2012, over 48 TWh of green electricity was sold to U.S consumers, despite being more expensive (REN21, 2014).

This suggests that consumers' decisions are not consistent with the conventional assumption of self-interested behaviour and thus it is important to better understand their behaviour.

[1] That is, there is a gap between consumers' positive attitudes toward green electricity and their actual purchasing behaviour.

This is the aim of an extensive literature investigating consumers' motivation for the support of green electricity. Factors that influence consumers' preferences include the 'warm glow' effect (Menges et al., 2005; Nyborg et al., 2006; Ek and Soderholm, 2008), income (Clark et al., 2003) and altruism (Wiser et al., 2001; Kotchen and Moore, 2007).

Another strand of current studies have investigated the regulatory incentive for green electricity, and the common theme of their conclusion is that regulated firms have incentives to postpone or simply avoid investment in green electricity. For instance, Joode et al. (2009) identifies how the business of the distribution system operator (DGO) is impacted by the increasing distributed generation (DG) driven by renewable energy penetration. Through a cost benefit analysis, they point out that the cost burden of connecting DG to the network negatively impacts the financial position of the DGO, thus the DGO intends to impede the deployment of DG. This implies that the prevailing regulatory regimes in Europe (i.e., the price cap regulation) which incentivise the lowest cost possible needs to be improved to facilitate the integration of DG in the network.

The same conclusion is drawn by Nykamp et al. (2012), who take Germany as a case and measure the influence of investments in green electricity on efficiency objectives of the grid operator. They show that the grid operators gain profitability by avoiding investment and the price cap regulation gives incentives to refuse investment. Similarly, Kucsera and Rammerstorfer (2013) examine how the uncertainty of renewable electricity generation affects the value and timing of investments in generation facilities. They find that, as the output of renewable energy sources is hardly predictable and highly volatile, an increased share of renewable energy in electricity production leads to investment postponement in both generation and transmission.

Nevertheless, consumers' preferences for green electricity are not concerned in these studies. When consumers are willing to pay a higher price for green electricity, suppliers can extract more rent from consumers by supplying more green electricity, thus the incentives for investment in green electricity may change. To our knowledge, few studies have identified how consumers' preferences for green electricity impact the regulatory incentives faced by suppliers that are embedded in a regulatory regime. Hence, this paper aims to explore the interaction of consumers' preferences for green electricity and the investment behaviour of regulated firms under various regulatory regimes.

To pursue this, we model consumers' preferences by following Hotelling (1929). We assume that consumers are uniformly distributed with respect to their willingness to pay for green electricity and each consumer purchases one unit of electricity. Their utility depends on the consumption of electricity, the price they pay for the particular type of electricity they choose and the environmental harm they perceive to result from their consumption. Assume that, compared with brown electricity, the price of green electricity is higher and its marginal environmental cost is lower. Then in order to maximise their utility consumers need to trade off between the price and environmental cost of each type of electricity. This implies that, given specific prices and environmental costs, consumers can choose either green or brown electricity, contingent on their environmental awareness.[2]

In our study the electricity supplier is a multiproduct monopolist who supplies both green

[2]Consumers' willingness to pay for green electricity reflects their awareness of the environmental cost of their own electricity consumption.

electricity and brown electricity to end users. Due to the distributed allocation of renewable energy and instability of green electricity, costly measures are required to promote green electricity.[3] The monopolist chooses whether or not to undertake an investment in it. Given that the investment usually takes the form of managerial effort, we assume that the monopolist's effort for green electricity development is not observable by the regulator. As in a standard moral hazard model, we also assume that the outcome of the effort is uncertain, that is, the monopolist's effort determines the marginal cost of green electricity in a probabilistic manner, with a higher level of effort being more likely to lead to lower marginal cost. As the monopolist's effort influences the marginal cost and thus the price of green electricity, consumers' participation in green electricity programs may be impacted. Since consumers have freedom with their purchasing behaviour, they are free to choose green electricity or brown electricity, or choose not to consume any electricity. To be in line with the fact that electricity is a necessity in the countries where green electricity programs are popular, we assume that the market is fully covered, i.e., all consumers are served with electricity.

Regarding the form of regulatory regime, this paper focuses on price cap regulation – which is prevailing around the world. In particular, we concentrate on two regimes: (*i*) a price cap on green electricity, and (*ii*) price caps on both green and brown electricity. In our setting, as the effort is not observable by the regulator and the resulted marginal cost of green electricity cannot be anticipated, a regulatory regime cannot explicitly compensate the firm for the effort exerted to develop green electricity.

We explore the impacts of consumers' preferences for green electricity from two dimensions. First, we investigate how they affect the electricity supplier's choice of investment under various regulatory situations. Second, we examine the welfare implication of the regulatory regimes. We also discuss, at the end of the study, the effect of information held by the regulator about consumers' perception of the environmental harm of their own electricity consumption.

We show that, the incentive for green electricity development is impacted by the form of regulatory regime. Compared with the socially efficient benchmark, the monopolist chooses to invest more often in green electricity when a price cap is imposed on green electricity only. This over-investment induced can be explained by the more rent the monopolist can extract, via the pricing of the unregulated brown electricity, from consumers willing to pay a higher price for green electricity. By contrast, the regulatory regime which caps the price of both types of electricity induces socially optimal investment in green electricity. This can be explained by the regulator's control over prices and his/her objective which is to maximise ex ante social welfare.

In terms of expected welfare, the social optimum cannot be achieved by either of the price cap regulatory regimes. This outcome is reasonable as there is technological uncertainty in production procedure and information asymmetry between the monopolist and the regulator. Besides, the regulator has to set the price caps before the realisation of production. If the effort cost is sufficiently high/low such that investment in green electricity is undertaken in none/all situations, the two-price-cap regulation dominates the one-price-cap regulation in terms of expected welfare. This result makes sense because the regulator can grant more

[3] For instance, the electricity supplier needs to invest in the infrastructures to integrate distributed green energy, energy storage technologies and system reliability and security (Lester and Hart, 2012).

pricing discretion to the monopolist if it were to increase welfare. For the intermediate values of effort cost, which form of regulation dominates in terms of welfare depends on the relative size of effort cost, as there is trade-off between the gains and costs related with positive effort.

The paper is organised as follows. Section 2 describes the elements of the model. Section 3 identifies the socially optimal solution. Section 4 lays out a benchmark model, which analyses the monopolist's optimal choice of effort in the absence of any form of regulation. Section 6 and Section 5 consider a price capped monopoly under which the regulator is not as well informed as the monopolist in terms of the effort exerted for green electricity. Section 7 compares the outcomes in all the cases examined. Section 8 discusses extensions and the robustness of our model, while Section 9 concludes.

2 The Model

This section lays out the key building blocks of the model. First, we derive a demand function on the basis of consumers' preferences for green electricity, by taking into account of consumers' environmental awareness and willingness to voluntarily pay a higher price for green electricity. Then, we describe the uncertainty of production technology for green electricity and give expected profits and welfare.

2.1 Demand with Preferences for Green Electricity

Assume that there is a mass of consumers normalised to one. Each consumer is independent and purchases one unit of electricity – either one unit of brown electricity or one unit of green electricity. The surplus a consumer derives from consumption of the brown electricity and green electricity is respectively given as:

$$U_b(\theta) = V - P_b - \theta h_b,$$
$$U_g(\theta) = V - P_g - \theta h_g,$$

where V is the reservation value of consumers regarding the consumption of electricity and is assumed to be the same across different consumers.[4] P_b and P_g respectively stand for the unit price of brown electricity and green electricity – which are charged at the same level to all consumers choosing a particular type of electricity. Parameters $h_b > h_g$ measure the environmental cost of their electricity consumption. $\theta \in [0,1]$ is the parameter that reflects a consumer's awareness of the environmental harm of their own electricity consumption. Larger values of θ indicate a higher marginal disutility from environmental harm. In this model, θ is assumed to distribute according to a uniform density function. Except for their awareness of environmental cost, indicated by θ, consumers are identical to each other. In particular, we assume that each consumer spends a small fraction of total expenditure on electricity, so that income effects can be ignored.

Consumers choose between green and brown electricity to maximise their utility. It follows that there exists an indifferent consumer $\widetilde{\theta}$ such that all consumers $\theta \leqslant \widetilde{\theta}$ buy brown

[4]Note that whether the consumer pays a premium or not, she receives electricity of the same quality, independent of the type of electricity.

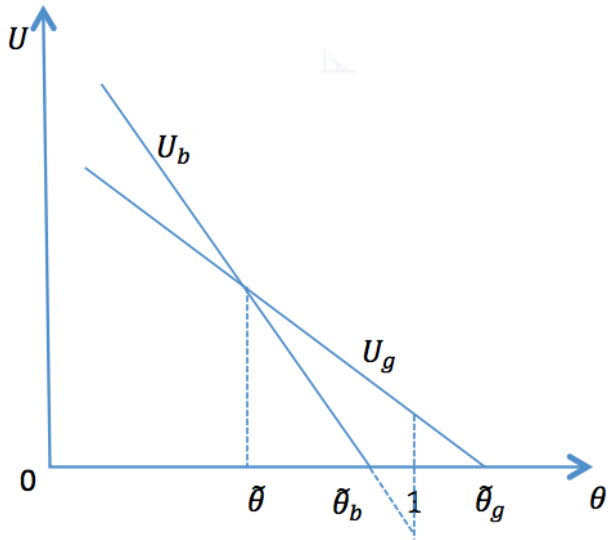
electricity and $\theta > \widetilde{\theta}$ buy green electricity. We can obtain the value of $\widetilde{\theta}$ as below:

$$U_b(\widetilde{\theta}) = U_g(\widetilde{\theta}) \Rightarrow \widetilde{\theta} = \frac{P_g - P_b}{h_b - h_g}. \tag{1}$$

Equation (1) implies that consumers' demand for brown electricity depends on the difference of prices and that of environmental costs between these two types of electricity. The demand for brown electricity increases/decreases in the price of green/brown electricity and the environmental cost of brown/green electricity.

As an essential and indispensable good, electricity is necessity in modern world, particularly in developed countries. For this reason, we focus on throughout the paper the case of a fully covered market where every customer is served with electricity.[5] Given consumers' purchase decision illustrated in Figure 1, we obtain that the demand for brown electricity is equal to $D_b(P_b, P_g) = \widetilde{\theta}$, and the demand of green electricity is $D_g(P_b, P_g) = 1 - \widetilde{\theta}$. It can be seen that, as green and brown electricity are imperfect substitutes for consumers, when the price of one type of electricity increases, the demand for this type goes down and that for the other increases.

Figure 1: Utility of the Two Types of Electricity



2.2 Electricity Supply and Investment

We consider a monopolist who provides both green electricity and brown electricity to consumers, and suppose that the costs to supply each type of electricity are separate. Denote the marginal cost of brown electricity and green electricity with c_b and c_g, respectively. Assume c_b is constant. By contrast, to incorporate the underlying technological uncertainty arising out of supply process, we assume that c_g is affected in a probabilistic way by the supplier's effort to facilitate green electricity. Table 1 defines the probabilities, where $\underline{c}_g$ and $\overline{c}_g$, with

[5] It is true that in many undeveloped countries the electricity market is not fully covered and the main aim for them is to facilitate electricity supply. However, the topic of this paper, green electricity, is popular mainly in developed countries; therefore, it makes sense to have this assumption about market coverage.

Table 1: Relationship between Effort Level and Marginal Cost of Green Electricity

	$\underline{c}_g$	$\overline{c}_g$
$X=0$	$1-\phi$	ϕ
$X=x$	ϕ	$1-\phi$

$\overline{c}_g > \underline{c}_g$, are the marginal cost levels to provide green electricity. $X \in \{0, x\}$ denotes the two effort levels the monopolist can take. ϕ denotes the probability that, with positive effort, the lower marginal cost of green electricity eventuates. Suppose that positive effort is more likely to lead to lower marginal cost, that is, $\phi > 1/2$.

To focus the analysis on the impact of preference for green electricity on the incentives embedded in various regulatory regimes, we assume that the marginal cost of any particular type of provided electricity is independent of the supply quantity. In addition, we assume that the marginal cost of green electricity is higher than or at least equal to that of the conventional brown electricity.[6] That is,

$$\underline{c}_g \geqslant c_b. \tag{2}$$

To ensure that the demand of each type of electricity is non-negative (i.e., $\widetilde{\theta}$ ranges between 0 and 1) and that the uncovered market share is non-positive, we assume that

$$\overline{c}_g + h_g \leqslant h_b + c_b. \tag{3}$$

Inequality (3) means that the total cost (i.e., sum of production cost and environmental cost) of green electricity is no larger than that of brown electricity. This assumption implies that it is more socially efficient to provide green electricity than to provide brown electricity.

Besides, since consumers have the freedom of not purchasing electricity, we need to impose some additional parameter restrictions to guarantee that the utility each individual enjoys from electricity consumption is non-negative, i.e., $U_i(\theta) = V - P_i - \theta h_i \geqslant 0$, with $i \in \{b, g\}$. Given $0 \leqslant \theta \leqslant 1$, this participation constraint can be rewritten as $V - P_i - h_i \geqslant 0$. As we can find in the coming analysis, the value of V in our model is assumed to satisfy

$$V \geqslant \overline{c}_g + h_g. \tag{4}$$

This assumption indicates that consumer's reservation value regarding electricity consumption is sufficiently high, so that it is always higher than the sum of the marginal production cost and the marginal environmental cost of green electricity.

