Hindawi
Discrete Dynamics in Nature and Society
Volume 2020, Article ID 8509834, 11 pages
https://doi.org/10.1155/2020/8509834

Research Article

Carbon Tax and Trading Price on Power Plant with Carbon Capture and Storage under Incentive Regulation Theory

Huan Zhang, Xinxin Xu, Jianli Jiang, and Meimei Zhang

Department of Economic Management, North China Electric Power University, Baoding 071100, China

Correspondence should be addressed to Meimei Zhang; 51851539@ncepu.edu.cn

Received 22 June 2019; Accepted 29 August 2019; Published 30 January 2020

Academic Editor: Paolo Renna

This paper investigates how the government can develop subsidies or tax policies to incent power plants to effectively carry out carbon capture to reduce carbon emissions. According to the government's incentive model for carbon capture power plants, the regulation mechanism is developed when government controls carbon emission. When regional or national carbon emission quota is tense, significant effect can be obtained when regulators make regulations to take off low efficiency power plants. In addition, it is verified that the regulators should not blindly pursue a reduction in carbon emissions regardless of the cost. Therefore, regulators need to pay more attention to control the costs of carbon capture equipment and technology. Finally, by parametric and numerical analyses, the conditions of the power plant to maximize corporate surplus are further studied.

1. Introduction

With the global warming problem becoming more and more serious, the international situation pays more and more attention to the issue of carbon emissions, and the low carbon issue has become an important aspect of China's participation in the world game. As one of the largest sectors of CO_2 emissions in China's national economy, the power industry accounts for about 40% of total carbon emissions and power generation industry plays an important role in the development of low carbon economy in china. The proportion of China's thermal power generation is more than 77%, the development of carbon emissions reduction policy for the thermal power industry is the most urgent and effective part of the low-carbon policy in the power generation industry [1–4]. However, the existing low-carbon policy research on the power industry is mainly focused on optimizing the power supply structure [5] and the development and application of low-carbon technologies [6], how to reduce the carbon emissions of thermal power enterprises through government regulation, but the research on the low carbon policy of thermal power enterprises is relatively lacking. As Xie [7] pointed out that such low carbon technology is one of the important factor of low-carbon electricity, but technological progress turning into energy-saving emission reduction performance needs a process, and need policy incentives and support. Considering Laffont et al. [8] pointed out that many implemented policy or important policy is brewing is always lack of economic theory under the guidance of. At the same time, China's power industry low-carbon policy formulation method is relatively simple [9, 10], lacking solid theoretical support, cannot demonstrate the interaction between the various factors.

Therefore, for the thermal power plant with carbon capture equipment, considering the carbon capture rate of the power plant as its private information, the controllable carbon capture rate of power plant as its efforts, this paper establishes the government's incentive model for carbon capture power plants and study how the government can develop subsidies or tax policies to incent power plants to effectively carry out carbon capture to reduce carbon emissions.

2. Literature Review

Early research involved multiple fields, here we main discuss the research that is highly relevant to this paper. With the increasing of CO_2 emissions, it brings the dramatic changes in climate and also has an affected on the development of social economy. Therefore, in order to achieve low-cost, high-efficiency carbon emissions, there is an urgent need for the government to set supportive and motivating regulations to reduce carbon emissions effectively [11]. In this context, scholars have explored this situation actively, a lot of research has been done and a series of related conclusions have been made on the power plant with carbon capture and storage (CCS) technology in carbon emissions and carbon tax and trading price on power plant under incentive regulation theory.

2.1. Power Plant with Carbon Capture and Storage (CCS) Technology in Carbon Emissions. There have been many papers studying carbon capture and storage (CCS) technology. To reduce the carbon emissions. Rubin et al. [12] used historical experience curves as the basis for estimating future cost trends for four types of electric power plants equipped with CO_2 capture systems. They first assessed the rates of cost reductions achieved by other energy and environmental process technologies in the past. Then, by analogy with leading capture plant designs, they estimated the future cost reductions that might be achieved by power plants employing CO_2 capture. Abu-Zahra et al. [13] studied for a CO_2 capture process from flue gas of a 600 MWe bituminous coal fired power plant, based on absorption process with MEA solutions, using ASPEN Plus with the RADFRAC subroutine, was performed. It is aimed to reduce the energy requirement for solvent regeneration, by investigating the effects of CO_2 removal percentage, MEA concentration, lean solvent loading, stripper operating pressure and lean solvent temperature. In addition, Abu-Zahra et al. [14] defined the economic baseline for post-combustion CO_2 capture from 600 MWe bituminous coal-fired power plant is described. The baseline capture process is based on 30% (by weight) aqueous solution of monoetha-nolamine (MEA). A process model has been developed previously using the Aspen Plus simulation programme where the baseline CO_2-removal has been chosen to be 90%. The results from the process modeling have provided the required input data to the economic modeling. Rongrong et al. [15] pointed out that the efficiency drop due to CO_2 removal plant is approximately 12.9%, and the cost of CO_2 captured and the cost of CO_2 avoided are respectively 13 euros/tCO_2 and 18 euros/tCO_2. In order to popularize large-scale CCS to power plants, technology improvement is greatly needed. Furthermore, the feasibility, mechanism, and options of flexible operation in capture plant are first clarified by Chen et al. [16], Then, based on a benchmark capture plant with post combustion and solvent separation technology, a generic quantitative model is established to formulate the process of CO_2 capture and the interaction between capture system and generation system. Plant performances as well as its effects on power-system operation are examined, revealing the different characteristics between CO_2 capture power plant and conventional non-capture plants. On this basis, typical operation modes of CO_2-capture power plant are defined and identified. Rasodjio and Darmawan [17] developed a model, optima carbon capture and storage (CCS), that combines economic and spatial optimization for the integration of CCS transport, storage and injection infrastructure to minimize costs. The model solves for the lowest-cost set of pipeline routes and storage/injection sites that connect CO_2 sources to the storage. Carbon capture and storage (CCS) policy in the United States, a new coalition endeavors to change existing policy are investigated by Pollak et al. [18]. Finally, they find that the newly formed climate coalition seeks to change existing geologic storage policy to support their proactive vision: to maximize energy supply or greenhouse gas reductions using CCS when climate policy is enacted. Stechow et al. [19] focused on the particular case of carbon capture and storage (CCS) technologies and conducts a qualitative multi-criteria analysis of different public policy support schemes for CCS demonstration to evaluate their suitability. The results show that two alternative schemes, a CCS bonus incentive or a carbon dioxide (CO_2) price guarantee, perform best in comparison with the other assessed instruments. While they reduce the uncertainty of CCS investments in the face of low European Union Allowance prices, they also avoid significant adverse impacts on operational and investment decisions in electricity markets. Meadowcroft [20] applied concepts, theories, and methodologies from the social and policy sciences, to elucidate how societies are engaging with CCS as a mitigation option and to point toward a future research agenda which, while exploring basic aspects of technology development as situated in a social context, would also be aligned with the needs of the climate and environmental policy community. Markusson et al. [21] explored the complexity of social learning associated with demonstration projects. Variety in expectations of the demonstration projects' objectives, learning processes, information sharing mechanisms, public engagement initiatives, financing and collaborative partnerships are highlighted. The result shows that multiple factors including the process of building support for the project, the governance context and the framing of the project matter for the learning in demonstration projects. Finally, Liu and Gallagher [22] examined the current state of Carbon Capture, Utilization, and Storage (CCUS) in China as well as the related climate change policy, laws, and initiatives that might be used to encourage the large-scale deployment of carbon sequestration in China. Meanwhile, Haszeldine [23] pointed that the capture of carbon dioxide at the point of emission from coal- or gas-burning power plants is an attractive route to reducing carbon dioxide emissions into the atmosphere. To commercialize carbon capture, as well as transport of liquified carbon dioxide and its storage in exploited oil fields or saline formations, many technological, commercial, and political hurdles remain to be overcome. The variation in the state-level energy context for CCS development by exploring energy policy stakeholder' perceptions of CCS in four geographically and demographically diverse states is accessed by Chaudhry et al. [24], the variation in state and stakeholder energy priorities and perceptions revealed in this study highlights challenges in the development and implementation of national-level energy policy and also specific challenges in the deployment of CCS. Kuckshinrichs [25] integrated the technology study to discuss and assess the technical, economic, environmental, and social perspectives of CCS technologies, in addition, the research described the contributions on using and storing CO_2 comprehensively.

