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Competition vs cooperation: renewable energy investment under cap-and-trade mechanisms

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Abstract

This paper explores the incentives of investment in renewable energy of two utility firms who compete or cooperate under either a cap-and-trade grandfathering mechanism (GM) or benchmarking mechanism (BM). We find that utility firms will invest in renewable energy more under BM than under GM, in both competitive and cooperative markets, and they will invest more in a competitive market than in a cooperative market, under either GM or BM. Furthermore, utility firms will produce more electricity and generate more total carbon emissions under BM than under GM. The profits of two firms, however, are higher in cooperative market than in competitive market. The government will benefit from implementing a BM to encourage utility firms to invest in renewable energy in a competing market.

Keywords: Cap-and-trade mechanism, Renewable energy investment, Competitive market, Cooperative market

Introduction

Greenhouse gases result in global warming (Pan et al. 2014), leading to challenges to economic development and human survival (Saidur et al. 2007). Of all greenhouse gases, carbon dioxide accounts for more than 50% of climate warming (Zhang et al. 2015). Therefore, reducing carbon emissions becomes a goal of society. Carbon emissions generated by the electricity industry are 31% of total global carbon emissions (Liang et al. 2019). Thus, encouraging utility firms to reduce carbon emissions has become a particular concern to the government.

Investing in renewable energy is one of the key methods used to reduce carbon emissions by the electricity industry (Miller et al. 2013; Béläid and Youssef 2017), as renewable energy generates much fewer emissions. Firms, however, usually are unwilling to invest in renewable energy without a carbon-pricing mechanism (Zarnikau 2012). As the ecological environment is a public asset, the revenue from investment in carbon emissions reduction is owned by the public collectively and the cost is borne by firms alone. Therefore, the government needs to adopt a carbon-pricing mechanism to internalize external costs. Cap-and-trade mechanisms are the most effective type of carbon emissions reduction mechanisms adopted by governments (Xu et al. 2016). Cap-and-trade mechanisms include two types: Grandfathering mechanisms (GM) and benchmarking mechanisms (BM; Ji et al. 2017). Under a GM, the government sets a free total carbon quota for firms based on their historical carbon emissions data. In general, under a GM, the total carbon quota is based on the average of enterprises' carbon emissions in the past three years, showing that a GM focuses on the enterprise's own reduction. For example, Shenzhen (Ji et al. 2017) and the European Union Phase I (Zetterberg et al. 2012) have adopted GMs. Under a BM, the government sets unit carbon quotas for firms based on the average emissions of the industry. The unit carbon quota under a BM is based on the average low-carbon enterprises' unit carbon emission in the industry, showing that a BM focuses on the emission reduction of the industry. For example, Beijing (Zhang et al. 2015) and the European Union Phase II (Zetterberg et al. 2012) have adopted BMs. China and the European Union (EU) have contributed 60% of global investment in renewable energy (Lv and Spigarelli 2015). Germany aims to achieve 100% renewable energy by 2050 (Hansen et al. 2019), while China will achieve 85% (Yang et al. 2016).

Investment in renewable energy under cap-and-trade mechanisms becomes a goal of many countries with a range of different electricity market attributes. For example, Chinese utility firms, such as State Grid and Southern Power Grid, cooperate to serve their consumers. State Grid and China Southern Power Grid transmit electricity to most areas in China. They are more cooperative than competitive, representing the leadership of the government and making the effort to meet residents' electricity consumption. In addition, their cooperation can help to reduce the security risks of power grid operation and improve the reliability of power supply (Wang 2020). In contrast, America utility firms, such as Eastern Regional Power Committee and Western Regional Power Committee, serve their consumers competitively, as each power grid system is basically self-sufficient and relatively independent. Market cooperation focuses on the overall profit, while competition focusing on the respective profit. Therefore, different market types require different investment in renewable energy.

Investment in renewable energy can reduce carbon emissions by replacing significant amounts of conventional energy. However, it remains unclear whether a BM or a GM is more effective in encouraging utility firms to invest in renewable energy, and which market, a cooperative or a competitive, is more effective in encouraging the investment in renewable energy. This paper attempts to address the following research questions:

1. Which cap-and-trade mechanism, a BM or a GM, encourages a utility firm to invest more in renewable energy?
2. Which market type, cooperative or competitive, encourages a utility firm to invest more in renewable energy?

Our paper makes three contributions to the literature on low-carbon management. First, motived by using both BM and the GM in China and the EU that encourages the utility firms to invest in renewable energy, we consider the different influences of the BM and the GM. This paper identifies which mechanism, the BM or the GM, encourages a utility firm to invest more in the renewable energy in either a cooperative or a competitive market. Second, the BM focuses on the regulation of the unit carbon emission, while the GM focuses on the regulation of the total carbon emissions. Chen et al. (2021a) compare the BM and the GM from the perspective of renewable energy investment, and they only considered a monopolistic firm in the market. Differing from Chen et al. (2021a), this paper considers the influence of not only the GM and the BM on the renewable energy investment, but also the competitive market and the cooperative market on renewable energy investment, to examine the different impacts of cooperative market and competitive market on the renewable energy investment. Third, the results show that BM is more effective in investing in renewable energy. Furthermore, the utility firms in a competitive market invest more under both mechanisms. Therefore, the government should implement a BM in a competitive market to encourage the utility firms to invest in renewable energy.

The rest of this paper is organized as follows: Sect. 2 reviews the relevant studies in the literature and Sect. 3 describes the model framework. Section 4 presents the models and equilibriums. The comparison of BM and GM is presented in Sect. 5. Section 6 provides numerical studies and additional managerial insights. Concluding remarks are presented in Sect. 7.

Literature review

Many studies have discussed carbon emissions reduction mechanisms. Here, we focus on studies closely related to our work, which are in two streams: cap-and-trade mechanisms, and carbon abatement innovation.

Cap-and-trade mechanisms

Cap-and-trade mechanism can classify into two widely used mechanisms, BM and GM. Existing literature on the operational decisions made under a GM can be summarized as single-firm and multiple-firm decision-making. Some scholars have studied the operational decisions making within one firm. For example, Hua et al. (2011) and Chen et al. (2013) point out that firms can use the Economic Order Quantity (EOQ) model to decide the optimal order quantity. Hua et al. (2011) find that the optimal order quantity occurs either at the best EOQ order or the minimum carbon emission order. Chen et al. (2013) determine the conditions to reduce carbon emissions by adjusting the optimal order quantity. He et al. (2015) compare the optimal carbon emissions under cap-and-trade and carbon-tax mechanisms. The mechanism that would produce lower carbon emissions was unclear; however, if unit carbon emission cost of the production is the same as that of holding the product, the difference between the two mechanisms is small. Moreover, Hasan et al. (2021) discuss the technology of the lowest carbon among regulations of the cap-and-trade, the tax, and strict carbon limit. They find that the carbon limit regulation would benefit the lower carbon technology investment.

Scholars have also extensively examined the impact of cap-and-trade mechanisms on the operational decisions of multiple firms, from the perspective of competition or cooperation. From the competition perspective, Du et al. (2013) propose an emissions-dependent supply chain with a manufacturer and an emissions permit supplier. They find that the manufacturer's profit increases with an emissions cap while the supplier's profit decreases, and the utility firms' profits would increase with the carbon quota.

