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An analysis of a feed-in tariff in Taiwan's electricity market

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ABSTRACT

For the earth's sustainable development, the proportion of power generated by renewable resources has risen, whereas the proportion of power generated by fossil fuel has fallen. Many small-sized power plants that generate power through renewable resources sell power to large-size traditional power plants that generate power using fossil fuel. In this study we employ the Stackelberg framework to analyze the feed-in tariff (FIT) regime in which a traditional power plant purchases power from a small-size green power plant. We conclude that such a FIT regime causes social welfare to decrease when the marginal cost of the public power plant decreases and the public power plant purchases too much renewable power.

1. Introduction

Economic growth brings about a rapid increase in electricity consumption. However, traditional fossil fuel power plants emit a lot of greenhouse gases that cause global warming and climate change. For the earth's sustainable development, many countries' governments are actively developing green power generated by renewable resources. Generation expansion planning (GEP) determines which kind of power plants should be constructed and when they should start to operate [25]. In recent years, because of energy shortages, many governments have encouraged private enterprises to build independent power plants [24]. Independent power producers (IPPs) can sell the electricity power to the traditional fossil fuel power plant. It is proved that IPPs will generate more profits in a cooperative game than in a non-cooperative game [15]. In other words, IPPs usually do not generate profits only by using their excess generation capacity, but by using their full generation capacity.

Since the Kyoto Protocol has asked member states to decrease their greenhouse gas emissions for the earth's sustainable development, the traditional generation method using fossil fuel is now viewed in an environmentally unfriendly way. On the other hand, the green power generated by using renewable resources such as solar and wind is taken to be environmentally friendly energy. Ameli et al. [3] study the optimal proportion of green power in overall electricity consumption and the economic advantage of green power. They present some models in which the power plants have different production cost functions to discuss the problem of augmenting power networks with solar power plants and find their optimal production point. Many countries have started to emphasize the generation of green power, such as the United Kingdom's (UK) target for the proportion of green power in overall electricity consumption to be 15% in 2015 and rise to 20% in 2020 [22]. The European Union set the target of green power supply to be 12% in 2010 [18]. In 2010, the European Commission published the Communication "Energy 2020 – A strategy for competitive, sustainable and secure energy", which mentions that the European Union will promote the target of the renewable energy supply to 20% in 2020 by introducing a legislative framework design. Some studies also discuss the operational risk of power generation by using renewable energy [13].

In order to encourage the adoption of renewable energy technology, many countries have established the feed-in tariff (FIT) regime in which the government asks the electricity utility companies to purchase the power at the price decided by a long-term contract. The FIT regime has been adopted by 20 countries in the European Union. For example, France offers a FIT price of 8.2 €cents/kW h for wind electricity power for the first 10 yr of operation. Portugal provides a FIT price for hydro-power ranging from 5.91 €cents/kW h (30 MW in capacity) to 7.04 €cents/kWh (10 MW in capacity). In Germany, the FIT price for a new installation has been cut by 1% for wind power plants and by 10% for photovoltaic systems in order to encourage technology improvements to the plant. In Ireland, since there are favorable wind conditions, the FIT price of wind electricity power ranges from a low of 5.6 €cents/kW h to 5.8 €cents/kW h. Taiwan's Legislative Yuan in 2009 passed the Renewable Energy Development Act as a basis for Taiwan's FIT regime. The most important issue in regard to Taiwan's FIT regime is to design a reasonable FIT price. In 2011, the Taiwan government announced a cut in the FIT price with

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respect to solar energy generators, because of the falling cost of installation equipment [5,6]. Similar actions such as reducing energy subsidies and cutting the FIT price have also been initiated in Germany, Greece, the UK, and Switzerland [21].

The model structure in this paper depends on the real story in Taiwan's electricity market. Taiwan Power Company (Taipower) is the only domestic public electricity company whose main power source is fossil fuels. There are many private electricity companies that use renewable resources to generate power. Since Taipower is a public electricity company, it not only needs to set a suitable power price for maximizing social welfare, but it must also buy the green power according to the FIT regime in order to encourage the renewable energy industry. Since the electricity market is a typical oligopoly competition, game theory is widely applied to the topic, especially in auctions for the purchase and sale of electricity [4,10,11,14,17]. Some studies on the electricity market have focused on generation expansion planning [8], transmission constrained networks [9], and power plant behavior in the short term [20].