However, the above studies mainly concentrated on CCS technology developing process, Few scholars study the problem that how the government can develop subsidies or tax policies to incent power plants to effectively carry out carbon capture to reduce carbon emissions. Therefore, we fill this gap and explore the optimal strategic decisions of the government.

2.2. Carbon Tax on Power Plant under Incentive Regulation Theory. Recently, the role of the government low carbon policies has also been considered. Studies mainly include two aspects: one is designing a carbon tax to control global warming, and the other is optimizing the incentive regulation of the government.

Regarding the first aspect, Borchiellini et al. [26] studied the carbon tax vs CO_2 sequestration effects on environmental analysis of existing power plants. Nissen [27] derived the efficient tax-subsidy policy in an energy-economy-environment growth model with carbon emission externalities, and a carbon capture and sequestration (CCS) sector with learning by doing (LBD) externalities. Abadie and Chamorro [28] assessed the option to install a carbon capture and storage (CCS) unit in a coal-fired power plant operating in a carbon-constrained environment and pointed out that that, at current permit prices, immediate installation does not seem justified from a financial point of view. This need not be the case, though, if carbon market parameters change dramatically, carbon capture technology undergoes significant improvements, and/or a specific governmental policy to promote these units is adopted. Jeong et al. [29] investigated the economic comparison between coal-fired and liquefied natural gas combined cycle power plants considering carbon tax of Korean case. It aims at making an economic analysis of Korea's power plant utilities. In addition, Kemmoku et al. [30] investigated the buying price of photo voltaic electricity under a carbon tax regime. It assuming that photo voltaic (PV) systems are adopted in residential houses under a carbon tax regime, the economic performance of PV systems is investigated from the standpoint of an electric utility. Mendelevitch et al. [31] presented a mixed integer, multi-period, cost-minimizing model for a carbon capture, transport and storage network in Europe. The model incorporates endogenous decisions about carbon capture, pipeline and storage investments. The capture, flow and injection quantities are based on given costs, certificate prices, storage capacities, and point source emissions. Huang et al. [32] conducted a optimal cleaning power generation investment strategy in a carbon tax and CO_2 emission trading framework and studied a two-staged cleaning energy investment problem under uncertainty. The results indicate that, because of the variation fluctuation of electricity price, the investor tends to delay investing when the electricity price is lower, whereas the higher price–price ratio of electricity is helpful for him to deploy ahead the carbon capture device. Renner [33] conducted a literature review on public studies about CCS costs and constructed a net present value model to calculate the cost of electricity and the break even CO_2 price to objectively assess the profitability of CCS plants. Oei et al. [34] developed a model to analyze the economics of carbon capture, transport, and storage in the wake of expected rising CO_2 prices. In addition, the model determined a cost minimizing strategy on whether to purchase CO_2 certificates, or to abate the CO_2 through investments into a CCTS-chain on a site by site basis. Cai et al. [35] considered a situation where a tax on emissions is imposed on carbon dioxide (CO_2) producers to encourage their participation in CCS. Operators of CO_2 transportation pipelines and storage sites enter into individual contracts with emissions producers to store CO_2. They also study the problem of selecting the optimal price and volume of these contracts under both cost and emissions uncertainty to optimize the storage operators expected profit.

For the second aspect, Yi et al. [36] gave an introduction to incentive regulation, and analyses the experiences and lessons of price cap, which is one of methods of the theory of incentive regulation, applied widely in these reforms. Jamasb and Pollitt [37] reviewed the recent experience of the UK electricity distribution sector under incentive regulation. Furthermore, Castillo and Linn [38] compared the incentives a carbon dioxide emissions price creates for investment in low carbon dioxide-emitting technologies in the electricity sector. Finally, Menezes and Xuemei [39] reviewed the incentives for pursuing a low-carbon electricity sector that are embedded in China's regulatory and policy framework and pointed out that different institutions and agents who face different and often conflicting incentives for pursuing environmental and energy efficiency objectives.

For now, most of the papers in this area is about the development of CCS technology or the establishment of a single incentive regulation, but there are a growing number of nations setting a carbon tax and trading price on power plant with carbon capture under incentive regulation theory. They attempt to force the power industry to reduce carbon emissions to relieve environmental stress, and while the government sets corresponding policies, it also encourages the power industry to use CCS emission reduction technologies. According to the Section 2, we find that there is relatively little research on this. Most studies focus on CCS technology to reduce carbon emissions. Therefore, we discuss the effect of the government sets policy on the power plant with carbon capture and storage. In the next section, we will describe the model used in this paper.

