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The robustness of low-carbon policies during China's electricity reform

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ABSTRACT

The progress in decarbonization that China has made coincides with its market liberalization process. However, whether the implemented and planned low-carbon policies designed before the reform will lose their effectiveness after the reform has not been analyzed. In this research, we introduce a new dimension of policy assessment into the discussion about low-carbon policies, namely, policy robustness during an economic transition. Here, robustness is used to assess whether a low-carbon policy can maintain its functions and effectiveness during a market reform. We develop a framework and the associated metrics for policy robustness analysis. We apply our framework to analyze China's fuel efficiency improvement project (FEIP) and compare the FEIP with the pricing-carbon policy (PCP) in two provinces, Guangdong and Fujian. The analysis shows that both the FEIP and PCP will lose some of their effectiveness during the market reform. However, implementing the PCP is more robust than implementing the FEIP because the PCP is able to promote the fuel efficiency improvement of cost-competitive coal-fired generators, whose market share will expand after the reform. The FEIP is particularly nonrobust in Fujian because of the distribution of the coal heat rates of Fujian's power plants. We further conclude that overinvestment in generation capacity leads to less robustness of both the FEIP and PCP during the reform. There has already been overinvestment in China's power generation capacity, but the current fuel efficiency policies can be seriously nonrobust and cause significant efficiency losses during electricity reform.

1. Introduction

China's energy transition in shifting towards a low-carbon energy sector coincides with its economic transition. When a sequence of low-carbon policies have been promulgated and implemented in China's energy sector, the reform of marketization is also on the progress and will reshuffle the structure of the energy industry. It is unclear whether those low-carbon policies implemented before the reform would still have the same economic effectiveness for carbon abatement after China's market-liberalization transition. To study this, we introduce the perspective of policy robustness to analyze how adaptive a low-carbon policy is in a reformed market if the policy was designed and implemented before the marketization reform.

Policy robustness is an important aspect of policy analysis. However, the robustness of low-carbon policy during China's electricity-market reform has not been systematically discussed. The concept of policy robustness reflects weather a policy can maintain its effectiveness when the market environment changes. For instance, whether a climate policy can always induce a high social welfare when the demand elasticity or other macro-economic parameters vary (Willenbockel, 2004; Antimiani et al., 2015). However, there lacks a sufficient discussion about the robustness of low-carbon policies during the economic transition of China's power sector. It is unclear whether the low-carbon policies implemented before the reform can maintain their effectiveness in the competitive market after the reform.

The robustness of low-carbon policies during China's market reform deserves attention but has not been systematically examined. China is the world's largest greenhouse gas (GHG) emitter, whose CO_2-abatement efforts coincident with the country's economic transition (Muntean et al., 2018; Wang and Chang, 1998; Wu et al., 2020; Cui et al., 2019). In China, the largest GHG-discharging department is the electricity sector, which is also the country's largest centrally-planned (Guan et al., 2009). China's electricity generation accounts for nearly one-third of the nation's GHG emissions (Liu, 2016). Thus, most current low-carbon policies are designed to reduce the CO_2 emissions generated by electricity generation (Chen et al., 2011; Zhao et al., 2008; Jia and Lin, 2020). On the other hand, China is reforming its electricity economy (Zeng et al., 2016; Lin et al., 2019; Yi et al., 2019). China's current electricity economy is not only centrally-planned but is also managed based on a unique egalitarianism principle: minimizing the profit difference between any two power plants caused by power-grid

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operation (Kroeze et al., 2004). The current electricity reform plans to replace the egalitarianism economy with a cost-bidding, competitive market (Zeng et al., 2016; Yin et al., 2019). It is unclear whether the low-carbon policies will maintain their effectiveness when the reform fundamentally reshuffles the rules of acquiring market sharing of the electricity sector (Zhao et al., 2008; Abhyankar et al., 2020; Yin et al., 2019; Xin-gang and Shu-ran, 2020).

Examining the robustness of China's low-carbon policies is also critical for global climate management. The magnitude of China's GHG emissions amplifies the impact of any variation in the effectiveness of low-carbon policies. Further, the robustness analysis is also necessary for international low-carbon policy assessment. The deepening penetration of new technologies, such as electric car and smart demand-responding facilities, have led to more innovation in the global energy sector (Yu et al., 2017; Orvis and Aggarwal, 2018). Consequently, the literature notes the requirements of the energy market's redesign (Yu, 2019; Munoz et al., 2018), which will change the effectiveness of the implemented low-carbon policies. Thus, exploring a robust low-carbon policy is critical for every country's CO_2 reduction, as well as for global management of climate- change.

In this research, we focus on the robustness of two alternative low-carbon policies. Once is the pricing-carbon policy (PCP) while the alternative is fuel-efficiency-improvement project (FEIP). Both policies can drive the coal-fired generation sector to retrofit their generators for improving their fuel efficiency. We focus on these two policies because that improving the fuel efficiency of coal-fired power plants plays a significant role in China's low-carbon management. Coal-fired technology occupies more than 60% of China's whole generation capacity (Liu, 2016). The coal-efficiency improvement plays a key role in China's energy management and GHG-abatement plan due to its potential of simultaneously reducing the GHG emissions as well as fuel costs (Zeng et al., 2019). The FEIP policy has been implemented during the 13th "five-year plan" (2016−2020) in the electricity sector (National Development of PRC and Reform Commission, China, 2014). The FEIP sets a mandatory coal-consumption-per-KWh standard: all existing power plants were required to reduce their average coal-heat rate to 310 g/KWh by 2020 (National Development of PRC and Reform Commission, China, 2014). Therefore, the FEIP policy aims at improving the fuel efficiency of inefficient generators that are also high carbon intensive. A comparative policy examined in this research is the pricing-carbon policy (PCP). We select the PCP policy as a comparison of the FEIP because of three reasons. First, the PCP policy is economically optimal no matter under which economic institutions. Second, the PCP policy can encourage both efficient and inefficient power plants to retrofit their generators in contrast that the FEIP only causes an improvement of inefficient ones. Third, the PCP is proposed as an alternative option of the FEIP policy for the next decade (Zhu et al., 2020).

We in this research focus on the alternative policies' robustness in short term during the electricity-market reform on the supply side. As a first step of discussing the low-carbon policy's robustness during China's economic transition, we analyze the effectiveness change of a policy implemented before the reform on the protocol defining how power plants obtain their market shares. China's electricity reform will change the economic institutions on both demand side and supply side. Here, we focus on the effect of the supply-side reform because of its primary impact on the efficiency of the implemented low-carbon policies, most of which regulate the emission from power plants. The electricity reform will fully change the rules determining how a power plant obtains its market share. Thus, the reform will change the effect of an implemented policy that has driven the power plants to retrofit their generators before the reform. In the short term after the reform, the power plants do not have time to further improve their fuel efficiency. Consequently, the carbon-reduction effect of the retrofit changes.

To the best of our knowledge, this is the first study that systematically discusses the robustness of low-carbon policies during China's electricity reform. In this research, we analyzed the change of economic efficiency of FEIP and PCP, and defined the concept of policy robustness of the fuel efficiency policy during market reform. The results demonstrated that policy robustness is a critical dimension for assessing low-carbon policies in an economy in transition.