The basic concept of the Stackelberg model is that at least one of the players in the market is able to pre-commit itself to a particular level of supply before other players have fixed their level of supply. The other firms observe the leader's supply decision and respond with their output decision. The players able to initially pre-commit their level of output are called the market leaders and the other players are the followers [19]. In this study, the renewable power plant is promised that all its power output will be purchased by the public power plant in the FIT regime. Even if the renewable power output, such as wind and solar production, is non-manageable, all renewable power output produced by the renewable power plant will be purchased by the public power plant. In other words, the renewable power plant firstly pre-commits an output level that depends on the natural condition and that this output level will be purchased by the public power plant, and later the public power plant decides its output level. In Taiwan's electricity market case, Taipower has an obligation to purchase all green power generated by private power companies, and thus Taipower is a Stackelberg follower and many private power companies are Stackelberg leaders.

The emergence of a green power plant causes the traditional monopoly of the electricity market structure to change. Ackermann [1] defines distributed generation as an electric power source that directly connects to a distribution network or on the customer side of the meter. The author analyzes the effect of distributed generation on market power by applying the cases of combined heat & power and wind power in western Denmark. He concludes that the distributed generation can reduce a power plant's market power. Peças Lopes et al. [18] mention that the integration forces of distributed generation include the environment, regulatory issues, and commerce. They also conclude that distributed generation will benefit the power plant located in a large industrial area or residential area since the power plant does not invest too much in infrastructure.

The concept of distributed generation is not to replace the current power system, but to integrate it into the system operation. Strbac et al. [22] assess the costs and benefits of wind generation in the UK electricity system and conclude that the system will be able to accommodate a significant increase in wind power generation with relatively small increases in overall costs of supply. Akhmatov and Knudsen [2] point out that although there is a large penetration of distributed generation in the Danish power system, the central large-size power plants still control the voltage and frequency of the grid. However, the trend is changing and large wind farms are playing an important role in supporting the services.

Some distributed generation business models have been discussed by Gordijn and Akkermans [12]. They survey cases in various countries, including Spain, Norway, the UK, and The Netherlands, and highlight some novel ideas. For example, the small-size local producer business model for renewable distributed generation is profitable. In many countries the reserve power generation capacity is decreasing due to deregulation, creating new opportunities for distributed generation.

The remainder of this paper is organized as follows. Section 2 shows the model set-up. Section 3 presents the model analysis. Section 4 provides the numerical analysis. Section 5 concludes.

2. The model set-up

The basic setting in this study is based on two power plants: one is the public power plant that generates power by using traditional fossil fuel, and the other one is a private power plant that generates power by using renewable resources. The relationship between the power market price (p) and the power demand (Q) takes a linear form:

$$p = a = bQ. \tag{1}$$

The parameter $a > 0$ represents the power market size, and the parameter $-b < 0$ indicates that there is a negative relationship between the power price and power demand. Since an equilibrium status requires that the power demand be equal to the power supply, $Q = x + y$, where x is the power output of the public power plant by using traditional resources; y is the power output of the private power plant by using renewable resources, where $x \in R^+$ and $y \in [0, \bar{y}]$; and $\bar{y}$ refers to the non-zero output level of the private power plant that depends on weather conditions.

The marginal costs of outputs x and y are c_x and c_y, respectively. The profit functions of the public power plant and private power plant are, respectively:

$$\begin{aligned} \pi_1 &= (p - c_x)x + (c_x - w)y, \\ \pi_2 &= (w - c_y)y, \end{aligned} \tag{2}$$

where w is a price whereby the public power plant purchases power from the private power plant. We define w as the electricity buy-back price. In short, the public power plant is only one power supplier by generating power x and purchasing power y from the private power plant. The term $(w - c_y)$ in Eq. (2) is an avoided cost mentioned by Xing and Wu [24] in which the public power plant escapes by purchasing the renewable power for resale instead of building a new plant. It consists of the capital cost and operating cost of the foregone power plant. The term $(w - c_y)$ in Eq. (2) is also the FIT price.