In this paper, we consider the problem of how the government develops subsidies or tax policy to encourage power plant make carbon capture to reduce carbon emissions more effectively, and use the government regulation incentive model to research the problem that regulators is in the information disadvantage considering the carbon capture rate of the power plant as its private information. The main contributions of this paper are: (1) A set of regulation mechanism which applies where the government regulates the power plant for capturing carbon emission have be established and be proved efficient to reveal the power plant private information and encourage it to improve carbon capture rates. (2) We obtain the conditions of the power plant achieve the largest corporate surplus. (3) We provide some meaningful advice for the regulators to make reasonable regulations.

The reminder of this paper is organized as follows. In Section 2, a literature review is presented. Section 3 presents the assumptions of the model. Section 4 presents the basic models of the problem. Sections 5 and 6 presents a numerical example

Table 1: Notations.

Notations	Explanations
β	Original carbon capture rate (real carbon capture rate) Effort made
e	by the power plant
r	Carbon capture rate with effort (monitored by government)
q	Power quantity
c	Unit output cost
I	Investment made by the power plant for effort
p_1	Power price to the power plant
p_2	Power price to the consumer
p_3	Carbon trading price
k	Coefficient of cost increase for carbon capture
λ	Coefficient of shadow cost
T	Transferring payment
U	Utility of the power plant
V	Utility of the consumer
N	Social welfare coefficient of power
W	Social welfare
A	Original carbon quota of the power plant
M	Coefficient of carbon emission

and parametric analysis for better understanding. In Section 7, Conclusions and suggestions for future research are presented.

3. Assumptions

The notations in paper to solve the problem is shown in Table 1, the game sequence is shown in Figure 1.

Assumption 1. We consider moral hazard and adverse selection in this paper.

The original carbon capture rate β is private information of the power plant, and it can be improved by effort e, which can't be observed by government, such as updating equipment, technical improvement and so on, but the effort costs $I(e)$. So the carbon capture rate with effort is shown as:

$$r = \beta + e. \tag{1}$$

Where $\beta \in [\underline{\beta}, \overline{\beta}]$, $F(\beta)$ means the absolutely continuous distribution function and its density is $f(\beta)$ While $\beta \in [\underline{\beta}, \overline{\beta}]$, $f(\beta) > 0$ and the monotone hazard rate $d[F(\beta)/f(\beta)]/d\beta \geq 0$, for most distributions, such as uniform distribution, normal distribution, logarithmic distribution, exponential distribution and Laplace distribution, satisfy the condition e is the moral hazard parameter, and it relates to the carbon capture rate, in other words, $e = e(\beta)$. Meanwhile, we assume $I'(\cdot) > 0$, $I''(\cdot) > 0$, and $I'''(\cdot) = 0$.

Assumption 2. Based on emissions trading scheme (ETS), the power plant obtains A units original carbon quota according to the natural absorption [40] and the power plant scale. If A is not sufficient, the power plant should purchase more, otherwise, it can sell some to obtain profit with price p_3. Let $I' = [A - Mq(\beta)(1 - r(\beta))]P_3$ be the relationship, where M is the coefficient of carbon emission.

Assumption 3. Carbon capture will increase the output cost of the power plant [41], and it follows:

$$c_1 = k \cdot r = k(\beta + e), \tag{2}$$

where k is coefficient of cost increase for carbon capture.

Assumption 4. We designate Np_2q as the utility to consumer when he consumes q unit power. p_2 is power price to the consumer and it satisfies:

$$p_2 = a - bq. \tag{3}$$

Assumption 5. Power plant aims at more profit. Government with the target of maximizing the social welfare, pays transferring payment T to encourage power plant to invest and get its private information β.

4. Model

4.1. Utility of the Power Plant. Power plant offers power with the price p_1, obtains the transferring payment T from government and suffers some costs, as it is shown below:

$$U(\beta) = p_1 q(\beta) + T(\beta) - (1 + kr(\beta))q(\beta)c - I(e) + I', \tag{4}$$

where c the unit output cost of the power plant.

4.2. Utility of the Consumer. We denote $Np_2q(\beta)$ as the power social welfare to the consumer, meanwhile, we consider the shadow cost λ in the model. Accordingly, the utility of the consumer is given by:

$$V(\beta) = Np_2 q(\beta) - (1 + \lambda)T(\beta). \tag{5}$$

4.3. The Target of Government. Government as the regulator maximizes the social welfare which includes the power plant and the consumer. In other words, it is $W = U + V$. Therefore, the total social welfare from various power plant with different carbon capture rate is given by:

$$\overline{W} = \int_{\underline{\beta}}^{\overline{\beta}} (U + V)\, dF(\beta). \tag{6}$$

4.4. The Incentive Constraints. The power plant chooses one contract offered by government according to $\hat{\beta}$ which is given by itself, and government pays transferring payment according to the contract chosen by power plant, which maybe cannot reveal the true carbon capture rate. So the power plant utility is the following function:

$$\begin{aligned} U(\beta, \hat{\beta}) = {} & p_1 q(\hat{\beta}) + T(\hat{\beta}) - (1 + kr(\hat{\beta}))q(\hat{\beta})c \\ & - I(r(\hat{\beta}) - \beta) + [A - Mq(\hat{\beta})(1 - r(\hat{\beta}))]P_3. \end{aligned} \tag{7}$$

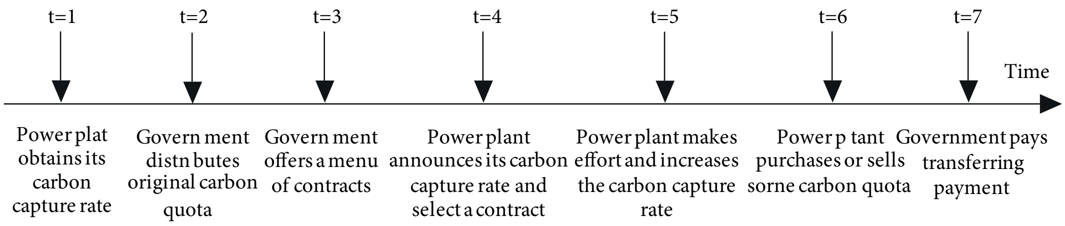

Figure 1: Game sequence.