The monopolist knows the distribution of θ, but does not observe each individual consumer's valuation. The monopolist's ex post profit from selling the two types of electricity is given as

$$\pi(P_b, P_g) = (P_b - c_b) D_b(P_b, P_g) + (P_g - c_g) D_g(P_b, P_g), \tag{5}$$

where the cost of undertaking effort is equal to X, and any fixed cost of supplying both types of electricity is negligible.

[6]Note that in real economy, it is usually the case that the supplier purchases electricity at wholesale market and then sells it to end users. In this sense, the marginal cost of each type of electricity is the wholesale price paid by the monopolist. Since a feed-in tariff is employed to offer a higher price for renewable energy generated electricity, it makes sense to have this assumption.

As green electricity is not distinct from brown electricity in physical form, to ensure that customers are getting exactly what is described in their purchased product, we suppose that the government can take charge of supervising or monitoring through means such as periodical auditing.

3 Socially Efficient Allocation and Investment

In this section, we will calculate the socially efficient solution in terms of demand allocation and investment in green electricity. In the socially optimal benchmark, we assume that the social planner has full information and can set electricity prices contingent on the realised costs. We will also check whether or not pricing at marginal cost can induce socially efficient outcomes.

3.1 Ex post Optimal Allocation

Prices are transfers from consumers to firms and welfare-neutral. Hence, for a given level of c_g and a market share of brown electricity, $\widehat{\theta}$, ex post total welfare is given by

$$W\left(\widehat{\theta}\right) = \int_0^{\widehat{\theta}} (V - \theta h_b - c_b)\, d\theta + \int_{\widehat{\theta}}^1 (V - \theta h_g - c_g)\, d\theta,$$

with $c_g \in \left\{\underline{c}_g, \overline{c}_g\right\}$. The optimal market share of brown electricity is obtained from the first-order condition (FOC), $\partial W(\widehat{\theta})/\partial \widehat{\theta} = 0$, which yields

$$\widehat{\theta}\,(h_b - h_g) = c_g - c_b.$$

The social planner allocates electricity such that the marginal consumer's gain from consuming green electricity equals society's marginal cost of producing it. The ex post socially efficient market share of brown electricity is thus

$$\widehat{\theta}^s\,(c_g) = \frac{c_g - c_b}{h_b - h_g}. \tag{6}$$

The optimal share of brown electricity increases in the marginal production cost and environmental harm of green electricity, and decreases in that of brown electricity. Note that marginal cost pricing implements the socially efficient allocation.

3.2 Optimal ex ante Investment

Ex ante social welfare as a function of effort is given by:

$$E[W^s(\widehat{\theta})\,|_{X=0}] = \phi W(\overline{\theta}^s) + (1-\phi)\, W(\underline{\theta}^s), \qquad \text{if } X = 0,$$
$$E[W^s(\widehat{\theta})\,|_{X=x}] = (1-\phi)\, W(\overline{\theta}^s) + \phi W(\underline{\theta}^s) - x, \quad \text{if } X = x,$$

where $\overline{\theta}^s = \widehat{\theta}^s\,(\overline{c}_g) = (\overline{c}_g - c_b)/(h_b - h_g)$, $\underline{\theta}^s = \widehat{\theta}^s\left(\underline{c}_g\right) = (\underline{c}_g - c_b)/(h_b - h_g)$, and $W(\overline{\theta}^s)$ and $W(\underline{\theta}^s)$ represent the ex post welfare with $c_g = \overline{c}_g$ and $c_g = \underline{c}_g$ respectively. Obviously, exerting positive effort is more likely to induce lower marginal cost for green electricity, however, it raises the total cost. Hence, the social planner needs to trade off the benefits brought about by positive effort with the cost it takes. To guarantee that the expected welfare with positive effort dominates that in absence of effort, we need to ensure that the incentive compatibility constraint holds, that is,

$$E[W^s(\widehat{\theta})\,|_{X=x}] \geqslant E[W^s(\widehat{\theta})\,|_{X=0}].$$

It requires that the cost of effort should be sufficiently low that

$$x \leqslant \widetilde{x}^s = (2\phi - 1)[W(\underline{\theta}^s) - W(\overline{\theta}^s)], \tag{7}$$

where $\widetilde{x}^s$ is the threshold of effort cost in socially efficient benchmark. The left-hand side is the cost of positive effort, and the right-hand side is the benefit obtained from positive effort. We can calculate the value of effort cost that makes expected welfare indifferent between positive effort and zero effort as:

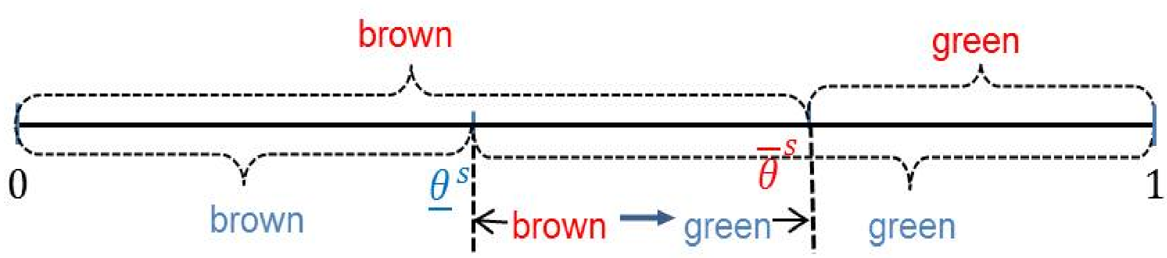
$$\widetilde{x}^s = (2\phi - 1)\left\{(1 - \overline{\theta}^s)(\bar{c}_g - \underline{c}_g) + \int_{\underline{\theta}^s}^{\overline{\theta}^s} \left[\left(V - \underline{c}_g - \theta h_g\right) - (V - c_b - \theta h_b)\right] d\theta\right\} \tag{8}$$

$$= (2\phi - 1)\left(\bar{c}_g - \underline{c}_g\right)\left(1 - \frac{\overline{\theta}^s + \underline{\theta}^s}{2}\right) \tag{9}$$

$$= (2\phi - 1)(\bar{c}_g - \underline{c}_g)\left[1 - \frac{\underline{c}_g + \bar{c}_g - 2c_b}{2(h_b - h_g)}\right], \tag{10}$$

As we can see from equation (8), the gain brought about by positive effort consists of two parts: *i*) the monopolist's cost savings from supplying electricity to those who always choose green electricity; and *ii*) the benefit gained by the consumers whose choice shifts from brown electricity to green electricity when higher rather than lower marginal cost of green electricity eventuates.[7] This decomposition is demonstrated in Figure **??**.

Figure 2: Ex post Market Share in the Socially Efficient Case



According to equation (10), the threshold value of effort cost is affected by several factors, including the likelihood that the higher marginal cost of green electricity eventuates in the presence with zero effort (i.e., ϕ, which is also the probability that the lower marginal cost

[7]That is, these consumers choose brown electricity if the realised marginal cost of green electricity is lower; however, if the realised cost is higher, they shift to green electricity.

occurs with positive effort), the alternative values of marginal cost of green electricity (i.e., $\overline{c}_g$ and $\underline{c}_g$), the marginal cost of brown electricity (i.e., c_b), and the value of environmental harm caused by the consumption of these two types of electricity (i.e., h_b and h_g). To be specific, $\widetilde{x}^s$ increases in ϕ, c_b, h_b and $\overline{c}_g$, and decreases in h_g and $\underline{c}_g$.

Proposition 1 provides a precise characterisation of the socially efficient situation.

Proposition 1 *In a fully covered market with perfect information,*

(i) The ex post market share of green electricity increases in c_b and decreases in c_g.

(ii) Marginal cost pricing implements the socially efficient ex post allocation of consumers.

(iii) When the effort cost size is sufficiently low such that $0 < x < \widetilde{x}^s$, positive effort dominates zero effort in terms of overall expected welfare; otherwise, zero effort is socially efficient whenever $x \geqslant \widetilde{x}^s$.

As marginal cost pricing requires costly information collection, this pricing regime is of little practical importance. Hence, it is necessary to examine a more realistic benchmark. In the section immediately below we will analyse the situation in absence of any regulation.

4 Unregulated Monopoly

In the unregulated monopoly case, we consider the impact of the monopolist's ex post pricing on green electricity expansion and on overall social welfare. The timing of activities is assumed as follows: in the first stage, based on the expected profits, the unregulated monopolist decides whether or not to exert any effort to facilitate green electricity. Then the monopolist carries out the production in the next stage. After that, s/he sets a profit maximising price for both green electricity and brown electricity, contingent on the realised marginal cost of green electricity. We solve this problem backwards.

4.1 Ex post Monopoly Pricing

Given the realised marginal cost of green electricity, the monopolist's objective is to maximise ex post profit, i.e.,

$$Max_{(P_b,\, P_g)}\ \pi(P_b, P_g).$$

The FOCs with respect to prices are respectively

$$\frac{\partial \pi}{\partial P_b} = \frac{2\,(P_g - P_b) - (c_g - c_b)}{h_b - h_g} = 0, \tag{11}$$

$$\frac{\partial \pi}{\partial P_g} = 1 - \frac{2\,(P_g - P_b) - (c_g - c_b)}{h_b - h_g} = 0. \tag{12}$$

Under assumption (4), these conditions imply that the monopolist prices at a corner solution, such that $P_g^m = V - h_g$, while P_b^m satisfies (11). This is shown in detail in the Appendix. The optimal price of brown electricity is $\overline{P}_b^m = P_g^m - (\overline{c}_g - c_b)/2$ if $c_g = \overline{c}_g$ or $\underline{P}_b^m = P_g^m - (\underline{c}_g -$

$c_b)/2$ if $c_g = \underline{c}_g$. Hence, the price for green electricity is cost independent, whereas the price for brown electricity changes with the marginal cost of green electricity. Moreover, given the assumption in (2) and (4), the unregulated monopoly price of both categories of electricity are above the marginal costs, which implies that the pricing in unregulated monopoly is not socially efficient.

As the optimal market share of brown electricity in the unregulated monopoly situation is $\overline{\theta}^m = (\overline{c}_g - c_b)/2(h_b - h_g)$ if $c_g = \overline{c}_g$ or $\underline{\theta}^m = (\underline{c}_g - c_b)/2(h_b - h_g)$ if $c_g = \underline{c}_g$, we can note that the market share of brown electricity in absence of regulation is always half of the socially efficient level. Given the assumption that the market is fully covered, the market share of green electricity in unregulated monopoly exceeds the socially optimal level.

We will briefly summarise the outcomes in Lemma 1.

Lemma 1 *Under unregulated monopoly,*

(i) The optimal ex post price for green electricity chosen by the unregulated monopolist is always equal to $V - h_g$, independent of the realised marginal cost of green electricity.

(ii) At this price, the consumer who is most environmentally aware is indifferent between buying green electricity and not buying.

(iii) The market share of green electricity in the unregulated monopoly situation is always higher than the socially efficient level.

4.2 Optimal Effort Choice

Now we turn to the monopolist's expected profit – which determines the choice of green electricity development. In doing so, we first calculate the associated ex post profits by substituting into expression (5) the optimal ex post prices of electricity.