Xu et al. (2016) investigate the carbon abatement technology with the consideration of environmental awareness of managing a green supply chain with a manufacturer and a retailer. They find that as the carbon price increases, the investment in carbon emissions reduction technology first increases and then is stable. They also find that with the increase in carbon price, profits of the utility firms increase under a BM and decrease under a GM. Wang et al. (2018) focus on refrigerated logistics services in a fresh-food supply chain under a GM. They find that a transfer payment mechanism encourages firms to accept the carbon mechanism. Sun and Yang (2021) compare carbon emissions of the two competitive manufacturers between GM and tax mechanisms, and they find that cap-and-trade mechanism would mitigate more carbon emissions and benefit social welfare more. From a firm's perspective, Ji et al. (2020) compare social welfares under a wholesale-price contract and a revenue-sharing contract. They find that social welfare under a revenue-sharing contract is higher (lower) than that under a wholesale-price contract if the consumer's environment awareness is high (low). Feng et al. (2020) focus on the issue of the joint replenishment among retailers under a GM, and find that the retailer with the most altruistic behaviour obtained surplus carbon allowances from other retailers. Cheng et al. (2022) discuss the lower carbon emissions technology for a closed-loop supply chain between GM and tax mechanisms, and they find that these carbon mechanisms could improve the lower carbon emissions technology investment. This paper differs from the above studies. Firstly, this paper focuses on the investment of renewable energy in the electricity market, while the above studies focus on the investment in the low-carbon technologies, to reduce emissions. The investment in renewable energy results in the increase in the production of electricity, while the investment in the low-carbon technology cannot increase the production of electricity. Secondly, the above studies only consider the market type either of cooperation or of competition, while this paper considers both in a unified analysis framework. Thirdly, the above studies focus on the influence of a BM on a firm's operations decision-making, while this paper considers the influence of not only a GM but also a BM on a firm's renewable energy investment.

Several papers have been on BM in the literature. Yang et al. (2018) consider the investment in carbon emission reduction technology for a two-level supply chain with manufacturers and retailers. They find that a BM would mitigates the channel conflict. Liu and Ke (2021) study a supply chain with a retailer and a manufacturer, and discuss the choice of retailers between the market mode and the distributor mode under a BM. They find that if the level of carbon emissions for a product in the retail process is moderate (low) or the platform rate is relatively low (high), both the retailer and the manufacturer prefer the market (distributor) mode. Moreover, Ji et al. (2017) examine the impact of the BM and the GM on carbon emissions considering environmental awareness in the online to the offline supply chain. They find that the BM is conducive to the investment in carbon emission reduction technology.

Renewable energy generates zero carbon emission, and a low-carbon technology is hard to achieve zero carbon emission. The difference that this paper has a focus on the investment in renewable energy while the above papers have a focus the investment in low-carbon technology. In addition, this paper considers the influence of both market types, (competition or cooperation) on renewable energy investment considering both BM and GM.

Carbon abatement innovation in the electric power industry

Investment in the carbon abatement innovation in the electric power industry has attracted much attention with a focus on the investment in carbon abatement technology and the investment in renewable energy. There is an essential difference in the effectiveness of investment between in carbon abatement technology and in renewable energy. The investment in carbon abatement technology can change the carbon-emissions efficiency of products but not the capacity, while the investment in renewable energy expands production capacity. Du and Mao (2015) adopt a coal-electricity enterprise's dataset from China to analyse the costs of carbon abatement and carbon efficiency. They find that the cost of carbon abatement increases from 142.14 $/t in 2004 to 163.14 $/t in 2008. Zhang et al. (2018) develop an option game model with asymmetric electricity enterprises to discuss the relationship between decarbonization price and carbon abatement technology. They find that a low (high) decarbonization price encourages an electricity enterprise with low (high) carbon emissions to invest in carbon abatement technology. Differing from the above papers with a focus on carbon abatement technology, this paper finds that the investment in renewable energy increases with carbon price, implying that an appropriate increase in the carbon price is conducive to the transformation of the low-carbon energy.

Some studies have discussed the investment in renewable energy. Alizamir et al. (2016) focus on the investment in renewable energy under a feed-in tariff policy. They point out that when the diffusion and learning rate of renewable energy is related to the region, Investors should invest in renewable energy in the current period, and otherwise they will delay the investment. Kök et al. (2016) study the impact of peak-flat pricing on renewable energy investment, and find that under certain conditions, peak pricing can motivate the utility firms to invest in renewable energy. Kök et al. (2020) discuss the impacts of subsidizing inflexible/flexible energy sources on the investment in renewable energy, and find that such subsidies will increase/decrease the investment in renewable energy. These papers did not to consider the impacts of cap-and-trade mechanisms on the investment in renewable energy. Differing from these papers, this paper examines the influence of different carbon allowances (GM and BM) on the investment decision in renewable energy, and the influence of market types on the investment in renewable energy.

Several studies have examined the influence of cap-and-trade mechanism on carbon abatement innovation in electric power industry. Chen et al. (2021a) discuss the renewable energy investment under cap-and-trade mechanisms for a utility firm. They find that BM is more conducive to renewable energy investment than GM. Chen et al. (2021b) discuss the carbon abatement technology investment under cap-and-trade mechanisms for an electricity supply chain with a peak-valley pricing policy. They find that the peak-valley pricing policy will encourage the electricity generator to invest more carbon abatement technology than the flat pricing policy. Yan et al. (2022) compare the cap-and-trade mechanism to the renewable portfolio standard mechanism for renewable energy investment. Their results suggest that firms should adopt these mechanisms.

Chen et al. (2021c) consider renewable energy investment with market effort under cap-and-trade mechanisms. They show that BM is beneficial to marketing efforts, while GM is not. These studies focus on the investment behavior of carbon abatement innovation in a single electricity market. Our paper focuses on the investment in renewable energy considering both competitive and cooperative electricity markets.

Model framework

We consider two utility firms in a regional market that invest in renewable energy in response to carbon emission restriction mechanisms. Each firm can purchase (sell) its carbon quota in a carbon-trading market when it has insufficient (excessive) carbon quota unit. The duopoly competes in electricity quantity under Cournot competition. The consumers are sensitive to electricity market prices. Following common practice and the studies in the literature (e.g., Willems 2002; Yan and Folly 2014), we assume that the same electricity market prices apply to both firms:

$$p = a - b(q_1 + q_2) \tag{1}$$

where a is the potential market demand for electricity, b is the sensitivity coefficient of electricity production, and q_i is the electricity production from utility firm i, where $i = 1, 2$. Electricity supply from a utility firm is equal to electricity demand since supply and demand are balanced in real-time in electricity markets.

As in Albadi (2008), Lee (2014), and Kök et al. (2016), the total cost is a function of conventional energy, which is assumed to be a convex function:

$$G(D_i) = \frac{1}{2} c_i D_i^2 \tag{2}$$

where c_i and D_i are the cost coefficient and production of conventional energy for utility firm i, where $i = 1, 2$. The convex function assumption is based on the fact that a utility firm usually uses its most efficient generators first and then uses less efficient ones. As a result, the marginal cost increases significantly with the increase in production.

We also assume that the cost function of the investment in renewable energy for firm i is:

$$F(k_i) = \frac{1}{2} d_i k_i^2 \tag{3}$$

where d_i and k_i are the cost coefficient and the investment in renewable energy of utility firm i. This assumption follows studies in the literature (Menanteau et al. 2003; Tahvonen and Salo 2001). As the advanced technology requires more investment, which results in the increase in demand for renewable energy, more expensive locations for solar and wind energy should be considered.

As the unit carbon quota (e_0) under the benchmarking mechanism (BM)and the total carbon quota ($\widetilde{E}_i$) under the grandfathering mechanism (GM) for Firm i are restricted by the government,$e_0 \geq 0$and$\widetilde{E}_i \geq 0, a > max\left\{ \frac{w(2bd_i+c_i(2b+d_i))d_je_j-2bwd_i(c_j+d_j)e_i}{c_id_i(c_j+d_j)}, \frac{w(2bd_i+c_i(2b+d_i))d_je_j-bwd_i(c_j+d_j)e_i}{(bd_i(c_j+d_j)+c_i(b+d_i)(c_j+d_j))} \right\}$, $\{i = 1, 2; j = 3 - i\}$, as in Ji et al. (2017) and Chen et al. (2021b).

In this paper, we consider two strategies of the duopoly ($R = \{M, C\}$), either cooperation (M) or competition (C) in the market (as illustrated in Fig. 1) under the two cap-and-trade mechanisms (GM and BM). We first discuss the strategy in which the two firms determine the electricity production and renewable energy investment decisions cooperatively to maximize their total joint profits, under both GM and BM. Then, we discuss the strategy where the two firms compete in a market and each firm determines the electricity production and investment in renewable energy to maximize its own profit, under both GM and BM. Therefore, four models will be discussed.