Furthermore, when each $\beta_1, \beta_2 \in [\underline{\beta}, \overline{\beta}]$, we get the incentive constraints:

$$\begin{aligned} &p_1 q(\beta_1) + T(\beta_1) - (1 + kr(\beta_1))q(\beta_1)c \\ &\quad - I(r(\beta_1) - \beta_1) + [A - Mq(\beta_1)(1 - r(\beta_1))]P_3 \geq p_1 q(\beta_2) \\ &\quad + T(\beta_2) - (1 + kr(\beta_2))q(\beta_2)c - I(r(\beta_2) - \beta_1) \\ &\quad + [A - Mq(\beta_2)(1 - r(\beta_2))]P_3. \end{aligned} \tag{8}$$

$$\begin{aligned} &p_1 q(\beta_2) + T(\beta_2) - (1 + kr(\beta_2))q(\beta_2)c \\ &\quad - I(r(\beta_2) - \beta_2) + [A - Mq(\beta_2)(1 - r(\beta_2))]P_3 \geq p_1 q(\beta_1) \\ &\quad + T(\beta_1) - (1 + kr(\beta_1))q(\beta_1)c - I(r(\beta_1) - \beta_2) \\ &\quad + [A - Mq(\beta_1)(1 - r(\beta_1))]P_3. \end{aligned} \tag{9}$$

4.5. The Participant Constraints. In order to let the power plant take part in the project willingly, government should let it keep the profit no less than that it is absent (normalized to 0 here). It is:

$$U(\beta, \hat{\beta}) \geq 0. \tag{10}$$

4.6. The Model and Solution. Above all, the general problem established is the following:

$$\begin{aligned} P : \overline{W} &= \max_{\{e(\cdot), q(\cdot)\}} \int_{\underline{\beta}}^{\overline{\beta}} (U + V)dF(\beta) \\ &\text{s.t. } (8), (9), (10). \end{aligned} \tag{11}$$

Let us consider the problem. We can combine Equations (8) and (9) to obtain Equation (12):

$$\int_{\beta_1}^{\beta_2} \int_{r(\beta_1)}^{r(\beta_2)} I''(x - y)dxdy \geq 0. \tag{12}$$

Since $I''(\cdot) > 0$, due to Equation (12), we know $\dot{r}(\beta)$ is the non decreasing function of β, we obtain $\dot{r}(\beta) \geq 0$, or equivalently:

$$\dot{e}(\beta) \geq -1. \tag{13}$$

The power plant with low carbon capture rate maybe fakes it for more profit, so we take the envelope theorem to Equation (7), we get:

$$\dot{U}(\beta) = I'(r(\beta) - \beta) \geq 0. \tag{14}$$

In order to save cost, government will let $U(\underline{\beta}) = 0$. From Equation (14):

$$U(\beta) = \int_{\underline{\beta}}^{\beta} I'\left(e\left(\tilde{\beta}\right)\right) d\tilde{\beta}. \tag{15}$$

Proposition 1. *The redundant profit obtained by power plant with high carbon capture rate is shown by Equation (15), and we also call it information rent.*

Proposition 1 shows that, the redundant profit is only related to the function of its effort under regulation. In reality, the government encourages the power plant to reduce the carbon emissions by effort and will make a portion of the investment up. So the benefit from investing to reduce carbon emissions is kept by the power plant reasonable.

Corollary 1. *Equation (14) shows that the redundant profit varies with its carbon capture rate β in the same direction. It means, the higher the carbon capture rate is, the more profit the power plant gets. Obviously, the regulation mechanism can encourage the power plant to improve the carbon capture rate for more redundant profit.*

So the total information rent from various β is formulated by Equation (16):

$$\begin{aligned} \int_{\underline{\beta}}^{\overline{\beta}} U(\beta)dF(\beta) &= \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\beta}}^{\beta} I'\left(e\left(\tilde{\beta}\right)\right) d\tilde{\beta}\, dF(\beta) \\ &= \int_{\underline{\beta}}^{\overline{\beta}} \frac{1 - F(\beta)}{f(\beta)} I'(e(\beta))dF(\beta). \end{aligned} \tag{16}$$

By replacing Equations (5), (7), and (16) into Equation (11), we can reformulate government's problem as:

$$\begin{aligned} \overline{W} = \max_{\{e(\beta), q(\beta)\}} \int_{\underline{\beta}}^{\overline{\beta}} &\left\{ \begin{array}{l} N(a - bq(\beta))q(\beta) \\ -(1 + \lambda)[(1 + kr(\beta))q(\beta)c + I(e) \\ -(A - Mq(\beta)(1 - r(\beta)))p_3 - p_1 q(\beta)] \\ -\lambda \frac{1 - F(\beta)}{f(\beta)} I'(e(\beta)) \end{array} \right\} dF(\beta) \\ &\text{s.t. } (13). \end{aligned} \tag{17}$$

We denote J as the integral part of Equation (17) and we obtain:

$$\frac{\partial^2 J}{\partial q^2} = -2bN \leq 0. \tag{18}$$

Furthermore, from $\partial J/\partial q = 0$:

$$q^* = \frac{a}{2b} - \frac{(1+\lambda)[(1+kr(\beta))c + Mp_3(1-r(\beta)) - p_1]}{2bN}. \tag{19}$$

Now let us consider the constraint Equation (13). From $\partial J/\partial e = 0$, we get:

$$I'(e) = (Mp_3 - kc)q(\beta) - \frac{\lambda}{1+\lambda} \cdot \frac{1-F(\beta)}{f(\beta)} \cdot I''(e). \tag{20}$$

Proposition 2. *The optimal effort level is decided by Equation (20) under regulation. Equation (20) describes a one-to-one correspondence between the carbon capture rate β and the optimal effort e. The power plant with different carbon capture rate will select different effort.*

Corollary 2. *The optimal effort level of power plant has the same trend with its carbon capture rate β.*

The derivative of β from Equation (20) is:

$$\dot{e}(\beta) = \frac{(1+\lambda)(Mp_3 - kc)^2 \dot{r}(\beta)}{I''(e)2bN} - \frac{\lambda}{1+\lambda}\left(\frac{d(1-F(\beta))/f(\beta)}{d\beta}\right). \tag{21}$$

Obviously, $\dot{e}(\beta) > 0$ and we get Corollary 2. And it satisfies the constraint Equation (13). Consequently, we can get $e^*(\beta)$ from Equation (20).