Let $E[\pi^m(P_g, P_b)]$ denote expected profit under unregulated monopoly, we can write it as

$$E[\pi^m(P_g, P_b)|_{X=0}] = \phi\pi\left(P_g^m, \overline{P}_b^m\right) + (1-\phi)\pi\left(P_g^m, \underline{P}_b^m\right), \quad \text{if } X = 0,$$
$$E[\pi^m(P_g, P_b)|_{X=x}] = (1-\phi)\pi\left(P_g^m, \overline{P}_b^m\right) + \phi\pi\left(P_g^m, \underline{P}_b^m\right), \quad \text{if } X = x.$$

To ensure that positive effort dominates zero effort in terms of expected welfare, the incentive compatibility which is

$$E[\pi^m(P_g, P_b)|_{X=x}] \geqslant E[\pi^m(P_g, P_b)|_{X=0}]$$

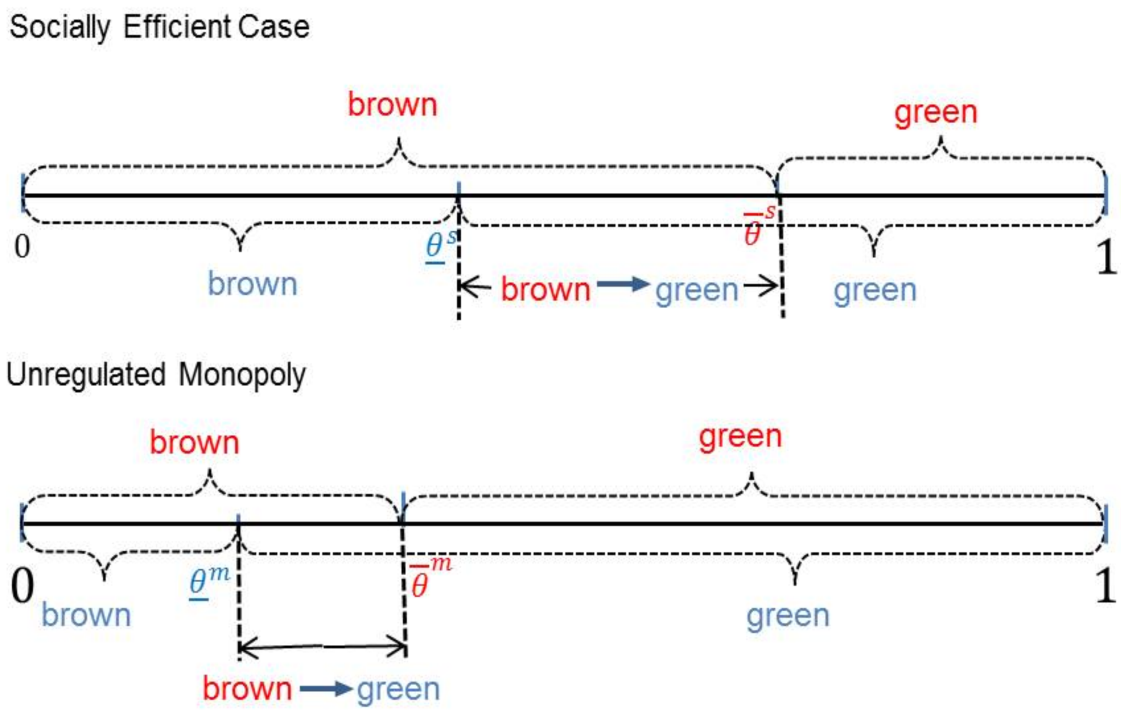
must be satisfied. That is, the value of effort cost should be sufficiently low that

$$x \leqslant \widetilde{x}^m = (2\phi - 1)(\overline{c}_g - \underline{c}_g)\left(1 - \frac{\overline{\theta}^m + \underline{\theta}^m}{2}\right),$$

where $\widetilde{x}^m$ is the threshold under unregulated monopoly. Note that the size of effort cost that the monopolist thinks feasible for positive effort is larger under unregulated monopoly than in the socially efficient situation. This implies that under unregulated monopoly the monopolist trends to over-invest in green electricity. The comparison is caused by the difference in the concern of the monopolist and the social planner, with the former concerning expected profit while the latter being concerned with expected welfare.

As shown in Figure 3, the demand elasticity of brown electricity is relatively smaller than that of green electricity. Therefore, increasing the price of brown electricity allows the monopolist to extract more rent from consumers. As assumed earlier, the monopolist knows the forms of consumers' utility function, thus s/he can set prices at the level which makes the marginal consumer indifferent between buying green electricity and not buying – which maximises the monopolist's expected profit.

Figure 3: Over-investment in Green Electricity under Unregulated Monopoly



Regarding welfare, as shown in the Appendix, we find that, compared to the socially efficient case, there is welfare distortion in unregulated monopoly. Usually, the welfare deviation from socially efficient level is caused by two effects of monopoly power: (*i*) the effect of inefficient monopoly pricing and (*ii*) the effect of transfer of surplus from consumers to the monopolist as profits. In our model, given the assumption of full market coverage, the inefficient monopoly prices – which are above marginal costs – do not reduce the total quantity of electricity supply. Thus the welfare losses in unregulated monopoly are attributed to surplus transfer. Aside from the surplus transferred from consumers to the monopolist, there exists deadweight loss suffered by consumers – particularly by those who shift to green electricity demand from brown electricity.

The outcome features in unregulated monopoly can be summarised in Proposition 2.

Proposition 2 *Under unregulated monopoly,*

(i) The unregulated monopolist will undertake positive effort for green electricity expansion if the required effort cost satisfies $0 < x < \widetilde{x}^m$*. Otherwise, zero effort is chosen.*

(ii) *The monopolist chooses to exert positive effort more often than in the socially efficient benchmark, as the range of effort cost for which the monopolist finds it worthwhile to exert positive effort is larger than that in the socially efficient case, i.e.,* $\widetilde{x}^m > \widetilde{x}^s$.

For the remainder of this study, we aim to explore the regulatory incentives of distinct regulatory regimes on green electricity supply by a monopolist. We presume that both the monopolist and the regulator are fully informed of the form of cost function, the marginal cost of brown electricity and the monopolist's cost effort matrix shown in Table 1. Neither of them is able to precisely anticipate the marginal cost of green electricity beforehand. Nevertheless, the monopolist possesses more private information than the regulator regarding the effort to facilitate green electricity.

In the presence of asymmetric information, the next two sections will examine two regulatory regimes with different pricing discretion granted by the regulator to the monopolist. In the first one, a price cap is imposed on green electricity only, while in the second regime price caps are set for both brown electricity and green electricity. In both regulatory regimes, we neglect the cost of running the regulatory regimes.

5 Price Cap on Green Electricity

This section analyses the case where a price cap is set for green electricity only. The timing of activities is summarised as follows: firstly, the regulator imposes a price ceiling on green electricity. Secondly, given the exogenously fixed price of green electricity, the monopolist chooses whether or not to undertake effort for green electricity. Then in the third stage s/he conducts the production of both types of electricity and, contingent on the realised marginal cost of green electricity, sets an optimal price for brown electricity. This problem is also solved backwards.

5.1 Optimal ex post Brown Electricity Price

We first look at the optimal ex post price the monopolist can set for brown electricity. Given the realised marginal costs and the price cap on green electricity, the monopolist's objective is to maximise ex post profit, i.e.,

$$Max_{(P_b)}\pi(P_b, P_g^I),$$

where P_g^I denotes the cap set by the regulator on green electricity price. From the FOCs, we obtain the optimal ex post brown electricity price as $\overline{P}_b^I = P_g^I - (\overline{c}_g - c_b)/2$ if $c_g = \overline{c}_g$, or $\underline{P}_b^I = P_g^I - (\underline{c}_g - c_b)/2$ if $c_g = \underline{c}_g$. It can be found that, the optimal brown electricity price chosen by the monopolist depends on the green electricity price cap imposed by the regulator and the realised marginal costs of both categorises of electricity. It follows that the ex post market share of brown electricity is $\overline{\theta}^I = (P_g^I - \overline{P}_b^I)/(h_b - h_g) = (\overline{c}_g - c_b)/2(h_b - h_g)$ if $c_g = \overline{c}_g$ or $\underline{\theta}^I = (P_g^I - \underline{P}_b^I)/(h_b - h_g) = (\underline{c}_g - c_b)/2(h_b - h_g)$ if $c_g = \underline{c}_g$. Note that the profit-maximising market structure in this case is identical to that under unregulated monopoly.

5.2 Optimal Effort Choice

The expected profit under this regulatory regime can be calculated as

$$E\left[\pi^I\left(P_b,P_g\right)|_{X=0}\right]=\phi\pi\left(P_g^I,\overline{P}_b^I\right)+(1-\phi)\pi\left(P_g^I,\underline{P}_b^I\right),\quad \text{if } X=0,$$
$$E\left[\pi^I\left(P_b,P_g\right)|_{X=x}\right]=(1-\phi)\pi\left(P_g^I,\overline{P}_b^I\right)+\phi\pi\left(P_g^I,\underline{P}_b^I\right),\quad \text{if } X=x.$$

To ensure that a positive effort is the optimal choice for the regulated monopolist, the following incentive compatibility needs to be met:

$$E\left[\pi^I\left(P_b,P_g\right)|_{X=x}\right]\geqslant E\left[\pi^I\left(P_b,P_g\right)|_{X=0}\right].$$

This requires that the effort cost of positive effort should be sufficiently low that

$$x\leqslant\widetilde{x}^I=(2\phi-1)(\bar{c}_g-\underline{c}_g)\left[1-\frac{\overline{\theta}^I+\underline{\theta}^I}{2}\right],$$

where $\widetilde{x}^I$ is the threshold under this form of price regulation. It is intriguing to note that $\widetilde{x}^I=\widetilde{x}^m$, which implies that, in terms of the effort cost size triggering positive effort, a single price cap is identical to the unregulated monopoly. This can be explained by the one monopoly profit theory – which shows that the monopolist is able to extract the monopoly rent through the unregulated price. In the unregulated situation, the profit-maximising price of green electricity chosen by the monopolist equals to $V-h_g$, independent of realised marginal costs. This fixed price of green electricity is essentially the same with the price cap exogenously set by the regulator for the green electricity. In this sense, the instrument that the monopolist can control to maximise profit in these two circumstances is just the price of brown electricity. Therefore, the one product monopoly profit theory applies and the choice of effort in these two cases is proved to be the same.

We then come to analyse expected welfare under this form of regulatory regime. To do so, we first derive the optimal price cap for green electricity by solving the problem which maximises expected welfare subject to the monopolist's break even constraint. Then we substitute the solution into the expression of expected welfare, which is a function of effort as follows:

$$E[W^I(\widehat{\theta})|_{X=0}]=\phi W(\overline{\theta}^I)+(1-\phi)W\left(\underline{\theta}^I\right),\qquad \text{if } X=0,$$
$$E[W^I(\widehat{\theta})|_{X=x}]=(1-\phi)W(\overline{\theta}^I)+\phi W\left(\underline{\theta}^I\right)-x,\ \text{if } X=x.$$

As shown in the Appendix, maximal expected welfare under this regulatory regime equals to the unregulated level, although the price cap on green electricity set by the regulator – which maximises expected welfare – is not equal to the green electricity price chosen by the unregulated monopolist – which maximises the expected profit.

Two main reasons explain why the overall level of social welfare is identical in these two cases. The first is the identical effort choice by the monopolist, which leads to the same production decision in the two cases. The second is the same demand allocation between brown electricity and green electricity – with which the utility loss suffered by consumers shifting from brown electricity to green electricity is also identical. Given the assumption that consumer surplus and the monopolist's profit share the same weight in total surplus, pushing up the price of one type of electricity merely transfers the surplus between consumers and the monopolist, not changing the total amount of surplus. Therefore, in spite of the distinct green electricity prices, in these two cases the general welfare deviates from the optimal level to the same magnitude. This also implies that the expected welfare induced by the one-price-cap regulatory regime is independent of the price cap set for green electricity.

Next we summarise the characterisation of one-price-cap regulation in Proposition 3.

Proposition 3 *When the price cap regulation imposes a ceiling solely on green electricity,*

(i) The incentive to invest is independent of the price cap of green electricity.

(ii) Given the same level of marginal cost for green electricity, the market share of green electricity induced by the one-price-cap regulatory regime is higher than the socially efficient level, that is, $\widehat{\theta}^{I}(\underline{c}_g) < \widehat{\theta}^{s}(\underline{c}_g)$ *and* $\widehat{\theta}^{II}(\overline{c}_g) < \widehat{\theta}^{s}(\overline{c}_g)$.

(iii) If the required effort cost is sufficiently low such that $0 < x < \widetilde{x}^{I}$ *, the monopolist will undertake positive effort to facilitate green electricity. Otherwise, no effort is preferred by him/her. This is identical to the situation in absence of regulation.*

6 Price Cap on Green and Brown Electricity

In this section, we extend the model to two price caps, that is, the regulator imposes ex ante price caps on both green electricity and brown electricity. The timing of activities in this case is assumed to be the same as above, except that the prices of both types of electricity are exogenously determined. That is, in the first stage, the regulator sets fixed price ceilings on both green electricity and brown electricity, not conditional on the realised marginal cost of green electricity. In the second, given the exogenously fixed prices, the monopolist chooses the effort level to promote green electricity. S/he conducts the electricity supply in the third stage. The monopolist's choice about effort also depends on the expected profits under different levels of effort.

6.1 Profit-maximising Market Share

Under this regulatory regime, denote the price cap for brown electricity and green electricity respectively with P_b^{II} and P_g^{II}, the market share of brown electricity can be given as $\widetilde{\theta}^{II} = (P_g^{II} - P_b^{II})/(h_b - h_g)$. Denote the monopolist's expected profit with $E\left[\pi^{II}(P_b, P_g)\right]$, then according to the incentive compatibility constraint which is

$$E\left[\pi^{II}(P_b, P_g)\,|_{X=x}\right] \geqslant E\left[\pi^{II}(P_b, P_g)\,|_{X=0}\right],$$

we can see that, to guarantee positive effort as the monopolist's optimal choice, the market share of brown electricity should be sufficiently low that

$$\widehat{\theta} \leqslant \widehat{\theta}^{II} = 1 - \frac{x}{(2\phi - 1)(\overline{c}_g - \underline{c}_g)} \tag{13}$$

where $\widehat{\theta}^{II}$ is the threshold of market share for brown electricity under this form of price regulation. This implies that when the market share of brown electricity is sufficiently low that it is less than $\widehat{\theta}^{II}$, positive effort is worthwhile. But if it exceeds $\widehat{\theta}^{II}$, no effort would be exerted by the monopolist.

It is obvious that the threshold of market share for brown electricity is a decreasing function of effort cost. Accordingly, the threshold of market share for green electricity increases in effort cost. The logic behind is as follows. In the presence of positive effort, the expected marginal cost of green electricity is relatively lower, contrasted with that of brown electricity which is independent of effort. Hence, the increase in market share of green electricity brings about more profit to the monopolist. At the marginal level, the cost saving enjoyed by the monopolist from supplying green electricity offsets all the cost of undertaking positive effort, i.e., $x = (2\phi - 1)\left(\overline{c}_g - \underline{c}_g\right)\widehat{\theta}_g^{II}$, where $\widehat{\theta}_g^{II}$ represents the threshold of market share for green electricity.