Models and equilibriums

Cooperation in the market

We first discuss the duopoly's strategy in which the two firms make decisions cooperatively, under both GM and BM ($R = M$), to maximize their overall profit. We start with a discussion under the GM.

Under a grandfathering mechanism (MG)

The two utility firms maximize their joint profit (π^{MG}) under GM by setting the electricity production (q_1^{MG}, q_2^{MG}) and their investment in renewable energy (k_1^{MG}, k_2^{MG}). The profit of the duopoly (π^{MG}) is as follows:

$$\pi^{MG} = \left\{ \begin{array}{c} p_1^{MG}q_1^{MG} + p_2^{MG}q_2^{MG} - \frac{1}{2}d_1(k_1^{MG})^2 - \frac{1}{2}d_2(k_2^{MG})^2 - \frac{1}{2}c_1(q_1^{MG} - k_1^{MG})^2 - \frac{1}{2}c_2(q_2^{MG} - k_2^{MG})^2 \\ -e_1 w\left(q_1^{MG} - k_1^{MG}\right) - e_2 w\left(q_2^{MG} - k_2^{MG}\right) + w\widetilde{E}_1 + w\widetilde{E}_2 \end{array} \right\} \tag{4}$$

With Eqs. (1)–(4), we have the optimal electricity production (q_1^{MG*}, q_2^{MG*}) and renewable energy investment (k_1^{MG*}, k_2^{MG*}) for the two firms, and the associated electricity price (p^{CB*}) and the total carbon emissions (E_1^{CB*}, E_2^{CB*}) can be summarized in Lemma 1 as follows.

Lemma 1 *Under MG, there exist the optimal electricity production quantities* (q_1^{MG*}, q_2^{MG*}) *and renewable energy investment levels* (k_1^{MG*}, k_2^{MG*}) *that are given in*

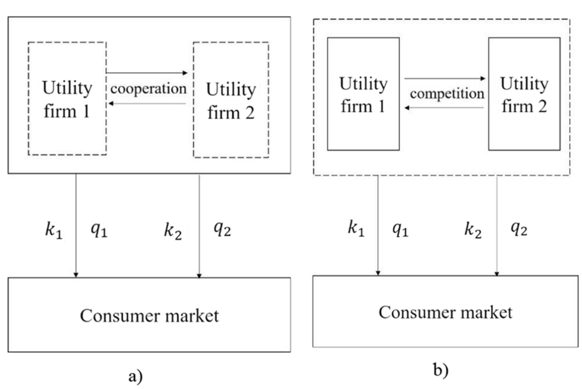

Fig. 1 Decisions of the duopoly in **a** cooperative and **b** competitive electricity markets

(5). The electricity price (p^{MG*}) and total carbon emissions (E_1^{MG*}, E_2^{MG*}) are given in Eqs. (6).

$$\begin{cases} q_1^{MG*} = \frac{d_2(c_1+d_1)(ac_2+2bwe_2)-wd_1e_1[2bd_2+c_2(2b+d_2)]}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}, \\ q_2^{MG*} = \frac{d_1(c_2+d_2)(ac_1+2bwe_1)-wd_2e_2[2bd_1+c_1(2b+d_1)]}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}, \\ k_1^{MG*} = \frac{d_2[2bwe_1c_2+c_1(ac_2+2bwe_2)]}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}, \text{ and} \\ k_2^{MG*} = \frac{d_1[2bwe_1c_2+c_1(ac_2+2bwe_2)]}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}. \end{cases} \tag{5}$$

$$\begin{cases} p^{MG*} = \frac{bc_2d_1d_2(a+we_1)+c_1\{ac_2[bd_1+d_2(b+d_1)]+bd_1d_2(a+we_2)\}}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}, \\ E_1^{MG*} = \frac{e_1\{c_2[ad_1d_2-we_1(2bd_2+2bd_1+d_1d_2)]+2bwd_1d_2(e_2-e_1)\}}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}, \text{ and} \\ E_2^{MG*} = \frac{e_2\{c_1[ad_1d_2-we_2(2bd_1+2bd_2+d_1d_2)]+2bwd_1d_2(e_1-e_2)\}}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}. \end{cases} \tag{6}$$

Under a benchmarking mechanism (MB)

In the cooperative market (M) under the BM, the two firms maximize the total profit (π^{MB}) by deciding the electricity production quantities (q_1^{MB}, q_2^{MB}) and the investment levels in renewable energy (k_1^{MB}, k_2^{MB}) jointly. The total profit of the two utility firms (π^{MB}) is:

$$\pi^{MB} = \left\{ \begin{array}{c} p^{MB}q_1^{MB} + p^{MB}q_2^{MB} - \frac{1}{2}d_1(k_1^{MB})^2 - \frac{1}{2}d_2(k_2^{MB})^2 - \frac{1}{2}c_1(q_1^{MB} - k_1^{MB})^2 - \frac{1}{2}c_2(q_2^{MB} - k_2^{MB})^2 \\ +e_0wk_1^{MB} - (e_1 - e_0)w(q_1^{MB} - k_1^{MB}) + e_0wk_2^{MB} - (e_2 - e_0)w(q_2^{MB} - k_2^{MB}) \end{array} \right\} \tag{7}$$

With Eqs. (4)-(7), we have the optimal electricity production quantities (q_1^{MB*}, q_2^{MB*}) and renewable energy investment levels (k_1^{MB*}, k_2^{MB*}) for two firms, and the associated electricity price (p^{CB*}) and the total carbon emissions (E_1^{CB*}, E_2^{CB*}) are summarized in Lemma 2.

Lemma 2 *Under MB, there exist the optimal electricity production quantities (q_1^{MB*}, q_2^{MB*}) and renewable energy investment levels (k_1^{MB*}, k_2^{MB*}) that are given in* (8). *The electricity price (p^{MB*}), and total carbon emissions (E_1^{MB*}, E_2^{MB*}) are given* (9).

$$\begin{cases} q_1^{MB*} = \frac{d_2(c_1+d_1)[c_2(a+we_0)+2bwe_2]-wd_1e_1[2bd_2+c_2(2b+d_2)]}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}, \\ q_2^{MB*} = \frac{d_1(c_2+d_2)[c_1(a+we_0)+2bwe_1]-wd_2e_2[2bd_1+c_1(2b+d_1)]}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}, \\ k_1^{MB*} = \frac{d_2\{c_1[(a+we_0)+2bwe_2]+2bwe_1c_2\}}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}, \text{ and} \\ k_2^{MB*} = \frac{d_1\{c_1[(a+we_0)+2bwe_2]+2bwe_1c_2\}}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}. \end{cases} \tag{8}$$

$$\begin{cases} p^{MB*} = \frac{\left\{ \begin{array}{c} bc_2d_1d_2(a-we_0+we_1)+c_1\{c_2[abd_1+ad_2(b+d_1)-bwe_0(d_1+d_2)] \\ +bd_1d_2(a-we_0+we_2)\} \end{array} \right\}}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}, \\ E_1^{MB*} = \frac{e_1\{c_2[d_1d_2(a+we_0)-we_1(2bd_2+2bd_1+d_1d_2)]+2bwd_1d_2(e_2-e_1)\}}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}, \text{ and} \\ E_2^{MB*} = \frac{e_2\{c_1[d_1d_2(a+we_0)-we_2(2bd_1+2bd_2+d_1d_2)]+2bwd_1d_2(e_1-e_2)\}}{2bd_1d_2c_2+c_1\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\}}. \end{cases} \tag{9}$$

Competitive market

In the competitive market, we consider the two utility firms competing for electricity production to maximize their respective profits. To examine the effects of GM/BM in a competitive market, we start with the discussion of GM.