The social welfare function is composed of a consumer's surplus, a producer's surplus ($\pi_1 + \pi_2$), and the environmental damage function of green house gas (GHG) emission. Under the assumption of a linear demand function, the consumer's surplus can be reduced to $(b/2)Q^2$ (the proof is in Appendix A). The environmental damage function is assumed to be convex in the GHG emission level. A convex environmental damage function implies that the marginal environmental damage increases with increased emissions. This functional form is used as $D(x) = (k/2)x^2$ by Chang et al. [7], where k is the increment in marginal environmental damage due to the GHG emission, and the functional form implicates that one unit power output of the public power plant by using traditional resources generates one unit GHG emission; however, the power output of the private power plant by using renewable resources does not generate any GHG emission. The social welfare function is described by:

$$W = (b/2)Q^2 + (\pi_1 + \pi_2) - (k/2)x^2. \tag{3}$$

This is a three-stage game. In stage 1, the social planner chooses the optimal power price p^* to maximize social welfare. In stage 2, the public power plant decides the optimal electricity buy-back price w^* according to the FIT regime established by the government. In stage 3, the two power plants choose the optimal outputs x^* and y^*. Since the public power plant must purchase all renewable power generated by the private power plant, the public power plant is a Stackelberg follower and the private power plant is a Stackelberg leader. We shall examine the following question: Would an FIT regime and the private power plant as a Stackelberg leader cause low social welfare?

3. Analytical results

In this section we try to compare the social welfare under the FIT regime with that in the benchmark model.

3.1. Benchmark model

In the benchmark model, we assume that the public power plant is a monopolist for supplying the power, i.e., $Q^m = x$, where superscript m represents the monopoly case. The social welfare function in this case is composed of the consumer's surplus, i.e., $(b/2)Q^{m2}$, the producer's surplus, i.e., $\pi^m = (p - c_x)Q^m$, and the environmental damage of GHG emission, i.e., $D = (k/2)Q^{m2}$. The social planner sets the optimal power price to maximize the social welfare function, i.e., $p^m = a - \frac{b(a-c_x)}{b+k}$. Given the optimal power price p^m, the consumer's surplus is $\frac{b(a-c_x)^2}{2(b+k)^2}$, the producer's surplus is $\frac{k(a-c_x)^2}{(b+k)^2}$, the environmental damage is $\frac{k(a-c_x)^2}{2(b+k)^2}$, and the maximized social welfare is $\frac{(a-c_x)^2}{2(b+k)}$.

3.2. The FIT regime

According to our basic model setup, the public power plant is a monopoly selling power in the market, and it not only generates power by itself, but also purchases power from the private power plant. We employ backward induction to obtain the optimal solution in this scenario.

(i) The case of $0 < c_y < c_x$

The decision making for the private power plant, i.e., the Stackelberg leader, in stage 3 is as follows:

$$y = \begin{cases} \bar{y}, & \text{if } w \geqslant c_y, \\ 0, & \text{if } w < c_y. \end{cases} \tag{4}$$

Eq. (4) means that if the electricity buy-back price makes the profit of the private power plant positive (negative), i.e., $w - c_y \geqslant (<)0$, then the private power plant will (not) sell all (any) power to the public power plant. According to Eq. (2), the public power plant chooses the output to maximize the profit as follows:

$$x = \frac{a - c_x}{2b} - \frac{y}{2}. \tag{5}$$

In stage 2, the public power plant decides the optimal electricity buy-back price according to the FIT regime established by the government. From the profit function of the public power plant, we find $\partial\pi_1/\partial w < 0$. Based on the concept of the avoided cost and the FIT regime, the optimal electricity buy-back price for the public power plant is:

$$w^* = c_x, \tag{6}$$

where * represents the case of $0 < c_y < c_x$. Referring back to Eq. (4), we realize that the private power plant will sell all power, i.e., $y^* = \bar{y}$, to the public power plant.

In stage 1, the social planner decides the optimal power price to maximize social welfare. Because of $w^* = c_x$, the social welfare function in Eq. (3) can be rewritten as follows:

$$W = (b/2)Q^2 + [(p - c_x)x + (c_x - c_y)\bar{y}] - (k/2)x^2, \tag{7}$$

where $Q = x + \bar{y}$. By the first-order condition of the social welfare function, we obtain the optimal quantity of power production for the public power plant as:

$$x^* = \frac{a - c_x}{b + k}. \tag{8}$$

The optimal market total output, the power price, and social welfare are, respectively:

$$\begin{aligned} Q^* &= \frac{a - c_x}{b + k} + \bar{y}, \\ p^* &= a - b\left(\frac{a - c_x}{b + k} + \bar{y}\right), \\ W^* &= \frac{(a - c_x)^2}{2(b + k)} + \left(\frac{b\bar{y}}{2} + c_x - c_y\right)\bar{y} > 0. \end{aligned} \tag{9}$$

From Eq. (9), we find that there is a positive social welfare in this case.