Finally, we know the optimal information rent, the carbon capture rate and the transferring payment follow the following formulations:

$$U^*(\beta) = \int_{\underline{\beta}}^{\beta} I'\left(e\left(\tilde{\beta}\right)\right) d\tilde{\beta} \tag{22}$$

$$r^*(\beta) = \beta + e^*(\beta) \tag{23}$$

$$\begin{aligned} T^*(\beta) = {} & U^*(\beta) + I(e^*(\beta)) + (1+kr^*(\beta))cq^*(\beta) \\ & - [A - Mq^*(\beta)(1-r^*(\beta))]p_3 - p_1 q^*(\beta). \end{aligned} \tag{24}$$

Replace $r^*(\beta)$ by its inverse function $\beta = \beta^*(r)$ into Equation (24), the optimal transferring payment is shown as:

$$\begin{aligned} T^*(r) = {} & \int_{\underline{\beta}}^{\beta} I'\left(e^*\left(\tilde{\beta}(r)\right)\right) d\tilde{\beta} + I(e^*(\beta(r))) \\ & + (1 + k(\beta(r) + e^*(\beta(r))))cq^*(\beta(r)) \\ & - [A - Mq(\beta(r))(1 - \beta(r) - e^*(\beta(r)))]p_3 \\ & - p_1 q(\beta(r)), \end{aligned} \tag{25}$$

where the carbon capture rate with effort r is visible for government.

Proposition 3. *To monitor the carbon capture rate with effort $r^*(\beta)$, the government derives the original carbon capture rate β from $r^*(\beta) = \beta + e^*(\beta)$, where $e^*(\beta)$ is given by Equation (20).*

Proposition 4. *$\{T^*(\beta), q^*(\beta)\}$ is the optimal regulation mechanism between the government and the power plant. In other words, the government decides the power quantity $q^*(\beta)$ and the transferring payment $T^*(\beta)$ according to Equation (19) and Equation (24) as soon as it obtains the carbon capture rate with effort $r^*(\beta)$.*

In summary, this paper provides a set of regulation mechanism (Proposition 4) which applies where the government regulates the power plant for capturing carbon emission. With this regulation mechanism, we can get: (1) The government can calculate the original carbon capture rate of the power plant while it monitors the carbon capture rate with effort (Proposition 3); (2) The power plant will select the optimal power quantity $q^*(\beta)$ and the transferring payment $T^*(\beta)$ that is one-to-one correspondence with its original carbon capture rate β; (3) The power plant makes optimal effort decided by Equation (20) (Proposition 2), and obtains some redundant profit(Proposition 1). In a word, the government reaches its goals that revealing the real carbon capture rate and encouraging the power plant to make optimal effort to reduce the carbon emission.

5. Numerical Example

Taking Hebei Province in China as example to analyze, and we list these data after investigating: the coefficient of shadow cost $\lambda = 0.1$; the coefficient of carbon emission $M = 0.997$; the social welfare coefficient of power $N = 0.47$; the coefficient of cost increase for carbon capture $k = 0.25$; the power price to the power plant $p_1 = 397$ yuan/MW, the carbon trading price $p_3 = 100$ yuan/t, the unit power production cost $c = 245$ yuan/MW, the original carbon quota of the power plant $A = 0$ t, the cost for the effort of the plant $I = (1/2)\,\delta e^2$, and $\delta = 10^5$; the market scale $a = 2000$, and $b = 5$; the carbon capture rate β is uniformly distributed on $[0, 0.7]$, with cumulative distribution function $F(\beta) = (10/7)\beta$, and density function $f(\beta) = (10/7)$.

We calculate these outcomes listing in Table 2 based on Proposition 1–4.

According to Table 2, regulators can regulate coal fired power plant in distinct ways, such as the regulation based on β (as shown in Table 2, column second), or the regulation based on r (as shown in Table 2, column third). For the original carbon capture rate reported by a power plant and the carbon capture rate observed by the regulator, the regulator provides the corresponding regulation rules, that is, the power generation and transfer payment.

In addition, we illustrate how the redundant profit U varies with the original carbon capture rate β and the carbon capture rate claimed by the power plant $\hat{\beta}$, shown in Figure 2.

As shown in Figure 2, the power plant with the lowest carbon capture rate obtains 0 redundant profit, $U(0,0) = 0$ or $U(\underline{\beta}) = 0$. Meanwhile, the redundant profit U increases

Table 2: Regulation mechanism and its effect.

		Regulation based on β	Regulation based on r
Original carbon capture rate β		β	$0.9135 * r - 0.0164$
Optimal effort made by power plant e^*		$0.0180 + 0.0947 * \beta$	$0.0865 * r + 0.0164$
Carbon capture rate monitored by government r^*		$0.0180 + 1.0947 * \beta$	r
Regulation mechanism	Power quantity q^*	$9.8511 * \beta + 212.4027$	$8.9990 * r + 212.2411$
	Transferring payment T^*	$4957.96\beta^2 - 7488.29\beta$ -11239.67	$4137.3296 * r^2 - 6989.1073 * r$ -11115.5286

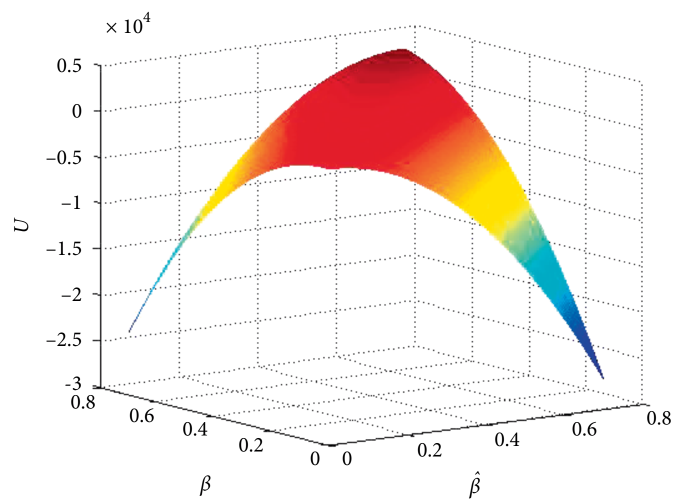

Figure 2: Figure of U varying with β and $\hat{\beta}$.