6.2 Threshold of Effort Cost

Before proceeding further, we need to derive the optimal market share of electricity. As assumed, the regulator's objective is to maximise the expected welfare, which is to solve

$$Max_{(\widehat{\theta})} E\left[W^{II}(\widehat{\theta})\right],$$

where $E[W^{II}(\widehat{\theta})]$ denotes the expected welfare under the two-price-cap regulatory regime. Let $\overline{W}(\widehat{\theta}^{II})$ and $\underline{W}(\widehat{\theta}^{II})$ denote the ex post welfare when $c_g = \overline{c}_g$ and $c_g = \underline{c}_g$ respectively, then the expected welfare as a function of market share is given as

$$\begin{array}{ll} E\left[W^{II}\left(\widehat{\theta}\right)|_{X=0}\right] = \phi\overline{W}(\widehat{\theta}^{II}) + (1-\phi)\underline{W}(\widehat{\theta}^{II}), & \text{if } \ \widehat{\theta} > \widehat{\theta}^{II} \\ E\left[W^{II}\left(\widehat{\theta}\right)|_{X=x}\right] = (1-\phi)\overline{W}(\widehat{\theta}^{II}) + \phi\underline{W}(\widehat{\theta}^{II}) - x, & \text{if } \ \widehat{\theta} \leqslant \widehat{\theta}^{II} \end{array}. \tag{14}$$

By deriving the FOCs, with respect to $\widehat{\theta}$, of the expected welfare above, we obtain the welfare-maximising market share of brown electricity as

$$\begin{aligned} \widehat{\theta}^{II}_{|X=0} &= \frac{\phi\overline{c}_g + (1-\phi)\,\underline{c}_g - c_b}{h_b - h_g} \quad \text{if} \quad \widehat{\theta} > \widehat{\theta}^{II}, \\ \widehat{\theta}^{II}_{|X=x} &= \frac{(1-\phi)\,\overline{c}_g + \phi\underline{c}_g - c_b}{h_b - h_g} \quad \text{if} \quad \widehat{\theta} \leqslant \widehat{\theta}^{II}. \end{aligned}$$

It can be found that the optimal market share of brown electricity is lower when positive effort is exerted, i.e., $\widehat{\theta}^{II}_{|X=0} > \widehat{\theta}^{II}_{|X=x}$. The relatively lower market share for brown electricity in the presence of positive effort is induced by the relatively lower expected marginal cost of green electricity.

As we can show in the Appendix, $\widehat{\theta}^{II}_{|X=x} \leqslant \widehat{\theta}^{II} \leqslant \widehat{\theta}^{II}_{|X=0}$ always holds. Through comparing the associated expected welfare, we derive the threshold of effort cost as

$$\widetilde{x}^{II} = (2\phi - 1)\left(\overline{c}_g - \underline{c}_g\right)\left[1 - \frac{\overline{c}_g + \underline{c}_g - 2c_b}{2\left(h_b - h_g\right)}\right].$$

It is of interest to note that, under the two-price-cap regulatory regime, the size of effort cost feasible for positive effort by the monopolist is equal to the socially optimal level, i.e., $\widetilde{x}^{II} = \widetilde{x}^{s}$. This yields that the two-price-cap regulation provides socially efficient incentive for investment in green electricity. The result can be explained by the regulator's objective which is to maximise expected welfare.

In this scenario, given the calculation of expected welfare in expression (14), we can show in the Appendix that the two-price-cap regulation cannot lead the expected welfare to the socially efficient level. The key reason for the welfare distortion is that price caps are set prior to the realisation of production. Other reasons include the technical uncertainty of production and asymmetric information between the monopolist and the regulator.

In brief, the characterisation of this type of regulation is summerised in Proposition 4.

Proposition 4 *Under a regulatory regime which imposes price caps on both green and brown electricity,*

(i) The firm's incentive to invest increases in the market share of green electricity, that is, it decreases in the price cap difference, $P_g^{II} - P_b^{II}$.

(ii) The market share of green electricity induced by the two-price-cap regulatory regime exceeds the socially optimal level if $c_g = \overline{c}_g$, *and it is under the socially efficient level when* $c_g = \underline{c}_g$, *i.e.,* $\widehat{\theta}^s(\underline{c}_g) < \widehat{\theta}^{II}_{|X=x}(\underline{c}_g) = \widehat{\theta}^{II}_{|X=x}(\overline{c}_g) < \widehat{\theta}^{II}_{|X=0}(\underline{c}_g) = \widehat{\theta}^{II}_{|X=0}(\overline{c}_g) < \widehat{\theta}^s(\overline{c}_g)$.

(iii) If the effort cost is sufficiently low such that $0 < x < \widetilde{x}^{II}$, *positive effort is undertaken. Otherwise, no effort is devoted. The incentive provided for investment in green electricity is socially efficient.*

7 Expected Welfare under Different Forms of Price Cap Regulation

This section compares the scenarios examined above from the perspective of expected welfare. The comparison is driven by the size of effort cost.

To do so, we first summarise the ranking of the effort cost feasible for the monopolist to exert positive effort for green electricity under different situation. From the analysis above we obtain that, if the market is always fully covered, given the parameter restrictions in (2), (3) and (4), the threshold value of effort cost is ranked as $\widetilde{x}^{s} = \widetilde{x}^{II} < \widetilde{x}^{I} = \widetilde{x}^{m}$.[8] That is, under the two-price-cap regulatory regime, the effort cost feasible for positive effort (i.e., $\widetilde{x}^{II}$) equals the socially efficient level (i.e., $\widetilde{x}^{s}$). By contrast, under the one-price-cap regulation, the effort cost under which the monopolist exerts positive effort (i.e., $\widetilde{x}^{I}$) is equal to that under unregulated situation (i.e., $\widetilde{x}^{m}$) – higher than the social optimum. This implies that the two-price-cap regulation induces socially efficient investment in green electricity, while the one-price-cap regulation leads to over-investment. The difference in the outcomes can be explained by the departure of the monopolist's objective from maximising expected welfare – which is the aim

[8]Since the outcome of marginal cost pricing is identical to the social optimum, in the comparison, we only consider the socially efficient case, which is marked with superscript s.

the regulator pursues, and the regulator's control power over electricity prices under different regulatory regime.

Based on the ranking of threshold values of effort cost, we will compare expected welfare in the next. The details of comparison are given in the Appendix and the result is demonstrated in Table 2. We summarise the characterisation of the comparison in Proposition 5.

Table 2: The Optimal Regulation

Effort Cost	**Effort Level** S/PC2	M/PC1	**Social Welfare Comparison**
$x \geqslant \widetilde{x}^{I}$	$X = 0$	$X = 0$	$E\left[W^s\right] > E\left[W^{II}\right] \geqslant E\left[W^m\right] = E\left[W^I\right]$
$\widehat{x} < x < \widetilde{x}^{I}$	$X = 0$	$X = x$	$E\left[W^s\right] > E\left[W^{II}\right] \geqslant E\left[W^m\right] = E\left[W^I\right]$
$\widetilde{x}^{II} \leqslant x \leqslant \widehat{x}$	$X = 0$	$X = x$	$E\left[W^s\right] > E\left[W^m\right] = E\left[W^I\right] \geqslant E\left[W^{II}\right]$
$x < \widetilde{x}^{II}$	$X = x$	$X = x$	$E\left[W^s\right] > E\left[W^{II}\right] \geqslant E\left[W^m\right] = E\left[W^I\right]$

where $\widehat{x}$ denotes the threshold such that if $x > \widehat{x}$ the two-price-cap regulation dominates the one-price-cap regulatory regime in terms of expected welfare, whereas if $x > \widehat{x}$ the expected welfare induced by the one-price-cap regulatory regime is relatively higher.

Proposition 5 *The relative performance of different regulatory regimes in terms of expected welfare can be summarised as follows:*

(i) Regardless of the effort cost for green electricity development, the socially efficient expected welfare cannot be obtained by any of the regulatory regimes.

(ii) One-price-cap regulation achieves the same expected welfare as the unregulated monopolist, independent of the effort cost.

(iii) When the size of effort cost is sufficiently large such that positive effort is never exerted, the two-price-cap regulation brings about higher expected welfare than the one-price-cap regulatory regime and the unregulated monopoly. The same holds when effort cost is sufficiently low such that positive effort is undertaken in all the cases.

(iv) For intermediate values, when positive effort is chosen under the one-price-cap regulation rather than under the two-price-cap regulation, unregulated monopoly may dominate either form of price-cap regulation from the perspective of expected welfare.

The result in (*i*) is straightforward and can be explained by three main reasons: 1) the uncertainty of production technology, 2) the asymmetric information between the regulator and the monopolist in terms of effort for green electricity development, and 3) the ex ante attribute of price cap regulation – which means that the regulator sets price caps before the realisation of production. For all these reasons, the regulator cannot observe or determine the behaviour of the monopolist and thus cannot induce the monopolist to pursue the socially optimal objective. Therefore, deviation from the social optimum is deemed to be created.

The logic behind result in (*ii*) can be explained by the one monopoly profit theory – which allows the monopolist to maximise his/her expected profit by pricing of the unregulated product. As pointed out in Section 6, the price of green electricity remains unchanged – no matter it is the price chosen by the monopolist under unregulated monopoly or that set by the regulator under the one-price-cap regulation. In the meanwhile, in both cases the monopolist is free to choose the price of brown electricity to maximise his/her profit. Thus it is the price of brown electricity that determines the monopolist's expected profit and thus the choice of investment in green electricity. As the price difference between the two types of electricity finally selected by the monopolist is identical, market structure of electricity is also identical. As a consequence, the utility loss of consumers shifting from brown electricity to green electricity is the same in the two cases. Given the assumption that consumers and the monopolist are assigned the same weight in total welfare, the loss of consumer surplus caused by raised brown electricity price is totally transferred to the monopolist. Thus even though the prices of both types of electricity are different, the associated expected welfare reaches is the same.

As illustrated in result (*iii*), if the effort cost is sufficiently high or low such that the choice of investment in green electricity selected by the monopolist is identical in all situation, the two-price-cap regulation is welfare superior to other possible scenarios. This ranking is reasonable, as a regulator may grant more pricing discretion for the monopolist if capping two prices yields relatively lower expected welfare.

For the intermediate values of effort cost – with which positive effort can be exerted under the two-price-cap regulation rather than under the one-price-cap regulation, the relative performance between the two types of regulatory regimes is impacted by the size of effort cost. If the effort cost is relatively high, the two-price-cap regulation yields higher ex ante welfare; otherwise, the expected welfare resulted from the one-price-cap regulation is higher. This outcome makes sense as the positive effort for green electricity development requires cost, which offsets the gains that can be obtained from the investment action.

Note that in our analysis, we assume that there is no cost in the process of regulation. However, in real economy, related activities (e.g. rate hearings and public forums) are resources intensive and require significant costs. Hence, in the case immediately above – where the expected welfare brought about by the two-price-cap regulation is dominated by that induced by the one-price cap regulation, given the finding that the one-price-cap regulation is equivalent to unregulated monopoly in terms of expected welfare, unregulated monopoly can be regarded as welfare superior to the price cap regulatory regimes.

8 Extension

In this section, we will consider two extensions of the model and discuss the robustness of the main results obtained in Proposition 5.. First, we relax the assumption that the social planner can set prices at socially efficient level, and suppose that the s/he has no control on pricing although s/he is perfectly informed about the prices chosen by the monopolist. Second, we consider the situation where consumers' perception of environmental harm is not concerned in social welfare. That is, we consider the actual environmental harm rather than the subjective value perceived by consumers.

8.1 Comparison with Second-best

In the socially efficient situation, the social planner is fully informed and can set optimal ex post prices contingent on realised costs. In this extension, we consider the situation where the social planner cannot control the pricing although s/he can observe the ex post prices set by the unregulated monopolist. As one optimality condition (i.e., the social planner can set prices to maximise overall welfare) is not satisfied, this extension concerns a second-best case.

Let $W(\overline{\theta}^m)$ and $W(\underline{\theta}^m)$ represent ex post welfare when $c_g = \overline{c}_g$ and $c_g = \underline{c}_g$ respectively, given the unregulated monopolist's ex post prices, the expected welfare can be calculated as

$$E[W^m(\widehat{\theta})|_{X=0}] = \phi W(\overline{\theta}^m) + (1-\phi)W(\underline{\theta}^m), \qquad \text{if } X = 0,$$
$$E[W^m(\widehat{\theta})|_{X=x}] = (1-\phi)W(\overline{\theta}^m) + \phi W(\underline{\theta}^m) - x, \text{ if } X = x.$$

Then we can calculate the threshold of effort that makes overall welfare indifferent between positive effort and zero effort as:

$$\begin{aligned} \widetilde{x}^{m'} &= (2\phi - 1)\left[W(\underline{\theta}^m) - W(\overline{\theta}^m)\right] \\ &= (2\phi-1)\left(\overline{c}_g - \underline{c}_g\right)\left[1 - \frac{3\left(\underline{c}_g + \overline{c}_g - 2c_b\right)}{8\left(h_b - h_g\right)}\right]. \end{aligned} \tag{15}$$

It follows that

$$\widetilde{x}^s < \widetilde{x}^{m'} < \widetilde{x}^m.$$

The first inequality reveals that, given the ex post prices set by the monopolist, the threshold of effort cost – which makes positive effort indifferent to zero effort in terms of ex ante welfare – is larger than the socially efficient threshold. This implies that, in absence of regulation, the welfare-maximising investment in green electricity exceeds the socially efficient level.