The rest of the paper is organized as follows: we first briefly review the relative literature in the rest of this section; Section 2 introduces China's centrally-planned and egalitarianism electricity economy; Section 3 defines the concept of policy robustness and theoretically analyzes the robustness of PCP and FEIP; Section 4 develops a partial-equilibrium model to assess the robustness of FEIP and PCP in two Chinese provinces according to real data; and Section 5 concludes the paper.

1.1. Literature review

Our research are mainly related with two streams of literature. One stream is the studies on policy robustness. The concept of policy robustness outlines the stability of a policy's effectiveness when the market is exposed to an uncertain progress (Capano and Woo, 2017; Dewulf and Biesbroek, 2018). The growing evidence has manifested that a policy implemented in one market can have unexpected outcomes due to the disturbance from another market or the natural environment or the political system (Hartley et al., 2019; Howlett et al., 2018). The unexpected disturbance can fully or partially disable the policy from effectively functioning (Patashnik and Weaver, 2020; Capano and Woo, 2018). Therefore, the policy researchers argue that it is important to discuss the robustness of a policy (Dewulf and Biesbroek, 2018; Hartley et al., 2019). According to the current discussion about policy robustness, a policy is robust if the social welfare induced by the policy will roughly remain when the market environment or design is changed (Capano and Woo, 2017; Willenbockel, 2004). Some policy studies discuss the principles of designing robust policies (Patashnik and Weaver, 2020; Capano and Woo, 2018; Van der Steen and van Twist, 2018). The current literature has addressed the robustness of the macroeconomic and monetary policies when financial conditions are uncertain Willenbockel (2004), Cogley et al. (2008), Wollmershäuser (2006). The current literature also discovers that the same policy can face different disturbances in various markets (Fitzpatrick and Monson, 2020). Thus, the discussions about the robustness of a policy have to include the consideration of the heterogeneity of different markets. Discussions about climate policies and ecological policies also have noted that robustness is a key dimension for policy analysis and design (Levy et al., 2000; Hermeling et al., 2013). However, the existing literature focuses on climate policies' robustness when the demand elasticity or other macro-economics parameters fluctuate (Willenbockel, 2004; Antimiani et al., 2015). The current literature assesses policies' robustness by using the computational general-equilibrium model that assumes the energy sector is already market-based (Willenbockel, 2004; Antimiani et al., 2015). Few discussions have addressed the robustness of low-carbon policies when China's centrally-planned energy sector is in the process of its market-liberalization reform.

The other stream of literature related with this work is the studies comparing the policy of charging carbon tax and alternative standard-based policies. The standard-based policy has attracted sufficient academic attention as it is widely adopted in practical low-carbon governance (Parry and Williams III., 1999; Van der Ploeg, 2016). For instance, standard-based policies, rather than the carbon tax, are main stream in current low-carbon policies (Lyon and Yin, 2010). Many countries have implemented renewable- portfolio standards and clean-car standards (Lyon and Yin, 2010; Austin and Dinan, 2005). However, only a few regions have levied carbon tax or organized a cap-and-trade program (Carattini et al., 2019; Zhu et al., 2020). Beyond the discussion of efficiency losses of standard-based policies, researchers have noticed that these policies contain loopholes that allow strategic players to manipulate the market (Austin and Dinan, 2005; Zhu et al., 2020). Many

studies explored the reasons driving the governments to use a standard-based policy rather than a carbon tax (Lyon and Yin, 2010; Carattini et al., 2019; Ito, 2014). One reason is the existence of the political barriers (Lyon and Yin, 2010; Carattini et al., 2019), as standard-based policies are politically more acceptable than tax-based policies, even though the latter is economically more plausible (Lyon and Yin, 2010; Carattini et al., 2019). Another reason for governments preferring the standard-based policies is individuals' cognitive difficulties (Ito, 2014). In most current electricity retail markets, household consumers are charged either a flat rate or a stable "Time-of-Use" rate rather than a real-time local marginal price (LMP), which is the most economically efficient. LMP's time-varying nature complicates consumers' decisions regarding their electricity use (Ito, 2014). The third obstacle is the difficulty in measuring emissions, which explains why the standard-based policy plays a dominant role in the environmental management of the transportation sector. It is difficult to monitor and audit the emissions being discharged by vehicles (Austin and Dinan, 2005).

2. China's centrally-planned egalitarianism electricity economy and market reform

2.1. China's electricity economy before and during the reform

China's electricity reform is more than decomposing the vertical monopoly utility and deregulating the sector's market competition. In the U.S. and Europe, before their electricity reform, the regulated vertical monopoly utilities operated their systems for profit maximization under the regulations' restriction. In contrast, China's current electricity system operation does not pursue profit maximization or cost minimization. Instead, it pursues an egalitarian consequence: the impact of grid operation has the egalitarian impact on every power plant's profit opportunity. In this section, we explain the difference between China's electricity reform and the deregulation in the U.S. and Europe.

China's electricity economy is organized by provinces and is fully regulated according to a sequence of egalitarianism rules. Depending on the forecasted annual demand and fuel costs, every power plant's yearly generation quota and the associated flat selling rate are predetermined by the government at the beginning of a given year. The power-grid operator must fully implement the government-determined quotas, while every power plant's operation must follow the commands of the grid-system operator. If the annual quota implementation deviates from the original allocation, the grid-operation companies are penalized significantly. The quota allocation follows an egalitarianism principle: the government distributes generation quotas to power plants to minimize the difference between their annual capacity factors. Here, a power plant's capacity factor is the ratio of its annual generation to its total annual generation capacity. Therefore, two power plants will generate the same amount of electricity once they have the same generation capacity.

In addition to the quota allocation, the Chinese government has also promulgated a sequence of other egalitarianism regulations, restricting the hourly power-system operation. For instance, the power-grid operation must guarantee that all power plants' hourly generation capacities are roughly the same. The power plants' on-off frequencies should also be roughly equal during the whole month in the same province. These regulations were designed to minimize the differences between the system operation's impacts on profits across various power plants. Thus, we refer to those egalitarianism regulations and quota regulation together as the egalitarianism-quota assignment and regulation (EQAR).

The current electricity reform plans to abolish the EQAR. After the reform, the power plants will compete for market share through a cost-based bidding according to the reform plan. However, although China has experimented with the reform in a group of selected provinces, the reform's future remains uncertain. Most pioneer provinces only partially reformed their markets by allowing the power plants to compete for parts of the total demand. It is unclear when those pioneer provinces will fully reform their markets. Moreover, the market design has been largely adjusted several times during the last five years in these provinces. The ultimate design for the national market reform remains uncertain.