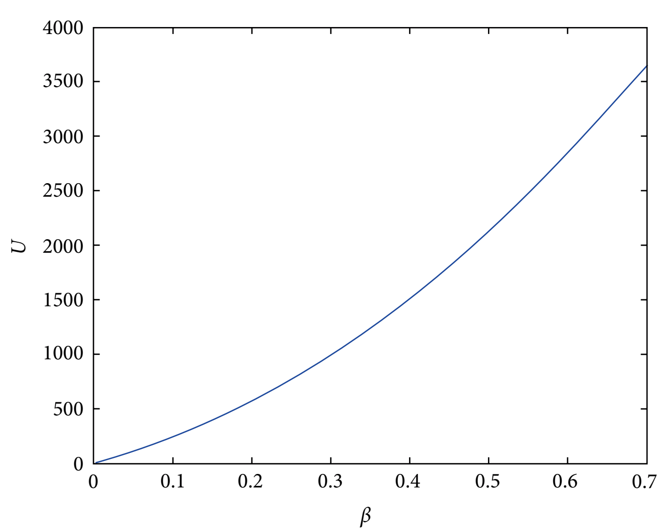

Figure 3: Relationship between U and β.

while the original carbon capture rate β increases just as Corollary 1, which is also shown in Figure 3 more clearly. Furthermore, when $x = y$ in Figure 2, z attains the peak. That is, if and only if the claimed carbon capture rate is the same with its real one ($\hat{\beta} = \beta$), the redundant profit is maximum. Hence, the power plant will reveal its real carbon capture rate and choose contract suitable for itself under this regulation mechanism.

We give Figure 4 to show how the optimal carbon capture rate with effort $r^*(\beta)$ and the optimal effort $e^*(\beta)$ change with the real carbon capture rate β.

As Figure 4 shown, both the carbon capture rate with effort $r^*(\beta)$ and the effort $e^*(\beta)$ increase while the original carbon capture rate β increases. Specially, at the point of $\beta = 0$, $r^*(\beta) = e^*(\beta) > 0$, it means the regulator encourages the power plant to reduce the carbon emission not only by

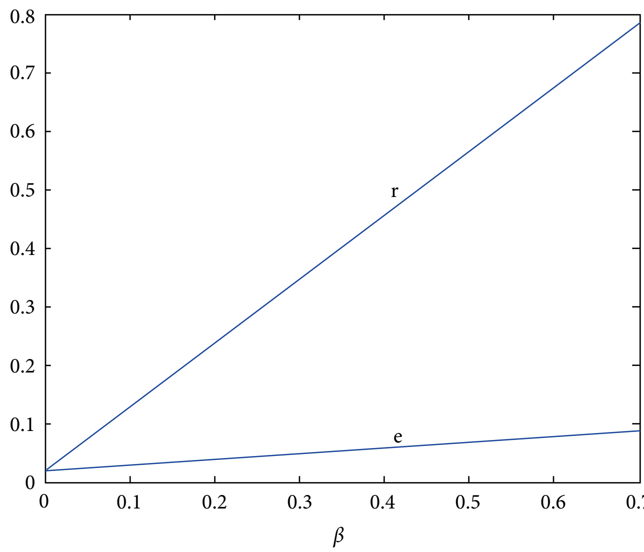

FIGURE 4: Figure of carbon capture rate and effort varying with β.

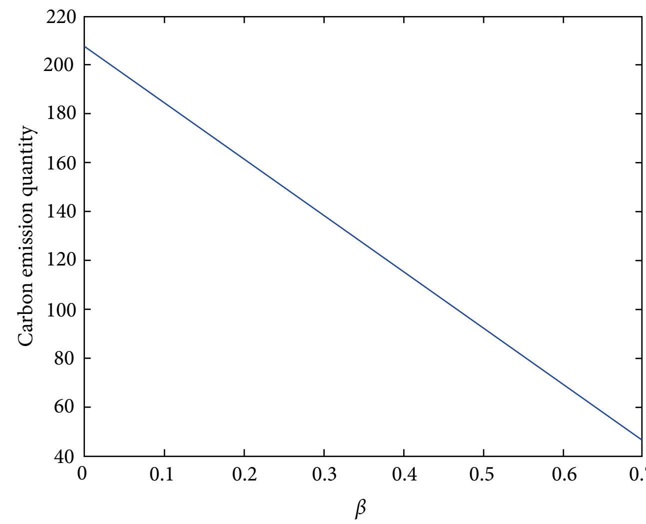

FIGURE 5: Figure of the coal power plants' total carbon emission quantity.

improving carbon capture technology but also by management or other methods (the effort e).

Under the regulation mechanism, the coal power plants' total carbon emissions quantity of different carbon capture rate is shown in Figure 5.

As seen in Figure 5, the coal power plants' total carbon emissions quantity decrease sharply with the increasing of β. The power quantity of power plants increases while the original carbon capture rate β increases according to corollary 3, so power quantity of power plants of the larger original carbon capture rate is more than the smaller. Although the power quantity of power plants with larger original carbon capture is bigger, but its total carbon emissions is much smaller and the ratio even up to 4 times (when, $Q_{carbon} = 182t$; and when $\beta = 0.7$, $Q_{\beta} = 42t$). Therefore, the power plants with small original carbon capture rate become the main source of carbon emissions, when regional or national carbon emissions quota tense, significant effect can be obtained when regulators make regulations to take off the low efficiency power plants (or the power plants with small original carbon capture rate).

6. Sensitivity Analysis

This paper focuses on the impact of carbon emissions related parameters, the changes of regulation parameter are given for the varies of the coefficient of cost increase for carbon capture k and the carbon trading price p_3 as shown in Tables 3 and 4, when $\beta = 0.4$.

With the increasing of the coefficient of cost increase for carbon capture k, power quantity of power plant q and the effort made by the power plant e will decrease under the regulation, the utility of the power plant will reduce at the same time (as shown in Table 3. Inside, the change of the effort made by the power plant e is the largest, and when the change range of k is $(\pm)10\%$, the change degree of e is more than $(\mp)24\%$. The increase in the cost of carbon capture will seriously affect power plant's enthusiasm of reducing carbon emissions by making efforts. So when regulators encourage carbon capture power plant to reduce carbon emissions by adding equipment or improve technology, regulators need to pay more attention to control the costs of carbon capture equipment and technology. In a short, regulators must not blindly pursue a reduction in carbon emissions regardless of their cost.

Nowadays, the rules of international and domestic carbon trading price have large difference. After a comprehensive comparison, this paper take carbon trading prices $p_3 = 100$ as a benchmark to research. The research found that when the carbon trading price increases, the carbon capture power plant power quantity q will reduce and the effort made by the power plant e will increase under government regulation (as shown in Table 4. The impact of carbon trading prices on the efforts of the plant to reduce carbon emissions is also evident. When the carbon trading price changes $(\pm)30\%$, the carbon capture effort parameter changes by more than $(\pm)100\%$, When the price of carbon trading is small ($p_3 = 70$), the carbon capture effort of the power plant will even drop to a negative number ($e = -0.0085$). That is, there will be reverse efforts such as lazy to make carbon emissions increasing. Therefore, increasing the price of carbon trading is an effective mean of reducing carbon emissions from power plants.