The logic behind is given as follows. From Equation (7) and (15), the range of effort cost feasible for investment in green electricity is determined by the difference between the ex post welfare under different levels of green electricity marginal cost, i.e., the difference between $W(\underline{\theta}^i)$ and $W(\overline{\theta}^i)$, with $i \in \{s, m\}$. When the marginal cost of green electricity reaches at the lower level, the optimal market share of brown electricity is lower than that with higher marginal cost for green electricity. Consequently, in the case with $\underline{c}_g$, the welfare-maximising share of green electricity is relatively higher, and the resulted ex post welfare is higher compared with the situation with $\overline{c}_g$, i.e., $W(\underline{\theta}^i) > W(\overline{\theta}^i)$. When the market share of green/brown electricity is higher/lower than the socially efficient level, the larger/smaller the market share of green/brown electricity is, the larger the difference between $W(\underline{\theta}^i)$ and $W(\overline{\theta}^i)$ becomes. In the unregulated circumstance, due to the monopolist's pricing which allows her/him to extract more rents from consumers, the market share of green electricity is higher than the socially efficient level. As a result, the difference between $W(\underline{\theta}^m)$ and $W(\overline{\theta}^m)$ is larger with monopoly prices than that in the socially efficient situation, i.e., $W(\underline{\theta}^m) - W(\overline{\theta}^m) > W(\underline{\theta}^s) - W(\overline{\theta}^s)$. Hence, the range of effort cost which allows for positive effort is wider than the socially optimal level.

The second inequality means that, in the unregulated situation, the range of effort cost value feasible for the monopolist to choose positive effort is wider than that which allows the social planner to encourage positive effort. This implies that there is space for the unregulated monopolist to over-invest in green electricity. This can also be explained by the more rents the monopolist can extract from a larger green electricity market share.

8.2 Regulation with Actual Environmental Harm

In the analysis above, we concerned consumers' perception regarding the environmental cost of their own electricity consumption – which is a subjective value. However, social welfare is more likely to be objective, thus it is of significance to consider the case where the environmental harm is taken as it is.

Assume that all other conditions maintain unchanged, then ex post welfare can be calculated as

$$\begin{aligned} W_1(\widehat{\theta}) &= \int_0^{\widehat{\theta}} (V - c_b - h_b)\, d\theta + \int_{\widehat{\theta}}^1 (V - c_g - h_g)\, d\theta \\ &= \widehat{\theta}\,(V - c_b - h_b) + (1 - \widehat{\theta})\,(V - c_g - h_g)\,, \end{aligned} \tag{16}$$

with $c_g \in \{\underline{c}_g, \overline{c}_g\}$ and the subscript '1' distinguishing this case from the one analysed in previous sections where consumers' environmental awareness is concerned in overall welfare.[9]

8.2.1 Socially Efficient Benchmark

Given the assumption that the total cost of green electricity is no larger than that of brown electricity – which is provided in expression (3), it is socially efficient for all consumers to choose green electricity. That is, the optimal market share of brown electricity is equal to zero, i.e., $\widehat{\theta}_1 = 0$. Then the optimal ex post welfare can be computed as $W_1^s(c_g) = V - c_g - h_g$. Given the expected welfare and the incentive compatibility constraint which is $E[W_1^s|_{X=x}] \geqslant E[W_1^s|_{X=0}]$, we obtain the threshold of effort cost in this case as

$$\widetilde{x}_1^s = (2\phi - 1)(\overline{c}_g - \underline{c}_g),$$

It equals to the cost savings that can be created by substituting zero effort with positive effort. Note that $\widetilde{x}_1^s > \widetilde{x}^s$, which yields that, compared with the case examined in early sections, the range of effort cost available for positive effort turns out to be wider when consumers' environmental awareness is not considered in welfare calculation. This outcome is certainly true for the reason as follows. As the total cost to provide one unit of green electricity is below that to supply one unit of brown electricity, increases in the market share of green electricity contribute to improve social welfare. Hence, in the case where consumers' environmental perception is not concerned, it is optimal to provide all consumers with green electricity.

[9] As we can prove in the Appendix, given a fixed market share for each type of electricity, the welfare is relatively higher when consumers' environmental perception is concerned, i.e., $W_1(\widehat{\theta}) < W(\widehat{\theta})$.

8.2.2 Unregulated Monopoly

In the unregulated case, the monopolist's decision making is not affected by how consumers' perception is treated in welfare. Hence, the resulted ex post market share remains unchanged, i.e., $\widehat{\theta}_1^m = \widehat{\theta}^m$. Furthermore, the threshold of effort cost calculated based on expected profit is also the same as the previous case, that is, $\widetilde{x}_1^m = \widetilde{x}^m$. Note that $\widetilde{x}_1^m < \widetilde{x}_1^s$, which implies that, compared with the socially optimal case, under-investment in green electricity exists in unregulated monopoly. This outcome contrasts with the over-investment in green electricity in absence of regulation when consumers' perception over environmental cost is concerned in overall welfare.

Given the same ex post market share, the ex post welfare does not change, either, i.e., $W_1^m(\widehat{\theta}) = W^m(\widehat{\theta})$. As we have shown in the socially efficient benchmark, the optimal market share of brown electricity equals to zero. Since there is market for brown electricity in unregulated monopoly, welfare distortion is created in unregulated monopoly, i.e., $W_1^m(\widehat{\theta}) < W_1^s(\widehat{\theta})$.[10] This can be explained by the same reason as in the case we examined in early sections.

In the next we will analyse the two forms of price cap regulatory regime.

8.2.3 One Price Cap Regulation

Similar with the unregulated situation, when a price cap is imposed only on green electricity, the threshold of effort cost is identical to that in the case examined previously, i.e., $\widetilde{x}_1^I = \widetilde{x}^I$. This outcome is reasonable and the logic behind is as follows. The monopolist's pricing choice for brown electricity depends on expected profit rather than expected welfare. Hence, when consumers' environmental perception is not concerned in welfare calculation, the monopolist's pricing decision is not essentially influenced. That is, the price difference between green electricity and brown electricity chosen by the monopolist remains unchanged. Therefore, the induced market share of each type of electricity also remains the same. This leads to an identical difference between expected profits under different levels of effort in both cases. Thus the monopolist's choice of effort does not change. The calculation procedure is quite similar with what we have done previously, thus omitted.

With respect to expected welfare, the regulatory regime imposing a cap only on green electricity also leads to distortion, and the magnitude of distortion equals to the level in the unregulated case, i.e., $E\left[W_1^I\right] = E\left[W_1^m\right] < E\left[W_1^s\right]$. This outcome is straightforward and can be explained by the reasons we discussed in the previous case.

8.2.4 Two Price Cap Regulation

As we can show in the Appendix, in this case expected welfare decreases in the market share of brown electricity. Thus the welfare maximising market share of brown electricity equals to zero, i.e., $\widehat{\theta}_1^{II} = 0$. By substituting this result into the threshold of brown electricity market share – which is identical with that in expression (13), we derive the threshold of effort cost in this case as

$$\widetilde{x}_1^{II} = (2\phi - 1)\left(\bar{c}_g - \underline{c}_g\right) = \widetilde{x}_1^s > \widetilde{x}^{II}.$$

[10] We have proved this in the Appendix.

Obviously, the threshold allowing positive effort arrives at social efficient level, i.e., $\widetilde{x}_1^{II} = \widetilde{x}_1^s$. This outcome is consistent with what we have obtained in the previous case, and can also be explained by the reason demonstrated in early sections – which is the welfare maximising objective of the regulator. It also yields that the range of effort cost which makes positive effort dominate zero effort in terms of expected welfare becomes wider compared with the previous situation, i.e., $\widetilde{x}_1^{II} > \widetilde{x}^{II}$. This outcome is also caused by the cost advantages of green electricity.

One point worth of emphasis is the comparison of effort cost threshold between the two forms of price cap regulation, which is $\widetilde{x}_1^{II} > \widetilde{x}_1^I$. This outcome shows that the two-price-cap regulation provides more incentive for green electricity investment than the one-price-cap regulation does, contrasted with the comparison in the previous case where $\widetilde{x}^{II} < \widetilde{x}^I$. This outcome can also be explained by the cost advantage of green electricity – which stimulates the regulator to push investment in green electricity. As the regulator's control power over prices is stronger under the two-price-cap regulation than under the one-price-cap regulation, the price caps set by the regulator provide more incentive for green electricity development under the two-price-cap regulation.

It is of interest to see that the expected welfare induced by the two-price-cap regulatory regime approaches the socially efficient level, i.e., $E\left[W_1^{II}\right] = E\left[W_1^s\right]$. Details are demonstrated in the Appendix. This outcome varies from what we derive in the previous case where consumers' environmental perception are concerned. The reason is that, in this case, since consumers' perception over environmental harm is not concerned, the regulator is certain about the welfare, and thus can set the price caps at the level which leads to zero market share for brown electricity.

In addition, regarding the comparison of expected welfare between the two forms of regulatory regime, we note that $E\left[W_1^I\right] < E\left[W_1^{II}\right]$ given the same effort exerted by the monopolist, . This outcome supports the conclusion we obtained in Section 8 – which confirms that if the effort cost is extremely high/low that positive effort is undertaken in no/all cases by the monopolist, the two-price-cap regulation results in higher expected welfare than the one-price-cap regulatory regime.

To sum up, if consumers' perceptions over environmental harm is not considered in overall welfare, the threshold of effort cost is ranked as $\widetilde{x}_1^{II} = \widetilde{x}_1^s > \widetilde{x}_1^I = \widetilde{x}_1^m$. The comparison of expected welfare is derived as $E[W_1^{II}] = E[W_1^s] > E[W_1^I] = E[W_1^m]$, and the rank holds despite of the size of effort cost. Calculation details are given in the Appendix.

We summarise the characterisation of the situation in Proposition 6:

Proposition 6 *If individual consumer's perception over the environmental cost of their own electricity consumption is not concerned in overall welfare,*

(i) Compared with the socially efficient benchmark, unregulated monopoly and the one-price-cap regulatory regime lead to under-investment in green electricity, while the two-price-cap regulatory regime induces socially efficient investment.

(ii) From the perspective of expected welfare, unregulated monopoly and the one-price-cap regulatory regime induce social welfare distortion to the same magnitude. By contrast, under the two-price-cap regulatory regime, expected welfare can reach the socially optimal level.

9 Conclusion

With more consumers willing to pay a higher price for green electricity, the space of rent that can be extracted by suppliers from consumers may increase, thus regulatory incentives faced by electricity suppliers may change. This study aims to explore the impacts of consumers' preferences for green electricity on electricity suppliers' investment behaviour in green electricity.

We find that the incentive for investment in green electricity provided by regulation is influenced by both the form of regulation. The regulatory regime which imposes caps on the price of both green electricity and brown electricity leads to socially optimal investment. This can be explained by the regulator's control power over electricity pricing and the regulator's objective which is to maximise ex ante welfare. By contrast, the price cap regulatory regime which imposes a price ceiling only on green electricity induces over-investment in green electricity. This is caused by the monopolist's capability to capture, if the investment is successful, more economic rent from consumers. To be more specific, under this regulatory regime, the monopolist can maximise his/her profit by the pricing of the unregulated price of brown electricity. Hence, the rent the monopolist can extract from consumers under this regulatory regime is higher, and as a consequence, the incentive for investment in green electricity is stronger.

In terms of expected welfare, neither form of price cap regulation can induce expected welfare to achieve at the socially optimal level. The main reasons explaining this include the technological uncertainty embedded in production procedure, the information asymmetry existing between the monopolist and the regulator, and the time when the regulatory sets the price caps. The comparison between the two forms of price cap regulation examined depends on effort cost size. When effort cost is extremely high or low, imposing a ceiling price on both types of electricity leads to higher expected welfare when compared with restricting only the green electricity price. This result makes sense as the regulator can leave more pricing freedom to the monopolist if controlling the price cap of both types of electricity leads to lower welfare. In the intermediate range, which regulatory regime is superior is conditional on effort cost. If the effort cost is relatively high, the two-price-cap regulation dominates; otherwise, the one-price-cap regulation performs better. The logic behind this outcome is the trade off between the gains from positive effort and the costs required by the effort.

When consumers' perception of environmental harm to result from their own electricity consumption is not concerned in welfare, the outcomes change a bit. With respect to the incentive for green electricity investment, under-investment rather than over-investment occurs in unregulated monopoly as well as under the one-price-cap regulatory regime. This is caused by the relatively larger total cost of brown electricity – which determines that it is socially optimal for all consumers to choose green electricity. However, the incentive provided by the two-price-cap regulatory regime remains the same. Regarding expected welfare, distortion is created in unregulated monopoly as well as in the presence of the on-price-cap regulation, and the magnitude of distortion is identical in these two cases. By contrast, the two-price-cap regulation can induce expected welfare to approach the socially efficient level.