(ii) The case of $0 < c_x < c_y$

In this case, based on the FIT regime, the optimal electricity buy-back price is:

$$W^{**} = c_y, \tag{10}$$

where ** represents the case of $0 < c_x < c_y$. Referring back to Eq. (4), we realize that the private power plant will sell all its power, i.e., $y^{**} = \bar{y}$, to the public power plant.

In stage 1, the social planner decides the optimal power price. Because $w^{**} = c_y$, the social welfare function in Eq. (3) can be rewritten as follows:

$$W = (b/2)Q^2 + [(p - c_x)x - (c_y - c_x)\bar{y}] = (k/2)x^2, \tag{11}$$

where $Q = x + \bar{y}$. By the first-order condition of the social welfare function, we obtain the optimal quantity of power production for the public power plant as:

$$x^{**} = \frac{a - c_x}{b + k}. \tag{12}$$

The optimal market total output, the power price, and social welfare are, respectively:

$$\begin{aligned} Q^{**} &= \frac{a - c_x}{b + k} + \bar{y}, \\ P^{**} &= a - b\left(\frac{a - c_x}{b + k} + \bar{y}\right), \\ W^{**} &= \frac{(a - c_x)^2}{2(b + k)} + \left(\frac{b\bar{y}}{2} - c_y + c_x\right)\bar{y}. \end{aligned} \tag{13}$$

From Eq. (13), because of the term $-c_y + c_x < 0$, there is an uncertain sign on the social welfare.

The optimal solutions under various scenarios are arranged in Table 1.

Table 1 shows that the FIT regime improves social welfare when $0 < c_y < c_x$; however, the FIT regime causes lower social welfare when $0 < c_x < c_y$ and c_y is larger than c_x by too much. We also find that the FIT regime must cause the consumer's surplus to increase. The result is caused by the electricity market becoming more competitive in the FIT regime than in a monopolistic market. When the market structure is a monopoly, the profit of the public power plant is necessarily larger than zero; however, the FIT regime may cause the profit of the public power plant to be negative. On the other hand, since the aim of the FIT regime is to encourage the development of a renewable power plant, the profit of the renewable power

Table 1
The optimal solutions under various scenarios.

		Monopoly ($c_y = c_x$)	FIT regime ($0 < c_y < c_x$)	FIT regime ($0 < c_x < c_y$)
Optimal pricing rule		$p^m = a - \frac{b(a-c_x)}{b+k}$	$p^* = a - b\left(\frac{a-c_x}{b+k} + \bar{y}\right)$	$p^{**} = a - b\left(\frac{a-c_x}{b+k} + \bar{y}\right)$
Consumer's surplus		$\frac{b(a-c_x)^2}{2(b+k)^2}$	$\frac{b(a-c_x)^2}{2(b+k)} + \frac{b(a-c_x)}{(b+k)}\bar{y} + \frac{b}{2}\bar{y}^2$	$\frac{b(a-c_x)^2}{2(b+k)} + \frac{b(a-c_x)}{(b+k)}\bar{y} + \frac{b}{2}\bar{y}^2$
Producer's surplus	π_1	$\frac{k(a-c_x)^2}{(b+k)^2} > 0$	$\frac{k(a-c_x)^2}{(b+k)^2} - \frac{b(a-c_x)}{b+k}\bar{y}$	$\frac{k(a-c_x)^2}{(b+k)^2} - \frac{b(a-c_x)}{b+k}\bar{y} - (cy - cx)\bar{y}$
	π_2	–	$(cx - cy)\bar{y} > 0$	0
Environmental damage of GHG emission		$\frac{k(a-c_x)^2}{2(b+k)^2}$	$\frac{k(a-c_x)^2}{2(b+k)^2}$	$\frac{k(a-c_x)^2}{2(b+k)^2}$
Social welfare		$\frac{(a-c_x)^2}{2(b+k)} > 0$	$\frac{(a-c_x)^2}{2(b+k)} + \left(\frac{b\bar{y}}{2} + cx - cy\right)\bar{y} > 0$	$\frac{(a-c_x)^2}{2(b+k)} + \left(\frac{b\bar{y}}{2} - cy + cx\right)\bar{y}$

Table 2
The data and parameter estimation of the power industry in Taiwan.