2.2. Impacts of EQAR on the effectiveness of low-carbon policies

The EQAR system distributes market share over generators by a central planner that guarantees every power plant an egalitarian generation quota. The EQAR distorts the effects of low-carbon policies by two mechanisms:

- Causing the market share of power plants to deviate from the socially optimal distribution and thus distorting the signal incentivizing power plants to retrofit their generators. If the market share is distributed according to socially optimal principle, some inefficient generators cannot obtain an opportunity of supplying electricity and will not retrofit their generators. In contrast, those inefficient power plants can gain market shares in EQAR. Therefore, charging a carbon tax will incentive those inefficient generators to retrofit their generators in EQAR. The EQAR distorts the retrofit decision of the inefficient power plants.
- Preventing the policies from affecting the market share of power plants. Consequently, the motivation of competing for more market share is blocked from incentivizing power plants to further retrofit their generators. In the U.S. and Europe, the implementation of an environmental policy affects every power plant's strategy, and the market share of all competitors. For instance, a carbon tax can simultaneously stimulate every power plant to cut down its emissions and expand its market share of cleaner power plants. In contrast, China's clean-electricity policies only encourage power plants to reduce their emissions. The EQAR prevents China's environmental policies from further reshuffling market share.

The above impacts mean that the same policy in China's current electricity economy will have different effects from in a fully competitive market. Under the EQAR system, all power plants will invest for energy-efficiency improvement after the carbon tax is added. However, under the market system, some power plants with high emissions and high costs will no longer generate electricity. This part of the transformation cost is wasted, resulting in a loss of efficiency. The size of the efficiency loss reflects the robustness of the carbon-tax policy.

3. Impacts of market reform and low-carbon policy's robustness

In this section, we define the concept of policy robustness during the electricity reform. According to the definition, we examine and compare the robustness of alternative low-carbon policies during the market reform. We consider an electricity economy whose generation sector consists of N coal-fired power plants. The i's power plant has the maximal generation capacity Cap_i and coal-heat rate e_i. We denote electricity demand and plant i's supply by D and q_i, respectively. The market share of plant i equals to $\frac{q_i}{D}$. The electricity supply will cause a generation cost $C_i^{gen}(q_i, e_i)$. We assumed that $C_i^{gen}(q_i, e_i)$ is convex and differentiable and an increase function of the coal-heat rate e_i. The electricity generation of power plant i will cause the emission of greenhouse gas. Here, λ_c refers to the social carbon cost due to per-ton coal consumption. Thus, the total social carbon cost caused by power plant i's power generation is $\lambda_c q_i e_i$. We assume that electricity demand in this study is inelastic for two reasons. First, China's electricity price on the demand side is still fully regulated. While we examine the policy's robustness in the short term after the reform, assuming the demand is inelastic captures the impacts of the current reform. Second, assuming that demand is inelastic, we can clarify the pure loss in

Table 1
Variable definition.

Definition	Variable
Number of power plants	N
Total electricity demand	D
Generation of plant i before reform	q_i
Generation capacity	Cap_i
Market share of plant i	$\rho_i = \frac{q_i}{D}$
Generation of plant i after reform	$\hat{q}_i$
Original coal-heat rate	e_i
Retrofit of plant i	ϵ_i
Social carbon cost rate	λ_c
Carbon cost rate of PCP	λ_{PCP}
Coal-heat rate after retrofit	$\hat{e}_i = e_i - \epsilon_i$
Retrofit cost	$C_i^{Imp}(\epsilon_i)$
Social carbon cost	$\lambda_c q_i e_i$
Generation cost	$C_i^{gen}(q_i, e_i)$
Overall benefit from improvement	$B_i^{Imp}(\epsilon_i)$
Social welfare from improvement	$J(\{\epsilon_i\}_{i=1}^n) = \sum_{i=1}^n B_i^{Imp}(\epsilon_i) - C_i^{Imp}(\epsilon_i)$

the effectiveness of policy implementation due to the direct impact of reforms on the supply side (see Table 1). We consider a scenario when a policy $\mathbb{P}$ is implemented before the reform and drives the power plant i to retrofit its generator. The retrofit reduces coal-heat rate of power plant i from e_i to $\hat{e}_i = e_i - \epsilon_{i,\mathbb{P}}$. The cost of retrofit for fuel efficiency is denoted by $C_i^{Imp}(\epsilon_{i,\mathbb{P}})$, which is convex and differentiable. After the reform, the retrofits of all power plants can still reduce the social cost of electricity generation. However, if the retrofit portfolio $\epsilon_{\mathbb{P}} = \{\epsilon_{i,\mathbb{P}}\}_{i=1}^N$ is not socially optimal in the competitive market scenario, a dead-weight loss will occur.

In this research, we use the dead-weight loss induced by $\epsilon_{\mathbb{P}}$ in the competitive market to develop the metric of the extent of the non-robustness of the policy $\mathbb{P}$. If the policy $\mathbb{P}$ is implemented before the reform but causes a very large dead-weight loss in the market after the reform, we can say that $\mathbb{P}$ is non-robust during the reform. Therefore, we have the following definition.

Definition. The extent of non-robustness of a policy $\mathbb{P}$ in the short term when the demand is inelastic is

$$\mathbb{NC}_{\mathbb{P}} = \frac{C_{market}(\epsilon_{\mathbb{P}}) - C_{market}(\epsilon^*_{market})}{C_{market}(\epsilon^*_{market})} \times 100\% \tag{1}$$

Here, $C_{market}(\epsilon_{\mathbb{P}})$ is the total cost that the whole electricity economy under the policy $\mathbb{P}$ after the reform. $C_{market}(\mathbb{P})$ consists of three components. One component is the total generation cost $\sum_{i=1}^n C_i^{gen}(\hat{q}_i, \epsilon_{i,\mathbb{P}})$. Note that in the reformed market, the generation of power plant $\hat{q}_i$ will be distributed through the generation cost-based bidding. The second component is the social carbon cost $\sum_{i=1}^n \lambda_c q_i e_i$. Another component of $C_{market}(\epsilon_{\mathbb{P}})$ is the total retrofit cost $\sum_{i=1}^n C_i^{Imp}(\epsilon_{i,\mathbb{P}})$. $C_{market}(\epsilon^*_{market})$ is the total social cost caused by the socially-optimal retrofit in the after-reformed market.

Note that $\mathbb{NC}_{\mathbb{P}}$ is the percentage of the dead-weight loss induced by $\epsilon_{\mathbb{P}}$ to the social cost induced by the optimal retrofit in the reformed market. Therefore, in the rest of this section, we will first clarify the optimal retrofit portfolio. Then, we will discuss the non-robustness of two alternative policies: the FEIP and the PCP.

3.1. Optimal retrofit in the after-reform competitive market

The optimal fuel efficiency policy maximizes the net social benefit from the technological improvement of each power plant. The overall benefit includes two terms: the fuel-cost saving and the carbon-cost saving from avoiding the carbon emission.

$$B_i^{Imp}(\epsilon_i) = \lambda_c \times (q_i e_i - \hat{q}_i(e_i - \epsilon_i)) + (C_i^{gen}(q_i, e_i) - C_i^{gen}(\hat{q}_i, e_i - \epsilon_i))$$

In a cost-competitive market, the retrofits of power plants not only change the power plants' coal-heat rates but also can reshuffle the distribution of market shares. We use $\hat{q}_i$ to denote the electricity generation of power plant i after the retrofit. Thus, the social optimal improvement portfolio $\epsilon^*_{market} = \{\epsilon^*_{1,market}, \epsilon^*_{2,market}, \dots, \epsilon^*_{n,market}\}$ are calculated from the social-welfare optimal problem given below:

$$\max_{\{\epsilon_i\}_{i=1}^n} J(\{\epsilon_i\}_{i=1}^n) = \sum_{i=1}^n \left(B_i^{Imp}(\epsilon_i) - C_i^{Imp}(\epsilon_i)\right) \tag{2}$$