References

Clark, C. F., Kotchen, M. J., Moore, M. R., 2003. Internal and external influences on pro-environmental behavior: Participation in a green electricity program. Journal of Environmental Psychology 23 (3), 237 – 246.

Diaz-Rainey, I., Tzavara, D. c., 2012. Financing the decarbonized energy system through green electricity tariffs: A diffusion model of an induced consumer environmental market. Technological Forecasting and Social Change 79 (9), 1693–1704.

Ek, K., Soderholm, P., 2008. Norms and economic motivation in the swedish green electricity market. Ecological Economics 68 (1-2), 169–182.

Gracia, A., Barreiro-Hurle, J., Perez, L., 2012. Can renewable energy be financed with higher electricity prices? evidence from a spanish region. Energy Policy 50, 784–794.

Hotelling, H., 1929. Stability in competition. The Economic Journal 39 (153), pp. 41–57.

Joode, J. d., Jansen, J., van der Welle, A., Scheepers, M., 2009. Increasing penetration of renewable and distributed electricity generation and the need for different network regulation. Energy Policy 37 (8), 2907 – 2915.

Kaenzig, J., Heinzle, S. L., Wuestenhagen, R., 2013. Whatever the customer wants, the customer gets? exploring the gap between consumer preferences and default electricity products in germany. Energy Policy 53 (1), 311–322.

Kotchen, M. J., Moore, M. R., 2007. Private provision of environmental public goods: Household participation in green-electricity programs. Journal of Environmental Economics and Management 53 (1), 1 – 16.

Kucsera, D., Rammerstorfer, M., 2013. Regulation and grid expansion investment with increased penetration of renewable generation. Resource and Energy Economics.

Lester, R. K., Hart, D. M., 2012. Unlocking energy innovation: how America can build a low-cost, low-carbon energy system. MIT Press, Cambridge, Mass.

Menges, R., Schroeder, C., Traub, S., 2005. Altruism, warm glow and the willingness-to-donate for green electricity: An artefactual field experiment. Environmental and Resource Economics 31 (4), 431–458.

Mozumder, P. b., Vasquez, W., Marathe, A. e., 2011. Consumers' preference for renewable energy in the southwest usa. Energy Economics 33 (6), 1119–1126.

Nyborg, K., Howarth, R. B., Brekke, K. A., 2006. Green consumers and public policy: On socially contingent moral motivation. Resource and Energy Economics 28 (4), 351 – 366.

Nykamp, S., Andor, M., Hurink, J. L., 2012. 'standard' incentive regulation hinders the integration of renewable energy generation. Energy Policy 47, 222 – 237.

REN21, 2014. Renewables 2014–global status report. Report, Renewable Energy Policy Network for the 21st Century.

Wiser, R. H., Fowlie, M., Holt, E. A., 2001. Public goods and private interests: understanding non-residential demand for green power. Energy Policy 29 (13), 1085–1097.

Appendix

Proof of Lemma 1

According to the FOCs of ex post profit to the prices, which are

$$\frac{\partial \pi^m(\bar{c}_g)}{\partial P_b^m(\bar{c}_g)} = \frac{2\left[P_g^m(\bar{c}_g) - P_b^m(\bar{c}_g)\right] - (\bar{c}_g - c_b)}{h_b - h_g} = 0, \tag{17}$$

$$\frac{\partial \pi^m(\bar{c}_g)}{\partial P_g^m(\bar{c}_g)} = 1 - \frac{2\left[P_g^m(\bar{c}_g) - P_b^m(\bar{c}_g)\right] - (\bar{c}_g - c_b)}{h_b - h_g} = 0, \tag{18}$$

$$\frac{\partial \pi^m(\underline{c}_g)}{\partial P_b^m(\underline{c}_g)} = \frac{2\left[P_g^m(\underline{c}_g) - P_b^m(\underline{c}_g)\right] - (\underline{c}_g - c_b)}{h_b - h_g} = 0, \tag{19}$$

$$\frac{\partial \pi^m(\underline{c}_g)}{\partial P_g^m(\underline{c}_g)} = 1 - \frac{2\left[P_g^m(\underline{c}_g) - P_b^m(\underline{c}_g)\right] - (\underline{c}_g - c_b)}{h_b - h_g} = 0, \tag{20}$$

we can see that (17) and (18) can not hold at the same time, neither can (19) and (20).

Without loss of generality, we take $c_g = \bar{c}_g$ as a case to demonstrate more details. Illustrate the graphs of $\partial\pi^m(\bar{c}_g)/\partial P_b(\bar{c}_g) = 0$ and $\partial\pi^m(\bar{c}_g)/\partial P_g(\bar{c}_g) = 0$ in Figure 4, then we can see that the potential optimal choice of price difference lies on the line indicated by $P_b^m(\bar{c}_g) = P_g^m(\bar{c}_g) - (\bar{c}_g - c_b)/2$ or $P_b^m(\bar{c}_g) = P_g^m(\bar{c}_g) - (\bar{c}_g - c_b + h_b - h_g)/2$. Since the two lines do not intersect, no interior solution can be achieved. In the next we will look at corner solutions. As the associated profits on line $P_b^m(\bar{c}_g) = P_g^m(\bar{c}_g) - (\bar{c}_g - c_b)/2$ is always higher than that with $P_b^m(\bar{c}_g) = P_g^m(\bar{c}_g) - (\bar{c}_g - c_b + h_b - h_g)/2$, we can observe that the monopolist's profit maximises at $P_b^m(\bar{c}_g) = P_g^m(\bar{c}_g) - (\bar{c}_g - c_b)/2$. The proof is given below.

To distinguish the two sets of alternative prices, we use the subscript 1 and 2, i.e.,

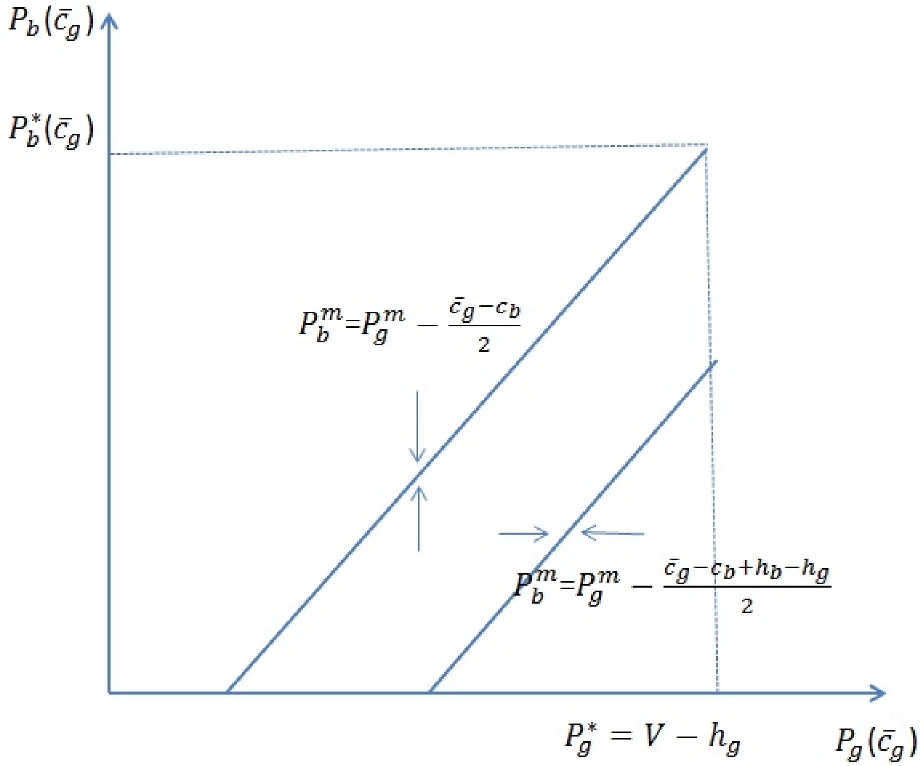
$$P_{g1}^{m*} - P_{b1}^{m*}(c_g) = \frac{c_g - c_b}{2},\; P_{g2}^{m*} - P_{b2}^{m*} = \frac{c_g - c_b + h_b - h_g}{2}.$$

Denote the associated profit with π_1^{m*} and π_2^{m*} respectively, then if $P_{g1}^{m*} = P_{g2}^{m*}$, we have

$$\begin{aligned}\pi_1^{m*} - \pi_2^{m*} &= \frac{(c_g - c_b)^2}{4(h_b - h_g)} + P_{g1}^{m*} - c_g - \left[\frac{(c_g - c_b)^2}{4(h_b - h_g)} - \frac{(h_b - h_g)}{4} + P_{g2}^{m*} - c_g\right] \\ &= \frac{h_b - h_g}{4} > 0.\end{aligned}$$

Hence, the optimal price gap between the two types of electricity for the unregulated monopolist is $P_g^* - P_{b^*} = V - h_g - (c_g - c_b)/2$.

Figure 4: Optimal Pricing by the Unregulated Monopolist



According to the assumption of fully covered market, the highest price the monopolist can charge for green electricity is $P_g(\overline{c}_g) = V - h_g$. Given $\partial\pi^m(\overline{c}_g)/\partial P_b^m(\overline{c}_g) = 0$, we have $\partial\pi^m(\overline{c}_g)/\partial P_g^m(\overline{c}_g) = 1 > 0$, then we can find that the monopolist's optimal choice for green electricity is

$$P_g^{m*}(\overline{c}_g) = V - h_g.$$

Accordingly, the optimal price of brown electricity is

$$P_b^{m*}(\overline{c}_g) = P_g^{m*}(\overline{c}_g) - \frac{\overline{c}_g - c_b}{2} = V - h_g - \frac{\overline{c}_g - c_b}{2}.$$

Proof of Proposition 4

We discuss three distinct cases contingent on the relationship between $\widehat{\theta}^{II}$, $\widehat{\theta}^{II}_{|X=0}$ and $\widehat{\theta}^{II}_{|X=x}$, i.e., $\widehat{\theta}^{II}_{|X=x} \leqslant \widehat{\theta}^{II} \leqslant \widehat{\theta}^{II}_{|X=0}$, $\widehat{\theta}^{II} < \widehat{\theta}^{II}_{|X=x}$ and $\widehat{\theta}^{II} > \widehat{\theta}^{II}_{|X=0}$.

First case: $\widehat{\theta}^{II}_{|X=x} \leqslant \widehat{\theta}^{II} \leqslant \widehat{\theta}^{II}_{|X=0}$

In the first case, we consider the interior solution. Substitute the value of $\widehat{\theta}^{II}_{|X=x}$ and $\widehat{\theta}^{II}_{|X=0}$ respectively into expression (13), we obtain that

$$\widetilde{x}_1 = x(\widehat{\theta}^{II}_{|X=0}) = (2\phi - 1)\left(\overline{c}_g - \underline{c}_g\right)\left[1 - \frac{\phi\overline{c}_g + (1-\phi)\underline{c}_g - c_b}{h_b - h_g}\right]$$

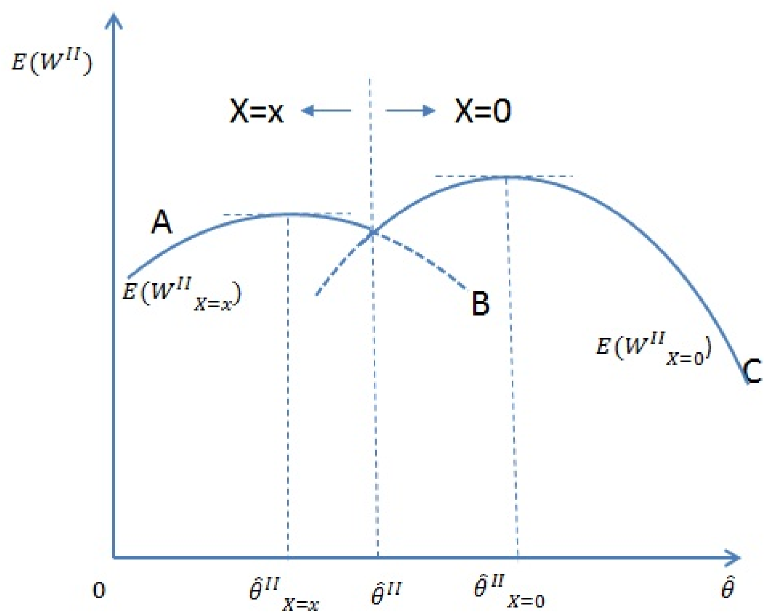
$$\text{and} \;\; \widetilde{x}_2 = x(\widehat{\theta}^{II}_{|X=x}) = (2\phi - 1)\left(\overline{c}_g - \underline{c}_g\right)\left[1 - \frac{(1-\phi)\,\overline{c}_g + \phi \underline{c}_g - c_b}{h_b - h_g}\right].$$