7. Conclusions and Suggestions for Future Research

Because the power industry plays an important role in the development of low carbon economy in our country, government can develop subsidies or tax policy to encourage power plant make carbon capture to reduce carbon emissions more effectively, and reasonable carbon capture power plant low carbon regulation incentive mechanism is of virtual important for the development of low carbon economy in china. In this paper, we use the government regulation incentive model to research the problem that regulators is in the information disadvantage considering the carbon capture rate of the power

Table 3: Sensitivity analysis for the coefficient of cost increase for carbon capture k.

k	q	e	U	T	P_2
−10%	217.1386	0.0695	2.0534e + 003	−1.3606e + 004	914.3068
−5%	216.7359	0.0627	1.7807e + 003	−1.3521e + 004	916.3206
0.25	216.3431	0.0559	1.5092e + 003	−1.3442e + 004	918.2843
+5%	215.9604	0.0492	1.2387e + 003	−1.3368e + 004	920.1982
+10%	215.5875	0.0424	969.3644	−1.3299e + 004	922.0625

Table 4: Sensitivity analysis for the carbon trading price p_3.

p_3	q	e	U	T	P_2
−30%	220.0232	−0.0085	−1.0666e + 003	−1.9887e + 004	899.8841
−10%	217.4711	0.0347	659.2488	−1.5515e + 004	912.6445
−5%	216.8949	0.0453	1.0852e + 003	−1.4469e + 004	915.5255
100	216.3431	0.0559	1.5092e + 003	−1.3442e + 004	918.2843
+5%	215.8157	0.0665	1.9314e + 003	−1.2432e + 004	920.9217
+10%	215.3123	0.0770	2.3520e + 003	−1.1439e + 004	923.4383
+30%	213.5390	0.1187	4.0208e + 003	−7.6276e + 003	932.3049

plant as its private information. We get the following conclusions

(1) A set of regulation mechanism which applies where the government regulates the power plant for capturing carbon emission have be established and be proved efficient to reveal the power plant private information and encourage it to improve carbon capture rates. On the basis, government can make a menu of contracts to regulate the power plant.

(2) Regulators can regulate coal fired power plant in distinct ways, such as the regulation based on β, or the regulation based on r. At the same time, when the carbon capture power plant companies report the true type of carbon capture, the power plant will obtain the largest corporate surplus. Therefore, under this regulation mechanism, the carbon capture power plant will choose the true type of carbon capture, and choose the corresponding contract package.

(3) The power plants with small original carbon capture rate become the main source of carbon emissions, when regional or national carbon emissions quota tense, significant effect can be obtained when regulators make regulations to take off the low efficiency power plants (or the power plants with small original carbon capture rate).

(4) Regulators must not blindly pursue a reduction in carbon emissions regardless of their cost. Because the increase in the cost of carbon capture will seriously affect power plant's enthusiasm of reducing carbon emissions by making efforts. So when regulators encourage carbon capture power plant to reduce carbon emissions by adding equipment or improve technology, regulators need to pay more attention to control the costs of carbon capture equipment and technology.

It is creative to note the model this paper based on the background of carbon capture power plant, so the conclusion are given with the background of carbon capture power plant. In fact, the conclusion can be spread to more backgrounds. Furthermore, although this paper distinct the high efficiency power plant with the low efficiency power plant and provide distinct policy for distinct power plant. That is, the high efficiency power plant can get some subsidies, but the low efficiency power plant will be closed. However, we do not add a closed policy constraint in the incentive regulation model of thermal power plant, so next we will add the closed policy constraint into our regulation model.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported in part by a project supported by Natural Science Foundation in Hebei province (G2019502154), and the Fundamental Research Funds for the Central Universities (2019MS134).

References

[1] C. H. Liao, "Study of the trend of development of low carbon sports tourism in China," *Journal of Physical Education*, vol. 18, no. 4, pp. 53–56, 2011.

[2] X. Ou and X. Zhang, "The status quo and development trend of low-carbon vehicle technologies in China," *Advances in Climate Change Research*, vol. 1, no. 1, pp. 34–39, 2010.

[3] Q. H. Zeng, C. L. Xu, B. Qi, and Z. Hong, "The trend analysis of low-carbon technology development of the yangtze river delta region in the post-world expo," *International Conference on Consumer Electronics*, 2011.

[4] G. Zhang, J. Yao, and H. Rong, "Patent analysis on the development trend of low-dimensional carbon nanomaterials by Derwent innovations index," *Chemical Industry & Engineering Progress*, 2016.

[5] A. Phdungsilp, "Integrated energy and carbon modeling with a decision support system: policy scenarios for low-carbon city development in Bangkok," *Energy Policy*, vol. 38, no. 9, pp. 4808–4817, 2010.

[6] R. Long, T. Yue, R. Yang, and S. Cailing, "Policy simulation of the low carbonization of coal utilization in coal-fired power industry," *Journal of Systems Engineering*, 2014.

[7] H. Xie, "Developing low carbon technology to promote green economy," *Energy of China*, vol. 32, no. 9, pp. 5–10, 2010, (In chinese).

[8] T. Laffont and L. Shi, "Incentive Theory in Government Procurement and Regulation," *Sanlian Bookstore, Shanghai People's*, Publishing House, Shanghai: Shanghai, 2004.

[9] Y. Y. He and X. Tan, "Policy effects assessment system dynamic model of regional low-carbon development," *Advanced Materials Research*, vol. 742, pp. 398–403, 2013.

[10] C. J. Kibert and M. M. Fard, "Differentiating among low-energy, low-carbon and net-zero-energy building strategies for policy formulation," *Building Research & Information*, vol. 40, no. 5, pp. 625–637, 2012.

[11] A. Višković, V. Franki, and V. Valentić, "CCS (carbon capture and storage) investment possibility in South East Europe: a case study for Croatia," *Energy*, vol. 70, pp. 325–337, 2014.

[12] E. S. Rubin, S. Yeh, M. Antes, M. Berkenpas, and J. Davison, "Use of experience curves to estimate the future cost of power plants with CO_2 capture," *International Journal of Greenhouse Gas Control*, vol. 1, no. 2, pp. 188–197, 2007.