	Original data				Estimated parameter		
	Average FIT price (NT$ per kW h)	Output level of private power plant (MW)	Output level of public power plant (MW)	Power market price (NT$ per kW h)	Market size (MW)	Marginal cost of public power plant (NT$ per kW h)	Slope of power demand curve
Parameter symbol	$c_x - c_y$	$\bar{y}$	x	p	a	c_x	b
2010	11.8741	64	19329993.6000	2.6098	603093809.3	1991.1840	30.2
2011	8.7245	70	19863993.0000	2.6001	581961004.5	53990.5240	28.3

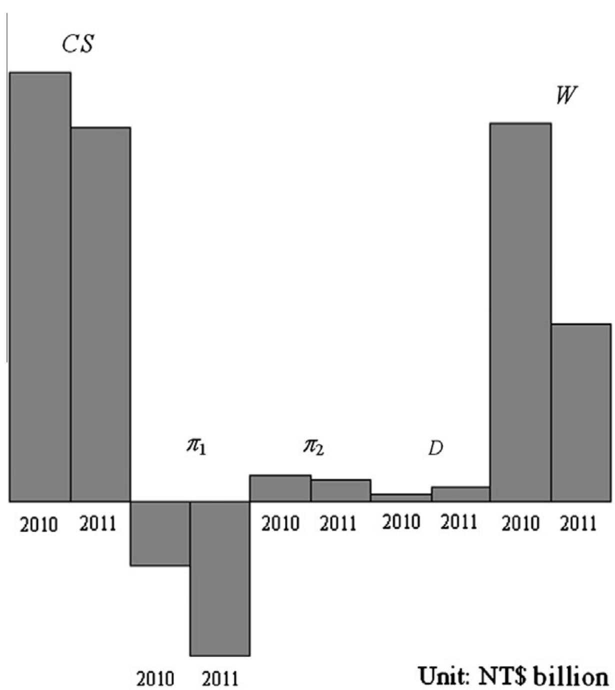


Fig. 1. A comparison of the consumer's surplus, the profit of the power plant, the environmental damage of GHG emission, and social welfare.

plant is non-negative. A more interesting result is that the environmental damage of GHG emission is the same no matter in the monopoly regime or in the FIT regime. Finally, we conclude with some important findings in Proposition 1 as follows:

Proposition 1. In the FIT regime,

(i) the consumer's surplus will be improved;
(ii) the profit of the public power plant may be negative; however, the profit of the private power plant is non-negative;
(iii) social welfare is lower when c_y is larger than c_x by too much.

3.3. Discussions

In Table 1, it is obvious that a decrease in the marginal cost of the public power plant will cause an increase in the consumer's surplus regardless of the kind of market structure. This result is from the public power plant being a monopoly selling power in the market.

We next concern ourselves about the effect of a change in the marginal costs of the private power plant and public power plant on social welfare. To arrive at the answer, we show some comparative statistical results as follows:

$$\frac{\partial W^*}{\partial c_y} = \frac{\partial W^{**}}{\partial c_y} = -\bar{y} < 0, \tag{14}$$

$$\frac{\partial W^*}{\partial c_x} = \frac{\partial W^{**}}{\partial c_x} = -\frac{(a - c_x)}{(b + k)} + \bar{y} > 0 \quad \text{if} \quad \bar{y} > \frac{(a - c_x)}{(b + k)}. \tag{15}$$

From Eq. (14) we find that a decrease in the marginal cost of the private power plant will cause social welfare to increase. This result is because the profit of the private power plant increases if $c_y < c_x$, or a loss suffered by the public power plant decreases if $c_y > c_x$. On the contrary, an increase in the marginal cost of the private power plant will cause social welfare to decrease. More importantly, a decrease in the marginal cost of the public power plant may cause social welfare to decrease when the purchased amount of power by the public power plant is too much, i.e., $\bar{y} > (a - c_x)/(b + k)$. The reason for the result is that a decrease in c_x causes a relatively high renewable power price c_y. If the public power plant purchases too much renewable power $\bar{y}$, then it will cause the social welfare to decrease. The results in this subsection are concluded in Proposition 2 as follows.