Under a grandfathering mechanism (CG)

In the competitive market, under a GM, the two utility firms decide on the levels of renewable energy investment first and then on electricity production quantities based on the total carbon quotas. The government sets the total carbon quotas according to the past records on the output of utility firm. Thus, the two utility firms in the competitive market under a GM have the motivation to invest in renewable energy. Each utility firm produces electricity and sells it to the consumer market. In addition, they can buy and sell carbon quotas in the carbon-trading market. Each utility firm's profit (π_i^{CG}) is as follows:

$$\begin{cases} \pi_1^{CG} = p^{CG}q_1^{CG} - \frac{1}{2}d_1(k_1^{CG})^2 - \frac{1}{2}c_1(q_1^{CG} - k_1^{CG})^2 + w\widetilde{E}_1 - e_1w(q_1^{CG} - k_1^{CG}) \\ \pi_2^{CG} = p^{CG}q_2^{CG} - \frac{1}{2}d_2(k_2^{CG})^2 - \frac{1}{2}c_2(q_2^{CG} - k_2^{CG})^2 + w\widetilde{E}_2 - e_2w(q_2^{CG} - k_2^{CG}) \end{cases}. \tag{10}$$

With Eqs. (1)–(3), and (6), we have the optimal electricity production quantities (q_1^{CG*}, q_2^{CG*}) and renewable energy investment levels (k_1^{CG*}, k_2^{CG*}) of the two firms, and the associated electricity price (p^{CB*}) and the total carbon emissions (E_1^{CB*}, E_2^{CB*}) are summarized in Lemma 3.

Lemma 3 *Under CG, there exist the optimal electricity production quantities (q_1^{CG*}, q_2^{CG*}) and renewable energy investment levels (k_1^{CG*}, k_2^{CG*}) that are given in* (11). *The electricity price (p^{CG*}), and total carbon emissions (E_1^{CG*}, E_2^{CG*}) are given in* (12).

$$\begin{cases} q_1^{CG*} = \frac{(c_1+d_1)[ac_2(b+d_2)+bd_2(a+we_2)]-wd_1e_1[2b(c_2+d_2)+c_2d_2]}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\left\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\right\}}, \\ q_2^{CG*} = \frac{(c_2+d_2)[ac_1(b+d_1)+bd_1(a+we_1)]-wd_2e_2[2b(c_1+d_1)+c_1d_1]}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\left\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\right\}}, \\ k_1^{CG*} = \frac{bwe_1[3bd_2+c_2(3b+2d_2)]+c_1[ac_2(b+d_2)+bd_2(a+we_2)]}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\left\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\right\}}, \text{ and} \\ k_2^{CG*} = \frac{bwe_2[3bd_1+c_1(3b+2d_1)]+c_2[ac_1(b+d_1)+bd_1(a+we_1)]}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\left\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\right\}}. \end{cases} \tag{11}$$

$$\begin{cases} p^{CG*} = \frac{[bd_2+c_2(b+d_2)][ac_1(b+d_1)+bd_1(a+we_1)]+bwd_2e_2[bd_1+c_1(b+d_1)]}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\}}, \\ E_1^{CG*} = \frac{e_1\left\{\begin{array}{c} c_2\{ad_1(b+d_2) - w[d_1(2b+d_2) + be_1(3b+2d_2)]\} \\ +bd_2[-bwe_1 + d_1(a - 2we_1 + we_2)] \end{array}\right\}}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\}}, \text{ and} \\ E_2^{CG*} = \frac{e_2\left\{\begin{array}{c} c_1\{ad_2(b+d_1) - w[d_2(2b+d_1) + be_2(3b+2d_1)]\} \\ +bd_1[-bwe_2 + d_2(a - 2we_2 + we_1)] \end{array}\right\}}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\}}. \end{cases} \tag{12}$$

Under a benchmarking mechanism (CB)

In a competitive market under GB, the two utility firms first decide on their renewable energy investment levels and then on the electricity production quantities simultaneously based on the unit carbon quota. The government sets the unit carbon quota according to the carbon emission level of the electric power industry. Thus, the two utility firms in the competitive market under a GB have the motivation to invest in renewable energy. Each utility firm produces electricity and sells it to the consumer market. In addition, they can buy and sell carbon quotas in a carbon-trading market. The utility firm i's profit (π_i^{CG}) is as follows:

$$\begin{cases} \pi_1^{CB} = p^{CB}q_1^{CB} - \frac{1}{2}d_1(k_1^{CB})^2 - \frac{1}{2}c_1(q_1^{CB} - k_1^{CB})^2 + e_0wk_1^{CB} - (e_1 - e_0)w(q_1^{CB} - k_1^{CB}) \\ \pi_2^{CB} = p^{CB}q_2^{CB} - \frac{1}{2}d_2(k_2^{CB})^2 - \frac{1}{2}c_2(q_2^{CB} - k_2^{CB})^2 + e_0wk_2^{CB} - (e_2 - e_0)w(q_2^{CB} - k_2^{CB}) \end{cases}. \tag{13}$$

With Eqs. (11)–(13), the optimal decisions of the two utility firms on the market electricity production quantities (q_1^{CB*}, q_2^{CB*}), renewable energy investment levels (k_1^{CB*}, k_2^{CB*}), and the associated electricity price (p^{CB*}) and the total carbon emissions (E_1^{CB*}, E_2^{CB*}) are summarized in Lemma 4.

Lemma 4 *Under CB, there exist the optimal electricity production quantities (q_1^{CB*}, q_2^{CB*}) and renewable energy investment levels (k_1^{CB*}, k_2^{CB*}) that are given in* (14). *The electricity price (p^{CB*}) and total carbon emissions (E_1^{CB*}, E_2^{CB*}) are given in* (15).

$$\begin{cases} q_1^{CB*} = \frac{(c_1+d_1)[c_2(b+d_2)(a+we_0)+bd_2(a+we_2+we_0)]-wd_1e_1[2b(c_2+d_2)+c_2d_2]}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\}}, \\ q_2^{CB*} = \frac{(c_2+d_2)[c_1(b+d_1)(a+we_0)+bd_1(a+we_1+we_0)]-wd_2e_2[2b(c_1+d_1)+c_1d_1]}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\}}, \\ k_1^{CB*} = \frac{bwe_1[3bd_2+c_2(3b+2d_2)]+c_1\{c_2(b+d_2)(a+we_0)+bd_2[a+w(e_0+e_2)]\}}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\}}, \text{ and} \\ k_2^{CB*} = \frac{bwe_2[3bd_1+c_1(3b+2d_1)]+c_2\{c_1(b+d_1)(a+we_0)+bd_1[a+w(e_0+e_1)]\}}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\}}. \end{cases} \tag{14}$$

$$\begin{cases} p^{CB*} = \frac{\left\{ \begin{array}{c} c_1\{c_2[a(b+d_1)(b+d_2) - bwe_0(2b+d_1+d_2) + bd_2[b(a-2we_0)] \\ +d_1(a-2we_0) + we_2(b+d_1)]\} \\ +bd_1\{c_2[b(a-2we_0) + d_2(a-we_0) + we_1(b+d_2)] + bd_2[a+w(e_1+e_2-2e_0)]\} \end{array} \right\}}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\}}, \\ E_1^{CB*} = \frac{e_1\left\{ \begin{array}{c} c_2\{(a+we_0)d_1(b+d_2) - w[d_1(2b+d_2) + be_1(3b+2d_2)]\} \\ +bd_2[-bwe_1 + d_1(a-2we_1+we_2+we_0)] \end{array} \right\}}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\}}, \text{ and} \\ E_2^{CB*} = \frac{e_2\left\{ \begin{array}{c} c_1\{(a+we_0)d_2(b+d_1) - w[d_2(2b+d_1) + be_2(3b+2d_1)]\} \\ +bd_1[-bwe_2 + d_2(a-2we_2+we_1+we_0)] \end{array} \right\}}{bd_1[3bd_2+c_2(3b+2d_2)]+c_1\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\}}. \end{cases} \tag{15}$$

The comparison of BM and GM

In this section, we compare the equilibriums under the BM and GM mechanisms in cooperative and competitive markets, $R = \{M, C\}$, respectively. We first compare the electricity production quantities and prices. We summarize the results in Proposition 1.

Proposition 1 *The results of comparing electricity demand and electricity prices in four models are:*

1. $q_i^{CG*} < q_i^{CB*}$ and $q_1^{RG*} + q_2^{RG*} < q_1^{RB*} + q_2^{RB*}$.
2. $p^{RB*} < p^{RG*}$.