Given $\widehat{\theta}^{II}_{|X=x} \leqslant \widehat{\theta}^{II} \leqslant \widehat{\theta}^{II}_{|X=0}$, it can be seen that the range of effort cost examined in this case is $\widetilde{x}_1 \leqslant x \leqslant \widetilde{x}_2$. The the graphs of expected social welfare with different levels of effort can be shown in Figure 5.[11] To derive the threshold of effort cost we need to compare $E[W^{II}(\widehat{\theta})_{|X=x}]$ and $E[W^{II}(\widehat{\theta})_{|X=0}]$, and obtain it as

$$\widetilde{x}^{II} = (2\phi - 1)\left(\overline{c}_g - \underline{c}_g\right)\left[1 - \frac{\overline{c}_g + \underline{c}_g - 2c_b}{2\,(h_b - h_g)}\right].$$

Note that $\widetilde{x}^{II}$ locates in the interval in examination.[12]

Figure 5: Interior Solution



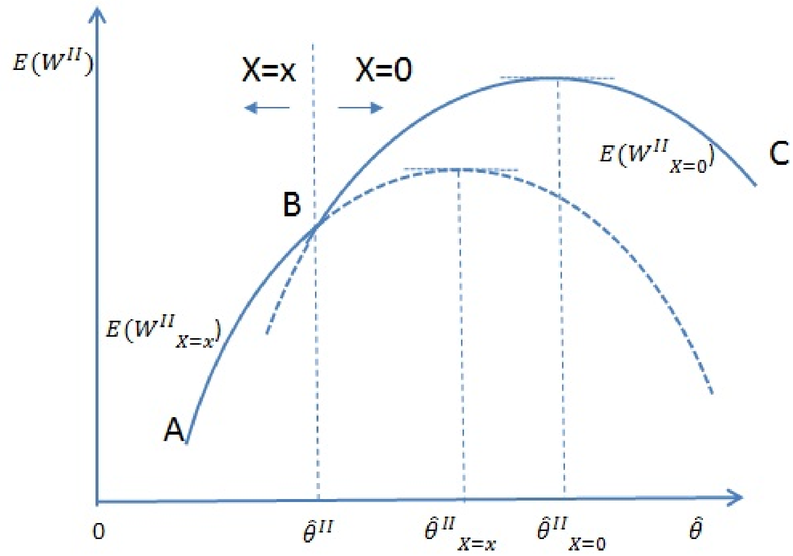
Second case: $\widehat{\theta}^{II} \leqslant \widehat{\theta}^{II}_{|X=x}$

Similarly, according to the relationship between effort cost and market share in expression (13), we obtain the range of effort cost discussed in this case as $x > \widetilde{x}_2$. Given this, the reduction of welfare induced by positive effort overweights the gains from it, thus zero effort is more preferable. Since $E[W^{II}(\widehat{\theta})_{|X=0}]$ is always higher than $E[W^{II}(\widehat{\theta})_{|X=x}]$, it is not necessary to consider the case with $\widehat{\theta}^{II} \leqslant \widehat{\theta}^{II}_{|X=x}$ to calculate the threshold of effort cost.

[11] Note that as $\widehat{\theta}^{II}_{|X=0} > \widehat{\theta}^{II}_{|X=x}$, the maximum of $E[W^{II}(\widehat{\theta})_{|X=0}]$ locates on the right of $E[W^{II}(\widehat{\theta})_{|X=x}]$.

[12] As $c_b \leqslant \underline{c}_g \leqslant \overline{c}_g$, given $\phi > \frac{1}{2}$, we have $\phi\overline{c}_g + (1-\phi)\,\underline{c}_g - c_b \geqslant \frac{\overline{c}_g + \underline{c}_g - 2c_b}{2} \geqslant (1-\phi)\,\overline{c}_g + \phi\underline{c}_g - c_b$.

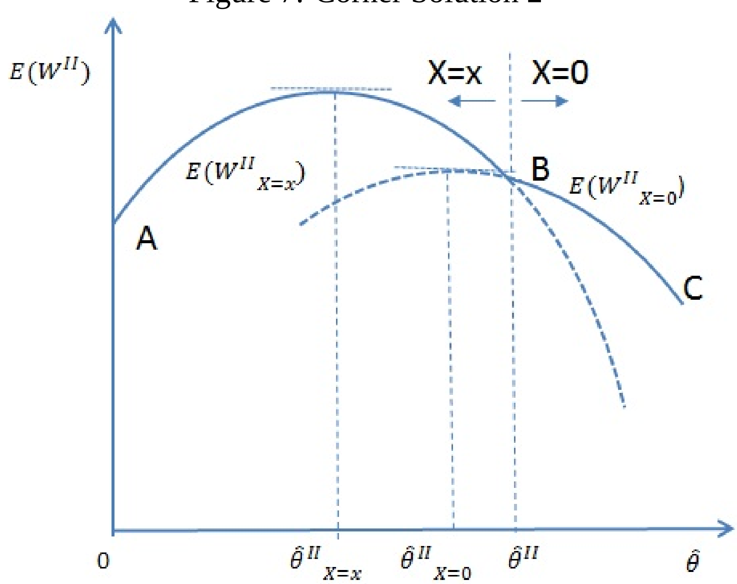
Figure 6: Corner Solution 1



Third case: $\widehat{\theta}^{II} > \widehat{\theta}^{II}_{|X=0}$

Likewise, in the third case, we can derive that the range of effort cost as $x < \widetilde{x}_1$. Similar with the case analysed immediately above, in the this case, positive effort is favorable, and $E[W^{II}(\widehat{\theta})_{|X=x}]$ exceeds rather than equate to $E[W^{II}(\widehat{\theta})_{|X=0}]$ for all $x < \widetilde{x}_1$, as shown Figure 7. This implies that we do not need to consider the case with $\widehat{\theta}^{II} > \widehat{\theta}^{II}_{|X=0}$ either for the calculation of effort cost.

Figure 7: Corner Solution 2



In short, $\widehat{\theta}^{II}_{|X=x} \leqslant \widehat{\theta}^{II} \leqslant \widehat{\theta}^{II}_{|X=0}$ always holds in the range concerned.

Proof of Proposition 5

Given the associated expression of expected social welfare in different models, which are calculated as

$$E[W^s|_{X=0}] = V - \frac{h_g}{2} - \left[\phi\bar{c}_g + (1-\phi)\underline{c}_g\right] + \frac{\phi(\bar{c}_g - c_b)^2 + (1-\phi)(\underline{c}_g - c_b)^2}{2(h_b - h_g)},$$
$$E[W|_{X=x}] = V - \frac{h_g}{2} - \left[(1-\phi)\underline{c}_g + \phi\bar{c}_g\right] + \frac{\phi(\underline{c}_g - c_b)^2 + (1-\phi)(\bar{c}_g - c_b)^2}{2(h_b - h_g)} - x,$$

$$E[W^m|_{X=0}] = \frac{3\left[\phi(\bar{c}_g - c_b)^2 + (1-\phi)\left(\underline{c}_g - c_b\right)^2\right]}{8(h_b - h_g)} - \left[\phi\bar{c}_g + (1-\phi)\underline{c}_g\right] + V - \frac{h_g}{2},$$
$$E[W^m|_{X=x}] = \frac{3\left[(1-\phi)(\bar{c}_g - c_b)^2 + \phi\left(\underline{c}_g - c_b\right)^2\right]}{8(h_b - h_g)} - \left[(1-\phi)\bar{c}_g + \phi\underline{c}_g\right] + V - \frac{h_g}{2} - x,$$

$$E[W^I|_{X=0}] = \frac{3\left[\phi(\bar{c}_g - c_b)^2 + (1-\phi)(\underline{c}_g - c_b)^2\right]}{8(h_b - h_g)} - \left[\phi\bar{c}_g + (1-\phi)\underline{c}_g\right] + V - \frac{h_g}{2},$$
$$E[W^I|_{X=x}] = \frac{3\left[(1-\phi)(\bar{c}_g - c_b)^2 + \phi(\underline{c}_g - c_b)^2\right]}{8(h_b - h_g)} - \left[(1-\phi)\bar{c}_g + \phi\underline{c}_g\right] + V - \frac{h_g}{2} - x,$$

$$E[W^{II}(\widehat{\theta})|_{X=0}] = \frac{\left[\phi\bar{c}_g + (1-\phi)\underline{c}_g - c_b\right]^2}{2(h_b - h_g)} + V - \frac{h_g}{2} - \left[\phi\bar{c}_g + (1-\phi)\underline{c}_g\right],$$
$$E[W^{II}(\widehat{\theta})|_{X=x}] = \frac{\left[(1-\phi)\bar{c}_g + \phi\underline{c}_g - c_b\right]^2}{2(h_b - h_g)} + V - \frac{h_g}{2} - \left[(1-\phi)\bar{c}_g + \phi\underline{c}_g\right] - x,$$

to do the comparison we need to discuss different cases based on the ranking of effort cost threshold value, which is $\widetilde{x}^s = \widetilde{x}^{II} \leqslant \widetilde{x}^I = \widetilde{x}^m$.

Case 1: $x \geqslant \widetilde{x}^I = \widetilde{x}^m$

In this case, effort cost is so high that no effort is carried on in any model and we need to compare $E[W^{s*}]|_{X=0}$, $E[W^m|_{X=0}]$, $E[W^I|_{X=0}]$ and $E[W^{II}|_{X=0}]$. It is obvious that

$$E[W^s|_{X=0}] > E[W^m|_{X=0}] = E[W^I|_{X=0}]$$

and

$$\begin{aligned}
&E[W^s|_{X=0}] - E[W^{II}|_{X=0}] \\
&= \frac{\phi(\bar{c}_g - c_b)^2 + (1-\phi)(\underline{c}_g - c_b)^2}{2(h_b - h_g)} - \frac{\left[\phi(\bar{c}_g - c_b) + (1-\phi)(\underline{c}_g - c_b)\right]^2}{2(h_b - h_g)} \\
&= \frac{\phi(1-\phi)(\bar{c}_g - \underline{c}_g)^2}{2(h_b - h_g)} > 0 \Rightarrow E[W^s]|_{X=0} > E[W^{II}|_{X=0}].
\end{aligned}$$

With respect to the comparison between $E[W^I|_{X=0}]$ and $E[W^{II}|_{X=0}]$, as

$$E[W^I|_{X=0}]-E[W^{II}|_{X=0}]$$
$$=-\frac{\left(\underline{c}_g-c_b\right)^2-\phi\left(\overline{c}_g-\underline{c}_g\right)\left(2c_b+3\overline{c}_g-5\underline{c}_g\right)+4\phi^2\left(\overline{c}_g-\underline{c}_g\right)^2}{8\left(h_b-h_g\right)},$$

we will demonstrate the comparison as follows.

Denote $y=4\phi^2(\overline{c}_g-\underline{c}_g)^2-\phi(\overline{c}_g-\underline{c}_g)(2c_b+3\overline{c}_g-5\underline{c}_g)+\left(\underline{c}_g-c_b\right)^2$, we can see that if $\overline{c}_g-3\underline{c}_g+2c_b\geqslant 0$, and $\alpha_1<\phi<\alpha_2$, with $\alpha_1=[5\underline{c}_g-2c_b-3\overline{c}_g-\sqrt{3}\sqrt{(3\overline{c}_g-\underline{c}_g-2c_b)(\overline{c}_g-3\underline{c}_g+2c_b)}]/8(\overline{c}_g-\underline{c}_g)$ and $\alpha_2=[5\underline{c}_g-2c_b-3\overline{c}_g+\sqrt{3}\sqrt{(3\overline{c}_g-\underline{c}_g-2c_b)(\overline{c}_g-3\underline{c}_g+2c_b)}]/8(\overline{c}_g-\underline{c}_g)$, $y<0$, i.e., $E[W^I|_{X=0}]>E[W^{II}|_{X=0}]$. Otherwise, $E[W^{II}|_{X=0}]\geqslant E[W^I|_{X=0}]$.