Here, the social welfare is defined as the total gain from energy saving and carbon avoidance subtracting following the literature (Spicker, 2017)(Deaton, 1980). The optimal retrofit portfolio ϵ^*_{market} trades off between the benefit from fuel efficiency improvement and the retrofit cost. Note that, the fuel cost saving from the retrofit is contingent to both the change of market-share distribution and the declines of those retrofitted power plants. According to the first-order condition of Eq. (2), the optimal retrofit portfolio ϵ^*_{market} satisfies the following condition:

$$\begin{aligned}\frac{\partial C_i^{Imp}(\epsilon_i)}{\partial \epsilon_i} =& \lambda_c \sum_{t=1}^T \{\hat{q}_{i,t} - \frac{\partial \hat{q}_{i,t}}{\partial \epsilon_i}[(e_i - \epsilon_i) + \sum_{j \neq i}(e_j - \epsilon_j)\frac{\frac{\partial \hat{q}_{j,t}}{\partial \epsilon_i}}{\frac{\partial \hat{q}_{i,t}}{\partial \epsilon_i}}]\} \\ &+ \frac{\partial C_i^{gen}(q_{i,t}, e_i - \epsilon_i)}{\partial \epsilon_i}\Big|_{\{\epsilon_i = \epsilon^*_{i,market}\}_{i=1}^n}\end{aligned} \tag{3}$$

Note that there are three terms inside the first brace on the right-hand side of the Eq. (3). The first two terms together denote the carbon-cost saving from a system's emission reduction, caused by i's efficiency improvement and market share expansion. The third term refers to the emission rebound due to i's increase in market share.

3.2. The non-robustness of FEIP

FEIP is a command-based policy, which requires the inefficient generators to retrofit their generators for satisfying a mandatory standard. We assume that the FEIP's mandatory standard is S ton$/MWh$. When the FEIP is implemented, the saving of social carbon cost reduction are not included into the consideration of power plants. Further, the retrofit will not influence the market shares of power plants in the EQAR scenario. Thus, when the FEIP is implemented before the reform, only those power plants whose coal-heat rates are higher than the standard will retrofit their generators to meet the standard. The retrofit portfolio $\{\epsilon_{i,FEIP-EQAR}\}_{i=1}^n$ is

$$\epsilon_{i,FEIP-EQAR} = \max\{0, e_i - S\} \tag{4}$$

We argue that the FEIP's retrofit portfolio $\{\epsilon_{i,FEIP-EQAR}\}_{i=1}^n$ must be different from the socially-optimal portfolio ϵ^*_{market} after the reform. In the reformed market, the most inefficient power plants usually can only have very limit market shares. Thus, the extent of optimal retrofits on the most inefficient power plants have to be limited. However, the FEIP forces the most inefficient power plants to improve by $e_i - S$, which is a significant extent. Thus, we have the following proposition.

Proposition 3.1. *The FEIP implemented before the reform lead to a retrofit portfolio $\{\epsilon_{i,FEIP-EQAR}\}_{i=1}^n$ that is different from the socially-optimal portfolio ϵ^*_{market} of the competitive market. Thus, the FEIP's non-robustness $\mathbb{NC}_{FEIP} = \frac{C_{market}(\epsilon_{FEIP-EQAR}) - C_{market}(\epsilon^*_{market})}{C_{market}(\epsilon^*_{market})} \times 100\%$ must be positive. The FEIP is more non-robust when the low-efficient power plants have large-size generation capacities.*

3.3. The non-robustness of PCP

If the PCP is implemented before the reform, the power plant i decides the extent of efficiency improvement by optimizing its net gain from the retrofit. In EQAR, the generation of each power plant is distributed according to an egalitarian generation quota which means q_i equals to $D\frac{Cap_i}{\sum_i Cap_i}$. And no matter what carbon emission reduction policy is implemented, the generation of each power plant remains unchanged. Therefore, the gain from the retrofit is only determined by cost saving during the power generation, which include two terms: the environmental gain from avoiding the carbon emission, and the economic gain from fuel-cost saving in the whole operation period.

$$\mathcal{B}_i^{Imp}(\epsilon_i) = \lambda_{PCP} q_i \epsilon_i + [C_i^{gen}(q_i, e_i) - C_i^{gen}(q_i, e_i - \epsilon_i)] \tag{5}$$

Where λ_{PCP} is the carbon tax of per ton coal consumption charged in PCP policy. The power plant i decides the extent of efficiency improvement by trading off between the gain and cost of the retrofit. The optimal $\epsilon_{i,PCP-EQAR}$ is solved from the net-gain maximization problem given below:

$$\max_{\epsilon_{i,PCP-EQAR}} J_i(\epsilon_i) = \mathcal{B}_i^{Imp}(\epsilon_i) - C_i^{Ret}(\epsilon_i) \tag{6}$$

Thus, we have the following proposition

Proposition 3.2. *power plant i's optimal range of retrofit driven by the PCP policy $\epsilon_{i,PCP-EQAR}$ satisfies the first-order condition:*

$$\frac{\partial C_i^{Ret}(\epsilon_i)}{\partial \epsilon_i} = \lambda_{PCP} \times q_i - \frac{\partial C_i^{gen}(q_i, e_i - \epsilon_i)}{\partial \epsilon_i}\Big|_{\epsilon_i = \epsilon_{i,PCP-EQAR}} \tag{7}$$

The above condition explains that a power plant i decides its efficiency improvement ϵ_i by balancing off the marginal cost of the efficiency improvement and the corresponding benefit from generation-cost saving and carbon-payment avoidance. In the Appendix, we raise an example of a power plant's optimal improvement decision when its marginal retrofit cost is a linear function.

Remark. The retrofit portfolio driven by the PCP is also socially optimal in the EQAR if the carbon rate charged by the PCP is equal to the social carbon cost of per-unit carbon emission. In fact, the social optimal improvement portfolio $\epsilon^*_{EQAR} = \{\epsilon^*_{1,EQAR}, \epsilon^*_{2,EQAR}, \dots, \epsilon^*_{N,EQAR}\}$ and associated social welfare are calculated from the social optimal problem given below:

$$\begin{aligned}\max_{\{\epsilon^*_{EQAR}\}_{i=1}^n} J(\{\epsilon_i\}_{i=1}^n) &= \sum_{i=1}^n \{\mathcal{B}_i^{Imp}(\epsilon_i) - C_i^{Ret}(\epsilon_i)\} \\ &= \sum_{i=1}^n \{\lambda_c q_i \epsilon_i + [C_i^{gen}(q_i, e_i) - C_i^{gen}(q_i, e_i - \epsilon_i)] - C_i^{Ret}(\epsilon_i)\}\end{aligned} \tag{8}$$

The first-order condition of ϵ^*_{EQAR} is the same as Eq. (7) when λ_{PCP} equals to λ_c.