Proposition 1 shows that as compared with GM, BM is more conducive to producing electricity. In the competitive market, the two utility firms compete for the marketing share. Under BM, the firms can obtain the unit carbon quota, leading to the reduced carbon emissions costs and renewable energy subsidies. At the initial stage of renewable energy development, a firm needs financial subsidies from the government, which is a mandatory policy. In the process of marketization, the government introduces a carbon cap-and-trade mechanism, such as a BM, and transforms it into a market-oriented policy. When a renewable energy utility firm starts to make profit, the government reduces the subsidies. For example, China's Ministry of Finance points out that carbon trading reduces the pressure of the government subsidies (MFPRC 2021). Thus, the utility firms are motivated to produce more electricity. On the other hand, the total carbon quotas under the GM that firms can obtain can be viewed as a one-time subsidy. Thus, the utility firms have less motivations to produce electricity, as compared to under a BM. This suggests that the BM can encourage the firms to invest more in renewable energy.

Proposition 1 also shows that as compared to the case under GM, the BM is a better solution in encouraging the utility firms to produce electricity in both cooperative and competitive markets. In the cooperative market, the utility firms aim to maximize their overall profit. When the government implements a BM, the utility firms bear lower costs of carbon emissions with the unit carbon quota. Thus, the utility firms produce more electricity to be profitable. Meanwhile, in the competitive market, the utility firms produce more electricity under the BM. Thus, the total electricity production will be higher under BM than under GM. This suggests that the BM can be effective in guaranteeing electricity production in any market type. As electricity production is an essential to the economics, the BM is a more suitable policy for the government.

Proposition 1 shows that the electricity price under the BM is lower than that under the GM in both market types. The reason is that the BM can provide utility firms a unit carbon quota to reduce their burdens in carbon emissions, resulting in a lower electricity price; utility firms who can obtain a total carbon quota under the GM will set a higher electricity price. From reports of the impacts of BM and GM on electricity prices in China, Shenzhen adopted a GM in the electric power industry and the electricity prices ranged between 9.71 and 13.71 ¢/kWh (DFE 2019); Beijing adopted a BM and the electricity prices varied between 6.86 and 11.00 ¢/kWh (STSBJ 2019). This suggests that the government should adopt a BM to set lower electricity prices for consumers.

With Lemmas 1–4, we compare the optimal renewable energy investment levels from the perspective of the utility firms. We summarize the results in Proposition 2.

Proposition 2. *The results of comparing renewable energy investment in four models are:* $k_i^{CG*} < k_i^{CB*}$ *and* $k_1^{RG*} + k_2^{RG*} < k_1^{RB*} + k_2^{RB*}$.

Proposition 2 shows that utility firms invest more in renewable energy under the BM than under the GM. Under the BM, the utility firms who invest in renewable energy receive a unit subsidy based on the unit carbon quota allocated by the government. Meanwhile, utility firms who invest in renewable energy will not receive a subsidy to reduce investment cost and will receive lower total carbon quotas as these quotas are based on historical emissions data, which reduces their investment enthusiasm. Thus, the BM is more suitable for encouraging utility firms to invest in renewable energy.

Proposition 2 also shows that the BM encourages the electric power market to invest more in renewable energy than it would under the GM. Many countries and regions have announced that renewable energy would be the dominant energy source by 2050. Encouraging utility firms to invest in renewable energy is critical in this process. The BM is undoubtedly more conducive to achieving the government's goals in increasing renewable energy investment in both competitive and cooperative markets. Note that there is no difference in renewable energy investment under the BM and the GM when the carbon price is zero.

With Lemmas 1–4, we compare the optimal total carbon emissions from the perspective of the utility firms. We summarize the results in Proposition 3.

Proposition 3. *The results of comparing total carbon emissions are:* $E_i^{CG*} < E_i^{CB*}$ *and* $E_1^{RG*} + E_2^{RG*} < E_1^{RB*} + E_2^{RB*}$.

Proposition 3 shows that under the BM, the utility firm will generate more carbon emissions than under the GM. Although the utility firm invests more in renewable energy under the BM, it also generates produce electricity, which may require more conventional energy generation that produces carbon emissions. While under the GM, the utility firm will produce less electricity that generates fewer carbon emissions. This suggests that the BM can encourage utility firms' investments in renewable energy, which reduces the production using conventional energy.

Proposition 3 also shows that the GM encourages utility firms to generate fewer carbon emissions in the electric power market. If a government's goal is to reduce carbon emissions, the GM is a better choice, as it reduces the usage of conventional energy.

We now discuss the impacts of carbon emission mechanisms on customer surplus and social welfare, which can be calculated as $Cs^* = \frac{(q_1^* + q_2^*)^2}{2b}$ and $Fs^* = Cs^* + \pi^*$, respectively. With Lemmas 1–4, we have the following results:

Lemma 5. *The result of comparing customer surplus in four models is:* $Cs^{RG*} < Cs^{RB*}$.

Lemma 5 shows that the customer surplus under the BM is higher than that under the GM, implying that customers can be more beneficial as a utility firm produces more electricity under the BM. Meanwhile, the utility firms will produce less electricity production under the GM, resulting in lower customer surplus. This suggests that the BM is better than the GM from the perspective of customer surplus.

Lemma 6. *The BM is better for renewable energy investment, while the GM is better for reducing the total carbon emissions.*

With Propositions 2–3 and Lemma 5, we can conclude that the BM is better for renewable energy investment and customer surplus, while the GM is better for reducing the total carbon emissions. Our results suggest that the government needs to balance the investment in renewable energy (customer surplus) and carbon emissions reduction.

In the long run, the BM is a better mechanism as it facilitates to improve energy infrastructure and customer surplus; in the short term, GM is better in reducing carbon emissions. The government can choose the appropriate carbon mechanism according to different goals.

We assume $\widetilde{E}_1 = \widetilde{E}_2 = \widetilde{E}$, in which two utility firms have the same total carbon quotas. This assumption does not affect the analyses and major insights in this paper, as the total carbon quotas are set by the government. By comparing the profits obtained under BM and GM in different markets, we have the results that are summarized in Proposition 4.

Proposition 4: *The results of comparing profits in four models are:*

1. *When* $\widetilde{E} < \frac{\bar{E}}{4wB^2}$, *then* $\pi^{MG*} < \pi^{MB*}$ *and* $\pi^{MG*} \geq \pi^{MB*}$ *otherwise.*

2. *When* $\widetilde{E} < \frac{\bar{\bar{E}}}{2wD^2}$, *then* $\pi_1^{CG*} < \pi_1^{CB*}$ *and* $\pi_1^{CG*} \geq \pi_1^{CB*}$ *otherwise.*

3. *When* $\widetilde{E} < \frac{\bar{\bar{\bar{E}}}}{2wD^2}$, *then* $\pi_2^{CG*} < \pi_2^{CB*}$ *and* $\pi_2^{CG*} \geq \pi_2^{CB*}$ *otherwise.*

Proposition 4 illustrates that which mechanism benefits the total profit of the two firms and the profit of each firm depends on the total carbon quotas. The total carbon quotas can be viewed as subsidies to the utility firms, which relieves the pressure of carbon emissions. Thus, if the government sets a lower total carbon quota, the utility firms will incur higher carbon emissions costs, leading to lower profits. On the other hand, if the government sets a higher total carbon quota, the utility firms are more profitable. The government's regulation affects the profits of utility firms via the carbon quota mechanism in any type of market. A low total carbon quota discourages the utility firms to produce electricity due to the costs of excessive carbon emissions. A high carbon quota encourages the investment in renewable energy because the total carbon emissions generated in one cycle are related to the next cycle. This suggests that the government should consider the production efficiency of the utility firms when setting total carbon quotas.

Let $c_1 = c_2, d_1 = d_2$, and $e_1 = e_2$. We then focus on discussion the impact of market type on the social welfare and profits of the utility firms. The results are summarized in Lemma 7 and Proposition 5, respectively.