Proposition 2. In the FIT regime,

(i) an increase in the marginal cost of the private power plant will cause social welfare to decrease;
(ii) if the marginal cost of the public power plant decreases and the public power plant purchases too much renewable power, then the social welfare will decrease.

4. Numerical analysis

We apply the model results in this paper to perform a numerical analysis. The original data including the average FIT price ($c_x - c_y$), the output level of the private power plant ($\bar{y}$), the output level of the public power plant (x), the power market price (p) and the estimated parameters including the market size (a), the marginal cost of the public power plant (c_x), and the slope of power demand curve (b) are shown in Table 2 (the calculation process of the estimated parameters is shown in Appendix B). The data period extends from 2010 to 2011. Fig. 1. shows the results of comparing the consumer's surplus (CS), the profit of the power plant (π_1 and π_2), the environmental damage function of GHG emission (D) and the social welfare (W) in 2010 and 2011.

In Fig. 1, we find that the profit of the public power plant has a greater loss in 2011 than that in 2010. This result can be confirmed by the financial statements of Taiwan Power Company in 2010 and 2011 where $\pi_1 = -18.1$ billion in 2010 and $\pi_1 = -43.3$ billion in 2011 [23]. The profit of the private power plant is positive in 2010, but the profit decreases in 2011. The environmental damage of GHG emission in 2011 is higher than that in 2010. The consumer's surplus and the social welfare are positive in 2010, but both of them decrease in 2011.

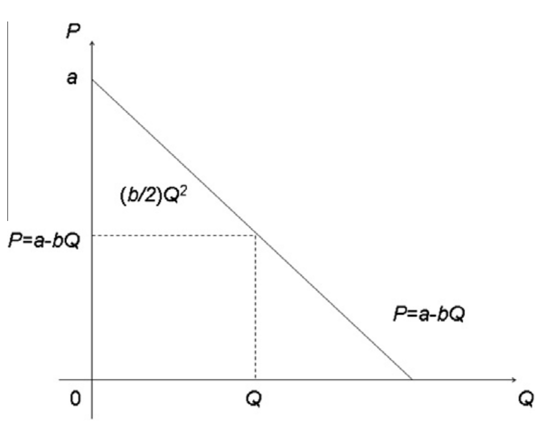
5. Conclusion

This study uses the Stackelberg game to analyze the effect of the FIT regime on social welfare. The main findings in this study are as follows: (i) In the FIT regime, the consumer's surplus will be improved. (ii) A surprising finding is that the FIT regime causes the social welfare to decrease when the marginal cost of the public power plant decreases and the public power plant purchases too much renewable power.

Lee et al. [16] simultaneously consider three major types of efficient energies, including electricity, coal, and gasoline oil. Their study points out a direction in which our paper can be extended. In our paper, we only have one kind of renewable power plant. However, there are many different kinds of renewable power plants such as solar power plants, wind power plants, and geothermal power plants in the market. Each of them faces a different FIT price and production cost. In a future study, we can broaden the range of renewable power plants to various other types.

Appendix A

The size of the consumer's surplus can be calculated by examining the area below the demand function and above the price. This area can be shown by the figure as follows:



The size of the triangular area is $(b/2)Q^2$.

Appendix B

According to the equilibrium results $p^* = a - b\left(\frac{a-c_x}{b+k} + \bar{y}\right)$ in Table 1 and $p^* = a - b(x + \bar{y})$ in Eq. (1), we obtain $x = \frac{a-c_x}{b+k}$. We substitute the original data $x\left(= \frac{a-c_x}{b+k}\right)$ and $\bar{y}$ into the profit function of the public power plant $\pi_1 = \frac{k(a-c_x)^2}{(b+k)^2} - \frac{b(a-c_x)}{b+k}\bar{y}$ in Table 1, given $k = 1$, $\pi_1 = -18.1$ billion in 2010 and $\pi_1 = -43.3$ billion in 2011 to estimate the parameter b [23]. Based on the estimated parameter b and the equilibrium result $p^* = a - b(x + \bar{y})$ in Eq. (1), we obtain the power market size a. Finally, we use $x = \frac{a-c_x}{b+k}$, the estimated parameters a, and b, and given $k = 1$ to estimate parameter c_x.

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