[13] M. R. M. Abu-Zahra, L. H. J. Schneiders, J. P. M. Niederer, P. H. M. Feron, and G. F. Versteeg, "CO_2 capture from power plants. Part I. A parametric study of the technical performance based on monoethanolamine," *International Journal of Greenhouse Gas Control*, vol. 1, no. 1, pp. 37–46, 2007.

[14] M. R. M. Abu-Zahra, J. P. M. Niederer, P. H. M. Feron, and G. F. Versteeg, "CO_2 capture from power plants: Part II. A parametric study of the economical performance based on mono-ethanolamine," *International Journal of Greenhouse Gas Control*, vol. 1, no. 2, pp. 135–1428, 2007.

[15] Z. Rongrong, Y. Yongping, D. Liqiang, and Y. Qin, "Economical performance study for NGCC system with CO_2 removal plant[C]," *International Conference on Sustainable Energy Technologies*, IEEE, 2009.

[16] Q. Chen, C. Kang, and Q. Xia, "Modeling flexible operation mechanism of co2 capture power plant and its effects on power-system operation," *IEEE Transactions on Energy Conversion*, vol. 25, no. 3, pp. 853–861, 2010.

[17] D. Rasodjo, "An economic study of carbon capture and storage system design and policy," *Dissertations & Theses - Gradworks*, 2011.

[18] M. Pollak, S. J. Phillips, and S. Vajjhala, "Carbon capture and storage policy in the United States: a new coalition endeavors to change existing policy," *Global Environmental Change*, vol. 21, no. 2, pp. 313–323, 2011.

[19] C. V. Stechow, J. Watson, and B. Praetorius, "Policy incentives for carbon capture and storage technologies in Europe: a qualitative multi-criteria analysis," *Global Environmental Change*, vol. 21, no. 2, pp. 346–357, 2011, https://doi.org/10.1016/j.gloenvcha.2011.01.011.

[20] J. Meadowcroft, "Caching the carbon: the politics and policy of carbon capture and storage," *Global Environmental Change*, vol. 21, no. 2, pp. 275–281, 2011.

[21] N. Markusson, A. Ishii, and J. C. Stephens, "The social and political complexities of learning in carbon capture and storage demonstration projects," *Global Environmental Change*, vol. 21, no. 2, pp. 293–302, 2011.

[22] H. Liu and K. S. Gallagher, "Driving carbon capture and storage forward in China," *Energy Procedia*, vol. 1, no. 1, pp. 3877–3884, 2009.

[23] R. S. Haszeldine, "Carbon capture and storage: how green can black be?" *Science*, vol. 325, no. 5948, pp. 1647–1652, 2009.

[24] R. Chaudhry, M. Fischlein, J. Larson et al., "Policy stakeholders' perceptions of carbon capture and storage: a? Comparison of four U.S. States," *Journal of Cleaner Production*, vol. 52, pp. 21–32, 2013.

[25] W. Kuckshinrichs, "Carbon capture and utilization as an option for climate change mitigation: integrated technology assessment," *Carbon Capture, Storage and Use*, pp. 1–9, 2015.

[26] R. Borchiellini, A. F. Massardo, and M. Santarelli, "Carbon tax vs CO_2 sequestration effects on environomic analysis of existing power plants," *Energy Conversion and Management*, vol. 43, no. 9-12, pp. 1425–1443, 2002.

[27] D. Nissen, "Pricing and policy for carbon capture and sequestration with learning by doing," *SSRN Electronic Journal*, 2008.

[28] L. M. Abadie and J. M. Chamorro, "European CO_2 prices and carbon capture investments," *Energy Economics*, vol. 30, no. 6, pp. 2992–3015, 2008.

[29] S.-J. Jeong, K.-S. Kim, J.-W. Park, D.-S. Lim, and S.-M. Lee, "Economic comparison between coal-fired and liquefied natural gas combined cycle power plants considering carbon tax: Korean case," *Energy*, vol. 33, no. 8, pp. 1320–1330, 2008.

[30] Y. Kemmoku, G. Shundoh, H. Takikawa, T. Kawamoto, and T. Sakakibara, "A study of the buying price of photovoltaic electricity under a carbon tax regime," *Electrical Engineering in Japan*, vol. 143, no. 2, pp. 38–49, 2003.

[31] R. Mendelevitch, A. Tissen, P.-Y. Oei, and J. Herold, "CO_2 highways for europe: modeling a carbon capture, transport and storage infrastructure for Europe," *SSRN Electronic Journal*, vol. 19, no. 1052, pp. 515–531, 2010.

[32] C. Huang, Y. Li, X. H. Lai, and X. Q. Li, "Optimal cleaning power generation investment strategy in a carbon tax and co2emission trading framework[J]," *Advanced Materials Research*, vol. 347353, pp. 2805–2810, 2011.

[33] M. Renner, "Carbon prices and CCS investment: a comparative study between the European Union and China," *Energy Policy*, vol. 75, no. 1, pp. 327–340, 2014.

[34] P.-Y. Oei, J. Herold, and R. Mendelevitch, "Modeling a carbon capture, transport, and storage infrastructure for Europe," *Environmental Modeling & Assessment*, vol. 19, no. 6, pp. 515–531, 2014.

[35] W. Cai, D. Singham, E. Craparo, and J. White, "Pricing contracts under uncertainty in a carbon capture and storage framework," *Energy Economics*, vol. 43, pp. 56–62, 2014.

[36] Z. Z. Yi, Y. S. Xing, and L. Y. Xiang, "Incentive regulation of power industry," *Journal of Chongqing University (Natural Science Edition)*, 2002.

[37] T. Jamasb and M. Pollitt, "Incentive regulation of electricity distribution networks: lessons of experience from Britain," *Energy Policy*, vol. 35, no. 12, pp. 6163–6187, 2007.

[38] A. Castillo and J. Linn, "Incentives of carbon dioxide regulation for investment in low-carbon electricity technologies in Texas," *Energy Policy*, vol. 39, no. 3, pp. 1831–1844, 2011.

[39] F. M. Menezes and X. Zheng, "Regulatory incentives for a low-carbon electricity sector in China," *Journal of Cleaner Production*, vol. 195, pp. 919–931, 2018.

[40] A. A. L. Kama, M. Fodha, and G. Lafforgue, "Optimal carbon capture and storage policies," *Environmental Modeling & Assessment*, vol. 18, no. 4, pp. 417–426, 2013.

[41] L. Sizhen, *Power System Power Planning in Low Carbon Economy [D]*, Huazhong University of Science and Technology, 2012.