However, as

$$\alpha_2=\frac{5\underline{c}_g-2c_b-3\overline{c}_g+\sqrt{3}\sqrt{\left(3\overline{c}_g-\underline{c}_g-2c_b\right)\left(\overline{c}_g-3\underline{c}_g+2c_b\right)}}{8\left(\overline{c}_g-\underline{c}_g\right)}$$
$$<\frac{5\underline{c}_g-2c_b-3\overline{c}_g+\sqrt{3}\sqrt{3\left(\overline{c}_g-c_b\right)\left(\overline{c}_g-c_b\right)}}{8\left(\overline{c}_g-\underline{c}_g\right)}=\frac{5(\underline{c}_g-c_b)}{8\left(\overline{c}_g-\underline{c}_g\right)}\leqslant\frac{5\left(\overline{c}_g-\underline{c}_g\right)}{16\left(\overline{c}_g-\underline{c}_g\right)}<\frac{1}{2},$$

we can see that in this case the rank of social welfare is given as

$$E\left[W^s|_{X=0}\right]>E[W^{II}|_{X=0}]\geqslant E\left[W^m|_{X=0}\right]=E[W^I|_{X=0}].$$

Case 2: $\widetilde{x}^s=\widetilde{x}^{II}\leqslant x<\widetilde{x}^I=\widetilde{x}^m$

In this case, positive effort is undertaken under unregulated monopoly or under the one-price-cap regulatory mechanism, then we need to compare $E\left[W^s|_{X=0}\right]$, $E\left[W^m|_{X=x}\right]$, $E[W^I|_{X=x}]$ and $E[W^{II}|_{X=0}]$. As

$$E\left[W^s|_{X=0}\right]-E[W^I|_{X=x}]$$
$$=\left(1-2\phi\right)\left(\overline{c}_g-\underline{c}_g\right)+\frac{\left(7\phi-3\right)\left(\overline{c}_g-c_b\right)^2-\left(7\phi-4\right)\left(\underline{c}_g-c_b\right)^2}{8(h_b-h_g)}+x$$

Given $x\geqslant\widetilde{x}^{II}=\left(2\phi-1\right)\left(\overline{c}_g-\underline{c}_g\right)\left[1-\frac{\overline{c}_g+\underline{c}_g-2c_b}{2(h_b-h_g)}\right]$, we have

$$E\left[W^s|_{X=0}\right]-E[W^I|_{X=x}]$$
$$\geqslant\left(1-2\phi\right)\left(\overline{c}_g-\underline{c}_g\right)+\frac{\left(7\phi-3\right)\left(\overline{c}_g-c_b\right)^2-\left(7\phi-4\right)\left(\underline{c}_g-c_b\right)^2}{8(h_b-h_g)}+\widetilde{x}^{pc2}$$
$$=\frac{\left(1-\phi\right)\left(\overline{c}_g-\underline{c}_g\right)\left(\overline{c}_g+\underline{c}_g-2c_b\right)+\left(\underline{c}_g-c_b\right)^2}{8(h_b-h_g)}>0,$$

therefore,

$$E\left[W^s|_{X=0}\right]>E[W^I|_{X=x}].$$

Regarding $E[W^I|_{X=x}]$ and $E[W^{II}|_{X=0}]$,we have

$$E[W^I|_{X=x}] - E[W^{II}|_{X=0}]$$
$$= \frac{3\left[(1-\phi)(\bar{c}_g - c_b)^2 + \phi(\underline{c}_g - c_b)^2\right]}{8(h_b - h_g)} - \frac{\left[\phi\bar{c}_g + (1-\phi)\underline{c}_g - c_b\right]^2}{2(h_b - h_g)} - x + (2\phi - 1)\left(\bar{c}_g - \underline{c}_g\right).$$

Denote $\widehat{x} = \frac{3\left[(1-\phi)(\bar{c}_g - c_b)^2 + \phi(\underline{c}_g - c_b)^2\right]}{8\left(h_b - h_g\right)} - \frac{\left[\phi\bar{c}_g + (1-\phi)\underline{c}_g - c_b\right]^2}{2\left(h_b - h_g\right)} + (2\phi - 1)\left(\bar{c}_g - \underline{c}_g\right)$, we have

$$E[W^I|_{X=x}] \geqslant E[W^{II}|_{X=0}], \text{ if } x \leqslant \widehat{x},$$
$$E[W^I|_{X=x}] < E[W^{II}|_{X=0}], \text{ if } x > \widehat{x}.$$

As a result, in this case, the outcome can be demonstrated in the following table:

Effort Cost	Welfare Comparison
$\widetilde{x}^{II} \leqslant x \leqslant \widehat{x}$	$E\left[W^s|_{X=0}\right] > E\left[W^m|_{X=x}\right] = E[W^I|_{X=x}] \geqslant E[W^{II}|_{X=0}]$
$\widehat{x} < x < \widetilde{x}^I$	$E\left[W^s|_{X=0}\right] > E[W^{II}|_{X=0}] \geqslant E\left[W^m|_{X=x}\right] = E[W^I|_{X=x}]$

Case 3: $x < \widetilde{x}^s$

In this case, effort cost is sufficiently low that positive effort is chosen by the monopolist in all the models in question, and what we need to compare is $E\left[W^s|_{X=x}\right]$, $E\left[W^m|_{X=x}\right]$, $E[W^I|_{X=x}]$ and $E[W^{II}|_{X=x}]$.

From the analysis above, we know that

$$E\left[W^s|_{X=x}\right] > E[W^{II}|_{X=x}] \text{ and } E\left[W^s|_{X=0}\right] \geqslant E\left[W^m\right]|_{X=x} = E[W^I|_{X=x}].$$

$$\text{As } E\left[W^s|_{X=x}\right] - E\left[W^s|_{X=0}\right] = (2\phi - 1)\left(\bar{c}_g - \underline{c}_g\right)\left[1 - \frac{\bar{c}_g + \underline{c}_g - 2c_b)}{2(h_b - h_g)}\right] - x,$$

given $x < \widetilde{x}^s = (2\phi - 1)\left(\bar{c}_g - \underline{c}_g\right)\left[1 - \frac{\bar{c}_g + \underline{c}_g - 2c_b}{2(h_b - h_g)}\right]$, we obtain that $E\left[W^s|_{X=x}\right] > E\left[W^s|_{X=0}\right]$.

Similar with the first case, we show the comparison as follows:

$$E\left[W^s|_{X=x}\right] > E[W^{II}|_{X=x}] \geqslant E\left[W^m|_{X=x}\right] = E[W^I|_{X=x}].$$

Finally, the comparison of expected welfare is summarised in Table 2.

Proof of Proposition 6

Given the ex post welfare in the two cases which are respectively

$$W_1(\widehat{\theta}) = \widehat{\theta}\,(V - c_b - h_b) + (1 - \widehat{\theta})\,(V - c_g - h_g)$$
$$W(\widehat{\theta}) = -\frac{(h_b - h_g)\widehat{\theta}^2}{2} + (c_g - c_b)\widehat{\theta} + V - c_g - \frac{h_g}{2},$$

we can obtain that $W_1(\widehat{\theta})$ equals $W(\widehat{\theta})$ at $\widehat{\theta} = -1$. Hence, it can be concluded that welfare considering consumers' environmental perception exceeds the level that does not concern it, i.e., $W_1(\widehat{\theta}) < W(\widehat{\theta})$.

Two Price Cap Regulation

As we did in Section 7, in this case the threshold of market share of brown electricity is calculated as:

$$\widehat{\theta}_1^{II} = 1 - \frac{x}{(2\phi - 1)\left(\overline{c}_g - \underline{c}_g\right)}. \tag{21}$$

Given the expected welfare as a function of effort

$$\begin{aligned} E[W_1^{II}(\widehat{\theta})_{|X=0}] &= (1-\phi)\left[\widehat{\theta}\,(V - c_b - h_b) + (1-\widehat{\theta})(V - \underline{c}_g - h_g)\right] \\ &\quad + \phi\left[\widehat{\theta}\,(V - c_b - h_b) + (1-\widehat{\theta})\,(V - \overline{c}_g - h_g)\right], \ \text{ if } \theta > \widehat{\theta}_1^{II} \end{aligned}$$

$$\begin{aligned} E[W_1^{II}(\widehat{\theta})_{|X=x}] &= \phi\left[\widehat{\theta}\,(V - c_b - h_b) + (1-\widehat{\theta})\left(V - \underline{c}_g - h_g\right)\right] \\ &\quad + (1-\phi)\left[\widehat{\theta}\,(V - c_b - h_b) + (1-\widehat{\theta})\,(V - \overline{c}_g - h_g)\right] - x, \ \text{ if } \theta \leqslant \widehat{\theta}_1^{II} \end{aligned}$$

we derive the FOC with respect to the market share of brown electricity as follows:

$$\frac{\partial E[W_1^{II}(\widehat{\theta})]}{\partial \widehat{\theta}} = E\left(c_g\right) - c_b - (h_b - h_g) \leqslant 0,$$

where $E\left(c_g\right)$ denotes the expected marginal cost of green electricity – which is contingent on the effort undertaken by the monopolist. It yields that the lower the market share of brown electricity is, the higher the expected welfare becomes. Given $\widetilde{\theta}_1 = (P_{g1} - P_{b1})/(h_b - h_g) \geqslant 0$, we derive that $\widehat{\theta}_1^{II} = 0$. By substituting this into the threshold of brown electricity market share given in expression (21), we can see that the threshold value of effort cost is

$$\widetilde{x}_1^{II} = (2\phi - 1)\left(\overline{c}_g - \underline{c}_g\right) > \widetilde{x}^{II}$$

Accordingly, the expected welfare are computed as

$$\begin{cases} E[W_{1|X=0}^{II}] = V - h_g - (1-\phi)\,\underline{c}_g - \phi\overline{c}_g, & X = 0 \\ E[W_{1|X=x}^{II}] = V - h_g - \phi\underline{c}_g - (1-\phi)\,\overline{c}_g - x, & X = x \end{cases}.$$

It is apparent the expected welfare induced by the two-price-cap regulation reaches the socially optimal level. This is because that the price caps set by the regulator incentivse all consumers choose green electricity, and consequently, the market share of brown electricity is zero.

Welfare Comparison

Expected welfare in these cases is calculated as:

$$\begin{aligned} E[W_1^s\,|_{X=0}] &= V - h_g - \phi\overline{c}_g - (1-\phi)\underline{c}_g, && \text{if } X = 0, \\ E[W_1^s\,|_{X=x}] &= V - h_g - (1-\phi)\overline{c}_g - \phi\underline{c}_g - x, && \text{if } X = x. \end{aligned}$$

$$E[W_1^m|_{X=0}] = \frac{\phi\,(\bar{c}_g - c_b)^2 + (1-\phi)\,(\underline{c}_g - c_b)^2}{2\,(h_b - h_g)} - \frac{3[\phi\bar{c}_g + (1-\phi)\underline{c}_g]}{2} + \frac{c_b}{2} + V - h_g, \qquad \text{if } \; X = 0,$$
$$E[W_1^m|_{X=x}] = \frac{(1-\phi)\,(\bar{c}_g - c_b)^2 + \phi\,(\underline{c}_g - c_b)^2}{2\,(h_b - h_g)} - \frac{3[(1-\phi)\bar{c}_g + \phi\underline{c}_g]}{2} + \frac{c_b}{2} + V - h_g - x, \;\; \text{if } \; X = x.$$

$$E[W^I_{1|X=0}] = \frac{\phi\,(\bar{c}_g - c_b)^2 + (1-\phi)\,(\underline{c}_g - c_b)^2}{2\,(h_b - h_g)} - \frac{3\left[\phi\bar{c}_g + (1-\phi)\,\underline{c}_g\right]}{2} + \frac{c_b}{2} + V - h_g,$$
$$E[W^I_{1|X=x}] = \frac{(1-\phi)\,(\bar{c}_g - c_b)^2 + \phi\,(\underline{c}_g - c_b)^2}{2\,(h_b - h_g)} - \frac{3\left[\phi\underline{c}_g + (1-\phi)\,\bar{c}_g\right]}{2} + \frac{c_b}{2} + V - h_g - x.$$

We do the comparison on the basis of effort cost size. As the threshold of effort is ranked as $\widetilde{x}_1^{II} = \widetilde{x}_1^s > \widetilde{x}_1^I = \widetilde{x}_1^m$, we will discuss three different cases as we do in early sections, i.e., $x \geqslant \widetilde{x}_1^{II} = \widetilde{x}_1^s$, $\widetilde{x}_1^I = \widetilde{x}_1^m \leqslant x < \widetilde{x}_1^{II} = \widetilde{x}_1^s$, and $x < \widetilde{x}_1^I = \widetilde{x}_1^m$.

As

$$W_1^s(\widehat{\theta}) = V - c_g - h_g,\; W_1^m(\widehat{\theta}) = \frac{(c_g - c_b)^2}{2\,(h_b - h_g)} - \frac{3c_g}{2} + \frac{c_b}{2} + V - h_g,$$

we have

$$W_1^s(\widehat{\theta}) - W_1^m(\widehat{\theta}) = V - c_g - h_g - \frac{(c_g - c_b)^2}{2\,(h_b - h_g)} + \frac{3c_g}{2} - \frac{c_b}{2} - V + h_g$$
$$= \frac{c_g - c_b}{2} - \frac{(c_g - c_b)^2}{2\,(h_b - h_g)} = \frac{(c_g - c_b)\,(h_b + c_b - h_g - c_g)}{2} > 0.$$

Therefore, in the case where $x \geqslant \widetilde{x}_1^{II} = \widetilde{x}_1^s$,the comparison of expected welfare is presented as

$$E[W^{II}_{1|X=0}] = E[W^s_{1|X=0}] > E[W^I_{1|X=0}] = E[W^m_{1|X=0}].$$

By contrast, in the case where $x < \widetilde{x}_1^I = \widetilde{x}_1^m$, the comparison of expected welfare is given as

$$E[W^{II}_{1|X=x}] = E[W^s_{1|X=x}] > E[W^I_{1|X=x}] = E[W^m_{1|X=x}].$$

In the intermediated case where $\widetilde{x}_1^I = \widetilde{x}_1^m \leqslant x < \widetilde{x}_1^{II} = \widetilde{x}_1^s$, positive effort is undertaken in the socially efficient benchmark and under the two-price-cap regulatory regime, whereas zero effort is chosen by the monopolist in the unregulated monopoly and the one-price-cap regulation. Thus we just need to compare $E[W^s_{1|X=x}]$ and $E[W^m_{1|X=0}]$. As $E[W^s_{1|X=0}] > E[W^m_{1|X=0}]$ and $E[W^s_{1|X=x}] > E[W^s_{1|X=0}]$, we can directly have that

$$E[W^{II}_{1|X=x}] = E[W^s_{1|X=x}] > E[W^I_{1|X=0}] = E[W^m_{1|X=0}].$$