We argue that $\{\epsilon_{i,PCP-EQAR}\}_{i=1}^n$ must be different from the socially-optimal portfolio ϵ^*_{market} after reform even if the PCP sets the carbon rate as the same as the social carbon cost of per-unit carbon emission. Comparing the two first-order conditions Eqs. (3) and (7), $\epsilon_{i,PCP-EQAR}$ is different from ϵ^*_{market}. In the EQAR scenario, the inefficient power plants have more market share than in the competitive market. Therefore, those inefficient power plants over-invest in the retrofits. In contrast, the highly-efficient power plants have smaller market share in the EQAR scenario than in the competitive market. Therefore, the efficient power plants under-invest in the retrofits for fuel-efficiency improvement. Therefore, the PCP policy's non-robustness is contingent on whether the large power plants are highly efficient. If the power plant's efficiency is positively correlated with their size, the PCP in EQAR encourages these efficient generators to further improve their efficiency. The benefits of those improvements' will be amplified after the reform because the highly-efficient generators can further expand their market share during cost competition.

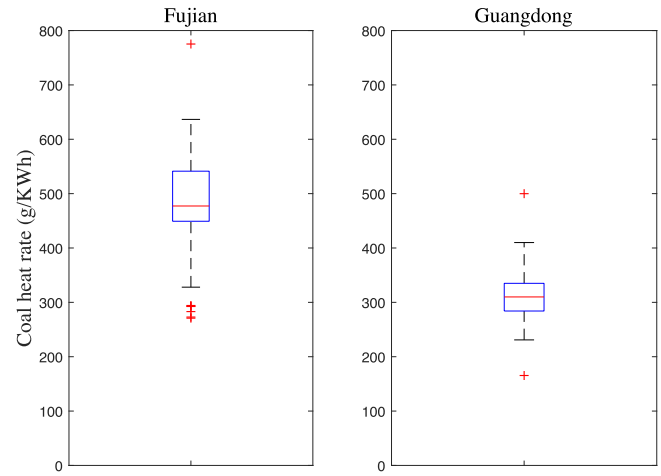

Fig. 1. Distribution of Power plants in Fujian and Guangdong.

Proposition 3.3. *The PCP implemented before the reform leads to a retrofit portfolio $\{\epsilon_{i,PCP-EQAR}\}_{i=1}^n$ that is different from the socially-optimal portfolio ϵ^*_{market} of the competitive market. Thus, the PCP's non-robustness $\mathbb{NC}_{PCP} = \frac{C_{market}(\epsilon_{PCP}) - C_{market}(\epsilon^*_{market})}{C_{market}(\epsilon^*_{market})} \times 100\%$ must be positive. The PCP is less non-robust when the power plant's efficiency is positively correlated with their size.*

4. Robustness of PCP and FEIP in various provinces

In this section, we analyze the non-robustness of the PCP and the FEIP policies according to the data from two sample provinces. We hope to understand how the non-robustness of the two policies are determined from the numerical experiments.

4.1. Data and scenario setting

Our power plant data are from China Southern Power Grid and we acquired our retrofit cost data from Zeng et al. (2019). In order to analyze the robustness of PCP and FEIP, we developed a partial-equilibrium model. Our model is designed to capture power plants' decisions about their generations and investment for retrofit of their efficiency improvement. The power system calculates the market share of the power plants according to egalitarian generation quota in EQAR and generation cost-based bidding in the reformed market, respectively. According to the market share allocation, the efficiency-investment model determines the efficiency-improvement extent of every power plant. Since we focus on the policy robustness during the reform, we assume that the demand is inelastic. We also concentrate our discussion on the case when power plants do not exercise their market power after reform so that the analysis results will not be contaminated by the market power's effect. Further, our model does not include the impacts of transmission congestion and losses because of China's sufficient intra-provincial transmission capacity and low transmission losses.

We use partial-equilibrium model to analyze the robustness of PCP and FEIP in the two selected provinces, Fujian and Guangdong. We compare these neighboring provinces, mainly because they both have different market environments and data availability. First, the power plants in the two provinces have divergent fuel efficiency distributions, as shown in Fig. 1. On average, Guangdong's power plants are more efficient. A large proportion of generators in Guangdong reached the FEIP standard even before its implementation. In contrast, only a small proportion of generators in Fujian have lower coal-heat rates than the current FEIP standard. Furthermore, the efficiency levels of Fujian's power plants are more varied than those in Guangdong. Thus, comparing the two provinces allowed us to examine how the original efficiency

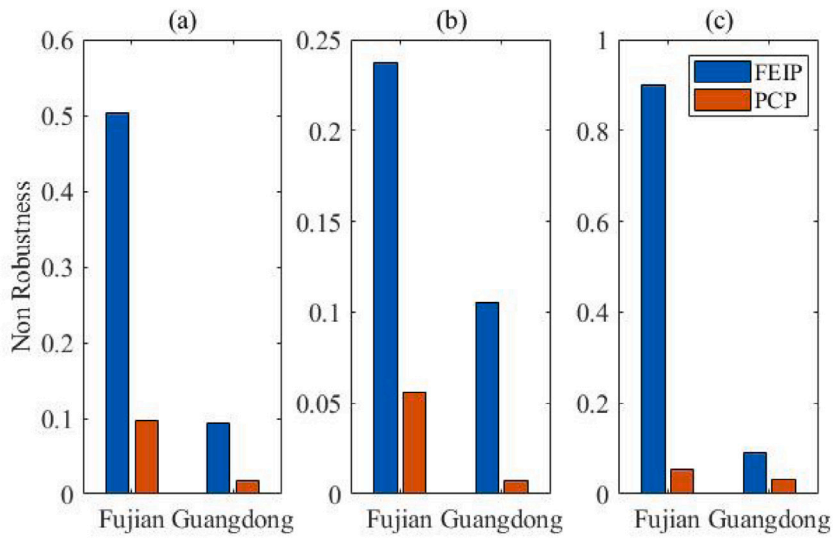

Fig. 2. The non robustness of FEIP and PCP in Fujian and Shandong. (a) low demand and low retrofit-cost scenario (b) high demand scenario (c)high retrofit-cost scenario.

distribution over power plants affects a fuel efficiency policy's robustness. Further, Guangdong and Fujian have different agendas for their electricity market reform; this means the urgency for implementing a robust policy in the two provinces are different. Guangdong is a pioneer province for electricity reform, while Fujian was not included in it at the beginning. Guangdong started to shift to a competitive wholesale electricity market and thus must immediately include policy robustness into their low-carbon transition. In contrast, Fujian has not promulgated a clear reform agenda for the power generation sector.

We also examined the consequence of varying demand, coal price, and efficiency-improvement cost in the same province. We collected the data for 2013, of each power plant's heat rate and standard-coal consumption from China's Environmental Statistics Database (CESD). We also collected the data of the total generation of both provinces' from coal-fired power plants during March 2015. We assumed the cost of the fuel efficiency improvement to be quadratic. The cost function of fuel efficiency improvement was generated according to the methodology proposed by Zeng et al. (2019).

4.2. Empirical simulation

Our results demonstrate that policy robustness is a key dimension for assessing a low-carbon policy in a transition economy. If the optimal carbon tax for coal use is 50 $yuan/ton$, the current FEIP standard that is $310g/KWh$ is much less robust than PCP in both markets. In both Guangdong and Fujian, the dead-weight loss caused by FEIP is roughly 10% higher than that caused by implementing PCP in EQAR as shown in Fig. 2. When the optimal tax for coal use is higher, the robustness difference between PCP and FEIP is larger, as shown in Fig. 3.