Lemma 7. *The results of comparing social warfare in four models are:*

1. *When* $\widetilde{E} < \widehat{E}$, *then* $Fs^{CG*} < Fs^{CB*}$ *and* $Fs^{CG*} \geq Fs^{CB*}$ *otherwise.*

2. *When* $\widetilde{E} < \widehat{\widehat{E}}$, *then* $Fs^{MG*} < Fs^{MB*}$ *and* $Fs^{MG*} \geq Fs^{MB*}$ *otherwise.*

Lemma 7 shows that which mechanism is better off for the social warfare depends on the total carbon quotas. If the total carbon quotas are lower, the social welfare is lower under the GM than under the BM in both competitive and cooperative markets. As the utility firms incur higher costs under the GM with lower total carbon quotas, leading to lower social welfare. If the total carbon quotas are higher, the social welfare is higher under the GM than that under the BM. Thus, the higher total carbon quotas result in a higher social welfare. This suggests that the government can set different total carbon quotas to influence the social welfare under the GM and the BM.

Comparing the profits in cooperative and competitive markets under different carbon mechanisms, we have the following results.

Proposition 5: *The results of comparing the total profits between cooperative market and competitive market are:* $\pi^{MG*} > \pi_1^{CG*} + \pi_2^{CG*}$ *and* $\pi^{MB*} > \pi_1^{CB*} + \pi_2^{CB*}$.

Proposition 5 shows that a cooperative market benefits the utility firms from obtaining more profits than they would in a competitive market. The intuition is that when the two utility firms cooperate, they reduce the costs of internal bargaining as they aim to maximize the overall profit. Meanwhile, when two utility firms compete to each other, they aim to maximize their profits. Moreover, the government's carbon mechanism will not affect the impacts of market attributes on the profits of the utility firms. From the perspective of profit, the utility firms have an incentive to cooperate. The government will encourage utility firms to cooperate but aim to prevent them from pursuing profits exclusively.

Numerical studies

We use numerical studies to illustrate major results and the influence of exogenous variables on the equilibrium results and provide additional insights. Specifically, we focus on (1) the impacts of a carbon price on renewable energy investment, electricity production, electricity price, and the profits of the utility firms; (2) the impacts of the unit carbon emission on renewable energy investment, electricity production, and the profits of the utility firms; (3) the impact of unit carbon quota on renewable energy investment and profits of the utility firms; and (4) impact of total carbon quotas on profits of the utility firms.

Impacts of carbon price

This subsection explores the impacts of a carbon price on renewable energy investment, electricity production, electricity price, and the profits of the utility firms. The following parameters are set according to the conditions of results derived in this paper, $\mathrm{a} = 100(\mathrm{MW}), \mathrm{b} = 0.8(\$/\mathrm{kWh}), c_1 = 0.1(\$/MW), c_2 = 0.1(\$/MW), e_1 = 3(kg/kWh)$, $e_2 = 3(Kg/kWh), d_1 = 0.2(\$/MW), d_2 = 0.2(\$/MW), e_0 = 2(Kg/kWh), E_1 = 20(t)$, $E_2 = 20(t)$, and $w \in \{0(\$/kWh), 1(\$/kWh)\}$. Results are shown in Fig. 2a–d, and observations are presented as follows.

Figure 2a shows the impact of carbon price on renewable energy investment. Firstly, renewable energy investment increases with the carbon price. An increase in carbon price result in the increase in the carbon emission cost of conventional energy, which encourages the utility firms to invest in renewable energy for zero carbon emissions. Secondly, as compared to the GM, the BM encourages more investment in renewable energy, because a utility firm can obtain carbon quotas from renewable energy. Finally, a competitive environment encourages more investment in renewable energy than a cooperative environment does because the utility firms face not only the constraints of carbon regulations in the competitive markets but also the pressure from competitors, leading to more investment in renewable energy by the utility firms.

Figure 2b shows the impact of carbon pricing on electricity production. Firstly, electricity production decreases with the carbon price because a higher carbon price forces the utility firms to bear more carbon costs, resulting in the decrease in the electricity production. Secondly, as compared to the GM, a utility firm can produce more electricity

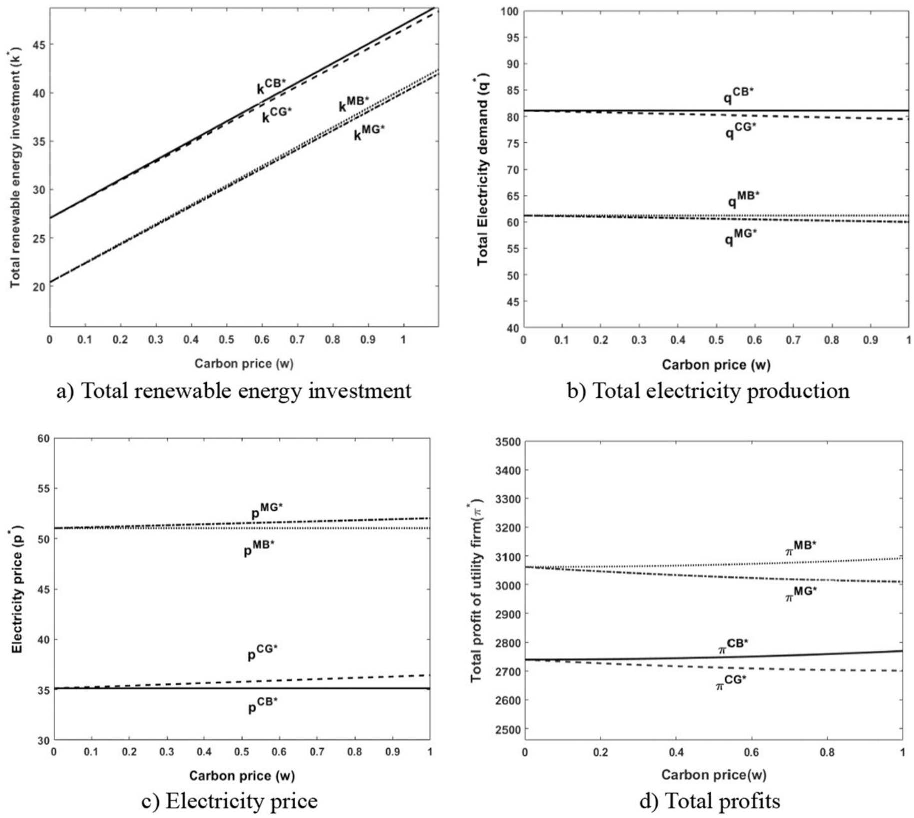

Fig. 2 The impacts of carbon price on total renewable energy investment, total electricity production, electricity price, and profits under the BM and the GM

under the BM because it can obtain a unit carbon quota, which helps to reduce the cost of current carbon emissions, leading to the increase in electricity production. Finally, as compared to a cooperative market, a competitive market encourages more production of electricity. In a competitive market, the utility firm tries to gain as much as possible in the marketing share, resulting in producing more electricity.

Figure 2c shows the impact of carbon pricing on electricity prices. Firstly, the electricity price increases with the carbon price. With the increase in carbon price, the utility firms bear higher carbon emission costs, which will be transferred to consumers due to higher electricity prices. Secondly, as compared to the GM, the utility firms can set a lower electricity price under the BM. Utility firms can enjoy subsidies from the unit carbon quota, resulting in the lower overall costs and electricity prices. Finally, as compared to the case in a cooperative market, a competitive market allows to set lower electricity prices. In a competitive market, the utility firm tries to capture the electricity market by setting a lower electricity price, which is also one of the motivations of electricity reform.

Figure 2d shows the impact of carbon pricing on profits. Firstly, with the increase in carbon price, the utility firms' profits increase under the BM and decrease under the GM. With the increase in carbon price, the utility firms obtain more carbon quotas by investing more in renewable energy and can be more profitable under the BM; meanwhile, under the GM, the utility firms still have to pay the costs of carbon emissions, leading to the decrease in their profits. Secondly, as compared to the GM, a utility firm can obtain a higher profit under the BM. Utility firms incur higher carbon emissions costs, which squeezes their profits. Finally, as compared to the case in the cooperative market, the profit of a utility firm in the competitive market is lower. Firms will set higher prices to obtain more profits in a cooperative market, and is less profitable in a competitive market due to intense price competition.