Our results confirm that the non-robustness of a policy $\mathbb{P}$'s is contingent on whether the improvement portfolio $\{\epsilon_{i,\mathbb{P}}\}_{i=1}^{n}$ caused by $\mathbb{P}$ is close with to $\{\epsilon^{*}_{i,market}\}_{i=1}^{n}$, the social-optimal. In Fig. 4, we present the efficiency-improvement portfolio caused by different policies, if the optimal tax for coal use is 50 $yuan/ton$. In Guangdong province, the FEIP-driven efficiency-improvement portfolio $\{\epsilon_{i,FEIP-EQAR}\}_{i=1}^{n}$ is nearly perpendicular to $\{\epsilon^{*}_{i,market}\}_{i=1}^{n}$ when the FEIP standard is $310g/KWh$ (Fig. 4 subplot B guangdong). In contrast, the PCP implemented in EQAR improves many power plants that would also be improved according to $\{\epsilon^{*}_{i,market}\}_{i=1}^{n}$. Consequently, in Guangdong province, PCP implemented before the reform is much more robust than FEIP. In Fujian province, both FEIP and PCP implemented before the reform causes the efficiency portfolios to be almost perpendicular to $\{\epsilon_{i,FEIP-EQAR}\}_{i=1}^{n}$ (Fig. 4 subplot A Fujian). Thus, neither policy is robust during the reform. Compared to FEIP, PCP triggers stronger efficiency improvements that significantly reduce the generators' coal-heat rate to an economically optimal level after the reform. Thus, in Fujian, FEIP is still less robust than PCP .

PCP is more robust than FEIP during the reform because PCP causes more investment on improving highly-efficient power plants than FEIP does. According to Eq. (3) the social optimal improvement portfolio requires the relatively higher efficiency power plants to significantly improved their efficiency (because they have the highest market share in a competitive market). However, FEIP requires a greater amount of investment to improve the least efficient generators to satisfy the $310g/KWh$ standards. The perpendicularity between the social optimal improvement plan and FEIP's effects results in a high dead-weight loss. In fact, a great amount of efficiency-improved generation capacity driven by FEIP will be idle after the reform. According to the result of our numerical experiment, there would be 58 power plants in Guangdong province retrofitting their power plants when the FEIP is implemented before the reform. Among those 58 plants, 27 of them will fully lose their market shares during the competition in the cost-competitive market after the reform. In Guangdong, over 70% of the retrofitted power plants cannot fully maintain their market share after the reform. In contrast, the PCP in EQAR will generate an efficiency-improvement incentive to every single power plant, irrespective of whether its coal-heat rate is lower than $310g/KWh$. Thus, the relatively highly efficient power plants will improve their efficiency under PCP even in EQAR, whose pay off will be amplified after the reform. Thus, PCP is more robust than FEIP.

In order to understand how the energy mix in a market influences the robustness of FEIP and PCP, we design a controlled numerical experiment. In the experiment, we let the two markets both have a flat demand that is equal to 40% of the total generation capacity. We flatten the demand profile to exclusive the impacts from the demand patterns while the capacity factor in China around 2015 is around 40%. For every given policy design, we compare the robustness of PCP and FEIP in the two markets that only differs from each other by their energy mix. Fig. 3. summarizes the results.

The results of our numerical experiment argue that the robustness of FEIP in Fujian is different from in Guangdong because the distribution of power plant's coal-heat rate varies by province. On average, Guangdong's power plants are highly efficient while Fujian's power plants are very inefficient. Most of Guangdong's power plants are already more efficient than FEIP's standard. In contrast, a great number of Fujian's power plants are less efficient than FEIP's standard. The difference in the power plant's efficiency causes three consequences:

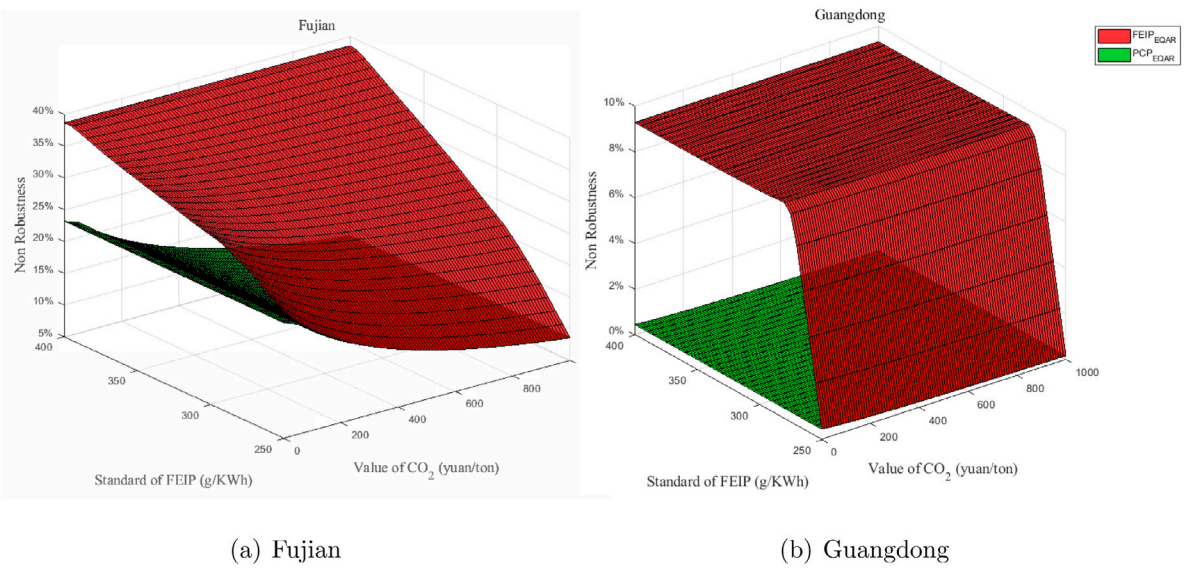

Fig. 3. The non-robustness.

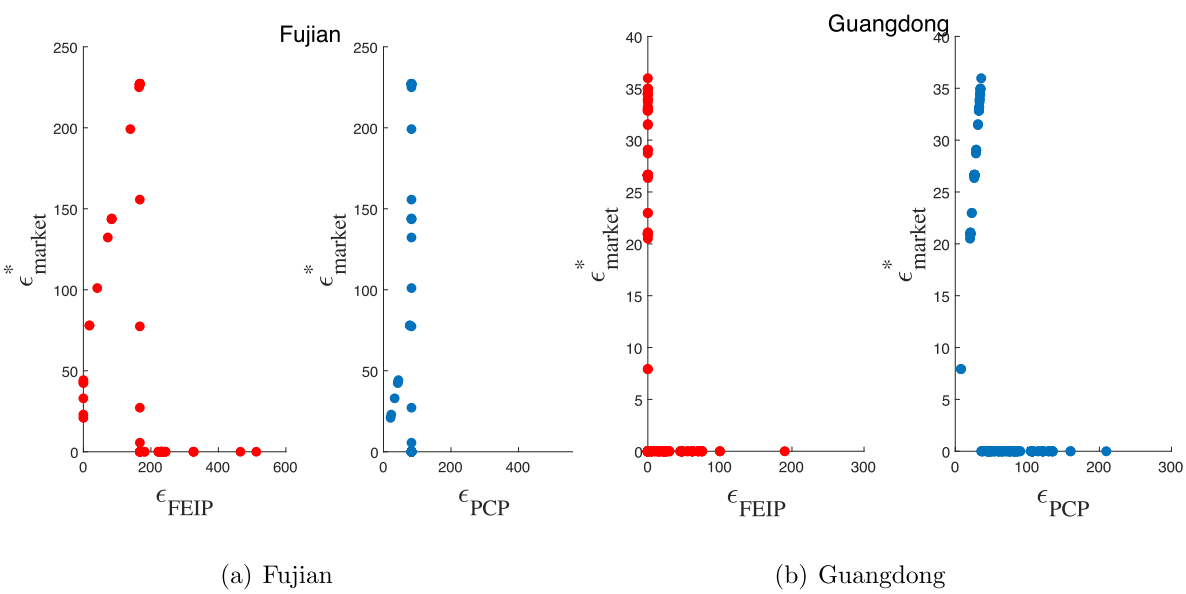

Fig. 4. Correlation between the power plants' improvements of fuel efficiency driven by the policies implemented in EQAR and the socially optimal power plants' improvements after reform.

1. FEIP causes much larger fuel-efficiency-improvement costs in Fujian than in Guangdong. FEIP only forces a small number of power plants in Guangdong to invest in fuel-efficiency improvement thus cause a small investment cost. In contrast, FEIP forces a large number of power plants to improve their fuel efficiency and causes a large investment cost.
2. After the reform, more improved power-generation capacity is idle in Fujian than in Guangdong. All improved power plants in Guangdong fully loss their market share. In contrast, Fujian's improved power plants loss around 30% of their market share that was allocated in EQAR. However, the size of improved power-generation capacity in Fujian is much larger than in Guangdong. Therefore, the total idle generation capacity in Fujian is still higher than in Guangdong.
3. Compared with Guangdong, Fujian has a higher efficiency loss caused by that FEIP discourages the improvement of efficient power plants. The power plants that have satisfies FEIP standard in Fujian are less efficient than those in Guangdong. Thus, improving those efficient power plants according to the social-optimal portfolio will incur a lower marginal cost in Fujian than in Guangdong. However, FEIP is unable to encourage those efficient power plants to further improve their fuel efficiency to the socially optimal level. Consequently, the opportunity cost of adopting FEIP is significantly higher in Fujian than in Guangdong.

The three consequences together cause that FEIP is less robust in Fujian than in Guangdong.

The robustness of both policies is contingent on their design. Fig. 3 shows the impacts of FEIP and PCP's design on their robustness after the reform. When the carbon cost is high, FEIP is very non-robust. The high carbon cost requires a significant efficiency improvement of those power plants that have already satisfied FEIP standard. Those power plants will expand their market share during the reform. Thus, the electricity reform will seriously amplify FEIP's efficiency loss. In contrast, PCP implemented in EQAR is more robust when the carbon

cost is higher since PCP will incentivize highly efficient power plants to improve their fuel efficiency thus more robust than FEIP.

FEIP and PCP's robustness are also contingent on the demand for electricity and the cost of fuel-efficiency improvement. As shown in Fig. 2, both FEIP and PCP are more robust when market demand, as well as the capacity factor, is high. When the demand is high, FEIP-improved inefficient generators will also acquire more market share. Consequently, the dead-weight loss decreases with an increase in demand. Similarly, PCP implemented in EQAR is also more robust when the demand is higher. However, demand does not change the conclusion that the PCP is more robust than FEIP in both markets.

The retrofit cost of fuel-efficiency improvement will significantly impact the robustness of both FEIP and PCP in Fujian rather than Guangdong (Fig. 2). The range of difference of fuel efficiency in power plants determines whether FEIP's robustness is sensitive to the efficiency-improvement cost. Fujian province has a large number of low-efficiency power plants, which can induce significant costs in complying with the FEIP standard. Thus, when the efficiency improvement is costly, the dead-weight loss of FEIP is high. In contrast, most of Guangdong's power plants have a lower coal-heat rate than the FEIP standard. Consequently, the cost of complying with FEIP is lower in Guangdong. Thus, FEIP's robustness is not sensitive to the variation of efficiency-improvement cost.

5. Conclusion

In this research, we introduce a new dimension for the study of low-carbon policy's assessment and design: the robustness of a low-carbon policy during the economic transition. The robustness of a low-carbon policy reflects the capability of a policy to maintain its effectiveness during an economic transition or market redesign. In contrast to traditional discussions about the efficiency and welfare effects of policies, the analysis on policy robustness addresses the stability of the low-carbon policy's effectiveness when the market environment is changing. We also develop a research framework for analyzing the robustness of environmental policies during the economic transition and define an associated metrics. To our best knowledge, we are the first research about the robustness of environmental policies during the economic transition.

As a first step of studying the robustness of low-carbon policies during a transition of economic institution, we examine the scenario when the power plants respond to a low-carbon policy according to the current economic institution. We develop a framework for studying the policy robustness when the power plants statically make their retrofit decision once a fuel-efficiency policy is implemented in EQAR. We apply our framework of robustness to analyze the robustness of FEIP policy in China and compare it with the socially optimal PCP policy. We demonstrate the robustness during the economy transition is an important feature of a low-carbon policy. We find that some current implemented policies such as FEIP are very non-robust so that will largely loss its effectiveness after the reform. In contrast, some other policies such as a carbon tax can be relatively more robust. The robustness of the current implemented policies also determines the uncertainty of carbon reduction in an electricity system. The differences between various policies' robustness remainder the policy makers that the design and selection of low-carbon policies have to include the consideration about the policy robustness during the market reform. In particular, China's policy makers must consider to adopt the PCP policy to replace the FEIP policy because the former is more robust than the latter during the market reform.

Our analyses also suggest that the relative robustness of alternative carbon policies varies over regions. For instance, FEIP is much less robust than PCP in Fujian province. In contrast, the difference between the two policies' robustness are moderate in Guangdong although FEIP is still less robust than PCP. The demand level, the carbon's value, and the retrofit cost determine the relative robustness of alternative carbon policies. From the robustness perspective, every electricity market in a transition economy ought to select their own robust carbon policy rather than that the whole nation has the uniform carbon policy for all markets.

As the first step of studying the non-robustness of low-carbon policies during an economic transition, our research only provide a basic framework for the relative studies. A sequence of future researches is necessary. We suggest four aspects deserve further exploration in future studies. First of all, it is necessary to analyze the robustness of low-carbon policies during the other parts of the electricity reforms. In this research, we focus on the policy robustness during the supply-side reform. Beyond the supply-side reform, the deregulation of the retail market and the reform on facilitating the service market can also affect the effectiveness of the low-carbon policies.