Unit carbon emission

The impacts of unit carbon emission on renewable energy investment, electricity production, and profits of the utility firm are illustrated by setting $\mathrm{a} = 100(\mathrm{MW})$, $\mathrm{b} = 0.8(\$/\mathrm{kWh}), c_1 = 0.1(\$/MW), c_2 = 0.1(\$/MW), e_2 = 3(Kg/kWh), w = 0.8(\$/Kg)$, $d_1 = 0.2(\$/MW), d_2 = 0.2(\$/MW), e_0 = 2(Kg/kWh), E_1 = 20(t), E_2 = 20(t)$, and $e_1 \in \{0\left(Kg/kWh\right), 1(Kg/kWh)\}$.

Impact of unit carbon emission on renewable energy investment

We analyse the impact of the unit carbon emission of utility firm 1 on renewable energy investment under different carbon regulations. Figure 3a, b show the renewable energy investment under the BM, while Fig. 3c, d show the renewable energy investment under the GM. We have the following observations.

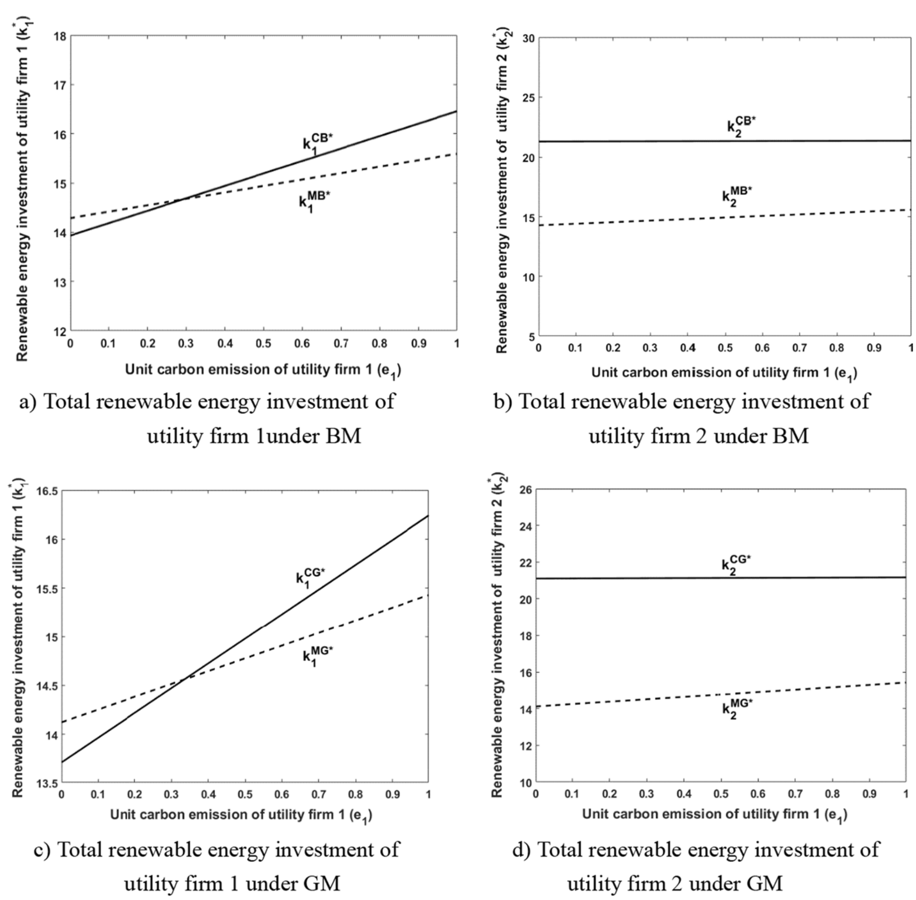

Fig. 3 Impacts of unit carbon emission on renewable energy investment

Figure 3a, b show that in both competitive and cooperative markets, renewable energy investment increases with the increase in the unit carbon emission of utility firm 1. The mechanism of the two markets is different. Specifically, in the competitive market, the unit carbon emission of utility firm 1 increases, which leads to more carbon emission costs from conventional energy. Thus, the utility firm is encouraged to invest more in renewable energy. Furthermore, to maintain market share, utility firm 1 will invest in renewable energy as much as possible to make up for conventional energy, which leads to the limited growth for utility firm 2. In the cooperative market, utility firms 1 and 2 aim to maximize their overall profit. Thus, when the unit carbon emission of utility firm 1 are high, utility firm 2 will invest more in renewable energy.

Figure 3c, d further illustrate the validity of the above conclusions. Whether the BM or the GM is adopted by the government, the market type and energy costs of renewable energy and conventional energy should be considered, which affects how utility firms invest in renewable energy.

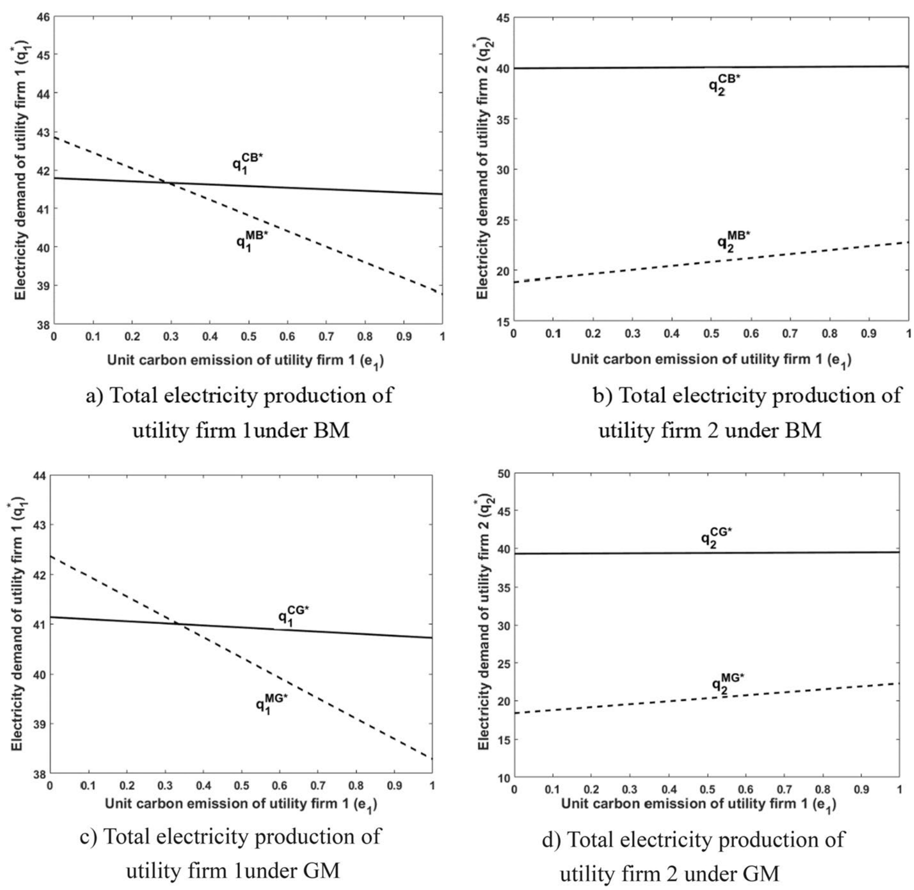

Fig. 4 Impact of unit carbon emission on electricity production

Impact of unit carbon emission on electricity production

We now analyse the impact of the u nit carbon emission of utility firm 1 on electricity production under different carbon regulations. Figure 4a, b show the electricity production under the BM, and Fig. 4c, d show the electricity production under the GM.

Figure 4a, b show that the electricity production of utility firm 1 decreases with unit carbon emission while that of utility firm 2 increases. An increase in unit carbon emission reduces its carbon emission efficiency and increases its carbon emission cost, which increases utility firm 2's market competitiveness. However, the market mechanism is different. In a competitive market, the reduction in its own efficiency will lead to a reduction in market share, which leads to the increase in utility firm 2's electricity production; in a cooperative market, the utility firms' demands will be adjusted internally to obtain market share.