Second, it is critical to comprehensively examine the robustness of the low-carbon policies in all provinces in China. In our research, the sample provinces allow us to analyze the dynamics that the market environment affects the robustness of the low-carbon policies. The robustness of the low-carbon policies in various provinces and the whole China has not been testified. The electricity sector is the largest carbon-discharging department of China where most current and planned low-carbon policies are designed to adapt the EQAR. While China has promulgated its carbon-mitigation plan for the next decade, the policymakers have to have a full understanding of the low-carbon policies' robustness during the reform in the whole country.

Third, the model framework of analyzing the policy robustness can be further developed. Our framework here is able to support the analysis on the robustness of a low-carbon policy when the power plants do not consider the possible market reform. Our current research can capture the main dynamic in China during the last decade while most provinces had not yet initiated their reform on developing a wholesale market by 2019. Therefore, our current conclusions mainly manifest the robustness of the low-carbon policies implemented in the last decade. In the next decade, while China's provinces start to promulgate their plan of developing wholesale markets, the power plants have an expectation about the reform. It is necessary to consider the policy robustness when the power plants select their retrofit strategies to adapt both the environments before and after the reform.

Last but not least, we suggest that the robustness of low-carbon policies during economic transition is an important issue not only in China but also all over the world. While the new energy technologies, such as renewable-energy and vehicle-to-grid technology, have started to reshape the power-grid system all over the world. The market design of the electricity sector is fundamentally changing. Thus, the low-carbon policy's robustness during the innovation of the electricity sector's market design will be a significant issue not only in China but also in other countries around the world.

CRediT authorship contribution statement

Yaoyu Zhang: Modeling, Analyzing, Writing. **Chenye Wu:** Discussion. **Nan Gu:** Discussion. **Yang Yu:** Proposing the research idea, Modeling, Analyzing, Writing.

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Table B.2
Statistics of power plants and demand.

	Variable	Mean	Standard deviation
Fujian	Heat rate of power plant (g/KWh)	477.2640	108.0398
	Capacity of power plant(MWh)	350	241.9400
	Demand	10105	2236
Guangdong	Heat rate of power plant (g/KWh)	309.9621	38.7150
	Capacity of power plant (MWh)	300	292.7344
	Demand (MWh)	23366	11603

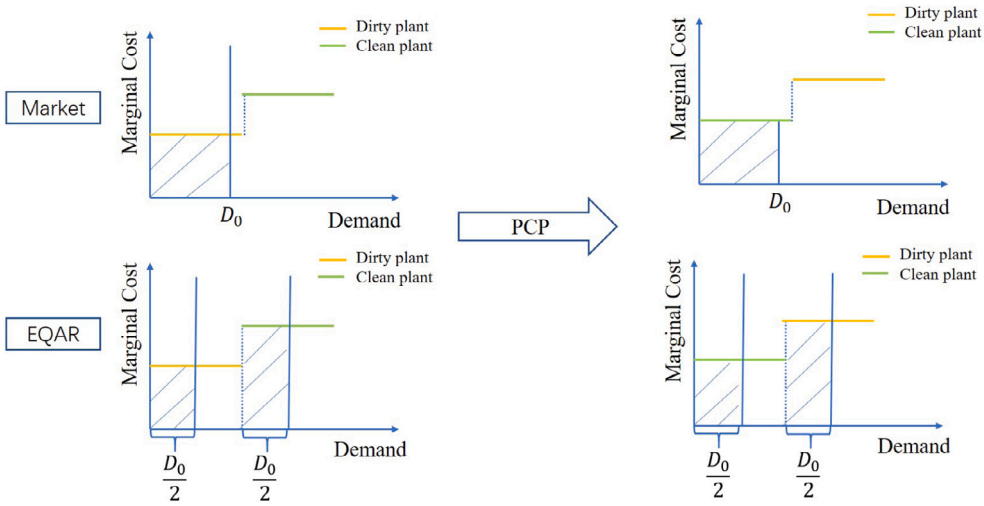

Fig. 5. Conceptual Figure-1.

Appendix A. A retrofit of PCP in EQAR

In EQAR, The amount of electricity generated by each power plant will not change. Suppose that the generation cost is proportional to the generation as below:

$$C_i^{gen}(q_i, e_i) = p_{coal} q_i e_i \tag{9}$$

Where p_{coal} is price of per ton coal.

Suppose that for every power plant, its cost for retrofit ϵ_i is

$$C_i^{Imp}(\epsilon_i) = \alpha_i \epsilon_i + \frac{\beta_i}{2}\epsilon_i^2 \tag{10}$$

So for power plant i, the first-order condition is:

$$\frac{\partial C_i^{Imp}(\epsilon_i)}{\partial \epsilon_i} = (p_{coal} + \lambda_{PCP}) \times q_i \tag{11}$$

Then, according to the first-order condition, optimal $\epsilon_{i,PCP-EQAR}$ can be calculated

$$\epsilon_{i,PCP-EQAR} = \frac{(p_{coal} + \lambda_{PCP}) \times q_i - \alpha_i}{\beta_i} \tag{12}$$

Appendix B. Descriptive statistics of samples

In this research, we select Guangdong and Fujian provinces as the studied provinces. In Table B.2, we summarize the mean and standard deviation of the hourly demand and the coal heat rate and generation capacity of the coal-fired power plants in the studied provinces. Averagely, the power plants in Fujian have a higher average carbon intensity than that in Guangdong.

In particular, we would like to emphasize that the two provinces have different distribution of heat rate of power plants. As shown in Fig. 1, the power plants in Fujian have much more divergent coal heat rates than those in Guangdong.

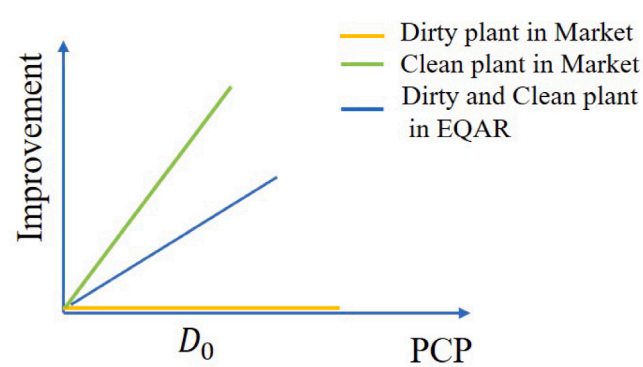

Fig. 6. Conceptual Figure-2.

Appendix C. Conceptual figure

Figs. 5 and 6 conceptually explain the two mechanisms that EQAR distorts the effectiveness of PCP. As shown in the first row of Fig. 5, a sufficiently high carbon price charged by the PCP policy can reorder the competitiveness of two power plants. Consequently, the market share of clean and dirty power plants change in market. In contrast, PCP cannot change the market shares over the two power plants in EQAR. Therefore, the EQAR disables the PCP from reducing GHG through redistribution market shares.

Fig. 6 explains how the EQAR further distorts the power plants' decision about improving their fuel efficiency. In a fully competitive market, the dirty power plant will not improve its fuel efficiency because it cannot obtain any market share, shown as the yellow line. The clean power plants will aggressively improve their fuel efficiency according to the rate of carbon price, shown as the green line. In EQAR, however, both dirty and clean generators will improve their fuel efficiency by the same range given a carbon rate because the two power plants equally split the market share.

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