Figure 4a, b also show that the electricity production of utility firm 1 in a cooperative market will decline at a more rapid rate than that in a competitive market, and that of utility firm 2 is lower in a cooperative market than in a competitive one. This is because the unit carbon emission of utility firm 1 increase, which indicates that its market competitiveness decreases. Thus, utility firm 1 will significantly reduce its market share from the perspective of maximizing overall profit under cooperation, while utility firm 1 will reduce the possibility of market share decline by investing in renewable energy

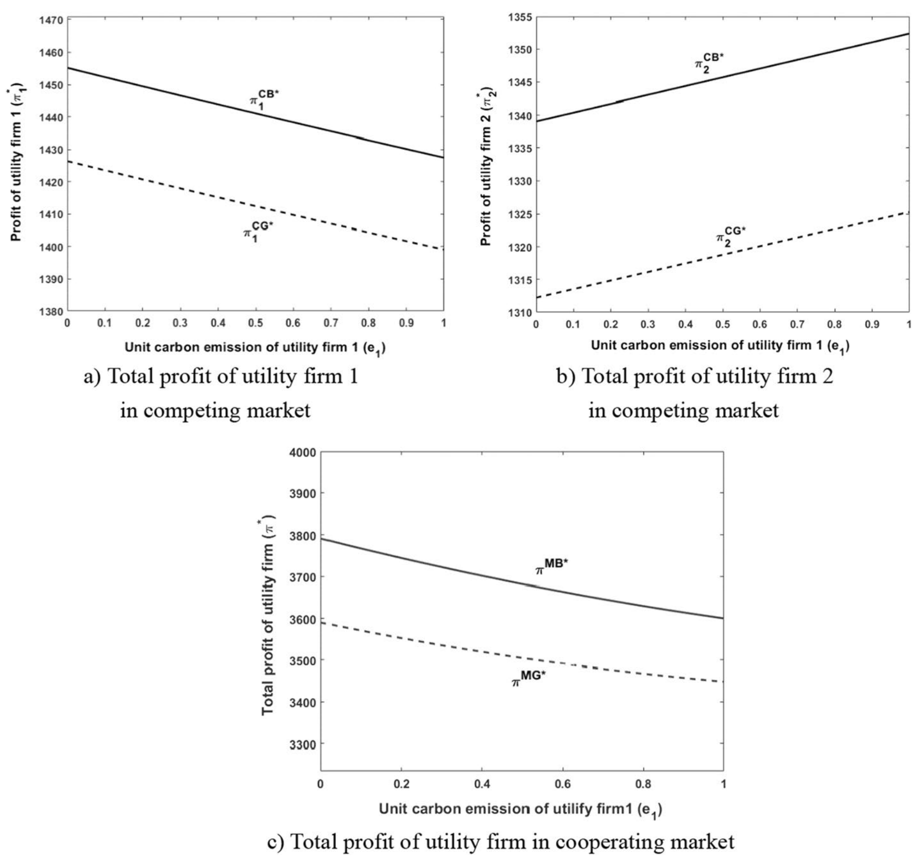

Fig. 5 Impact of unit carbon emission on profit

in a competitive market. Moreover, utility firm 2 competes for more market share in a competitive market, which leads to more electricity production than in a cooperative market.

Figure 4c, d further illustrate the validity of the above conclusions. Whether the BM or the GM is adopted by the government depends on the market type as it affects investment in renewable energy by the utility firms.

Impact of unit carbon emission on profit

We now analyse the impact of unit carbon emission on electricity profits under different market types. Figure 5a, b show the electricity profits in a competitive market and Fig. 5c, d show these impacts under cooperation.

Figure 5a, c show that the profit of utility firm 1 decreases with unit carbon emission in a cooperative market, while the profit of utility firm 2 increases. Figure 5a shows that the profit of utility firm would decrease under the competitive market because the increase in unit carbon emission leads to a reduction in carbon emission efficiency, which increases the cost of carbon emissions and decreases the profit. Figure 5b shows that the profit of utility firm 2 will increase because the increase in the unit carbon emission of utility firm 1 gives utility firm 2 more market share, resulting in an increased profit. Figure 5c shows that the increasing unit carbon emission would lead to a decrease in profits due to the cost of carbon emissions.

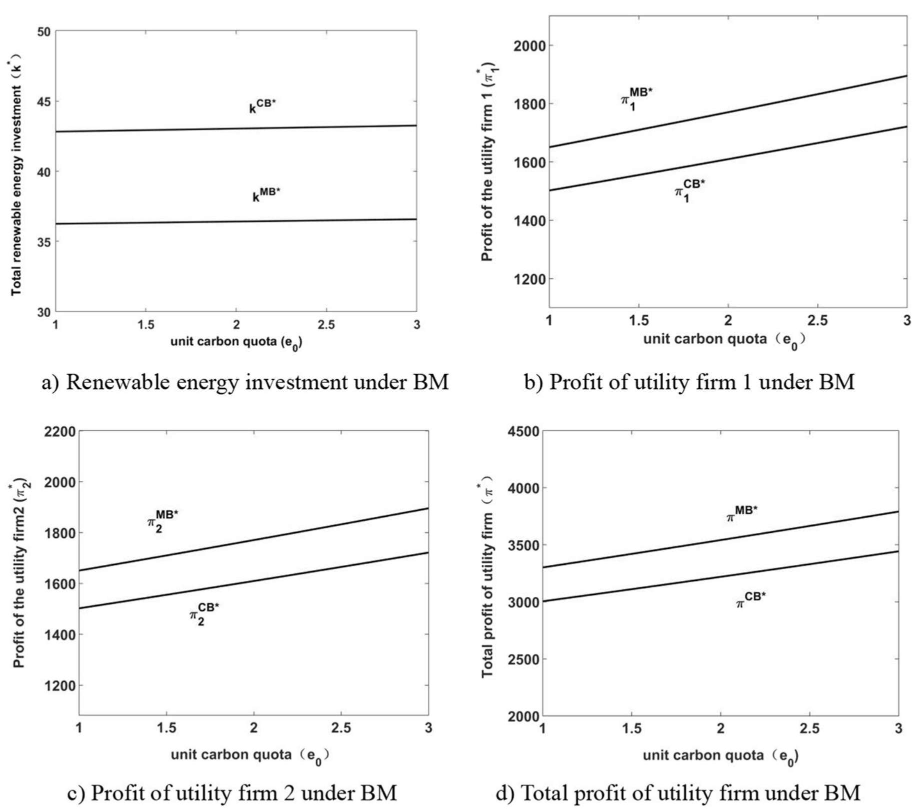

Fig. 6 Unit carbon quota

Figure 5a–c also show that the profits under the BM are higher than that under the GM, as a utility firm under the BM can obtain a unit carbon quota from the government, which increases its profit. From the perspective of utility firms, the implementation of the BM may be more attractive.

Impact of unit carbon quota

This subsection explores the impacts of a carbon quota on renewable energy investment and profits of the utility firms using parameters, $\mathrm{a} = 100(\mathrm{MW}), \mathrm{b} = 0.8(\$/\mathrm{kWh})$, $c_1 = 0.1(\$/MW), c_2 = 0.1(\$/MW), e_1 = 3(kg/kWh), e_2 = 3(Kg/kWh), d_1 = 0.2(\$/MW)$, $d_2 = 0.2(\$/MW), w = 0.8(\$/kWh), E_1 = 20(t), E_2 = 20(t)$, and $e_0 \in \{1\left(kg/kWh\right), 3(kg/kWh)\}$. From Fig. 6a–d, we have the following observations.

The investment in renewable energy will increase in both the competitive and cooperative markets with the unit carbon quota. The main reason is that with the increase in unit carbon quota, the investment in renewable energy will receive more subsidies. Therefore, utility firms have the incentive to invest more renewable energy. Moreover, the investment in renewable energy in a competitive market is higher than that in a cooperative market.The reason is that in the competitive market, both utility firms have the motivation to invest more in renewable energy to have a higher marketing share.

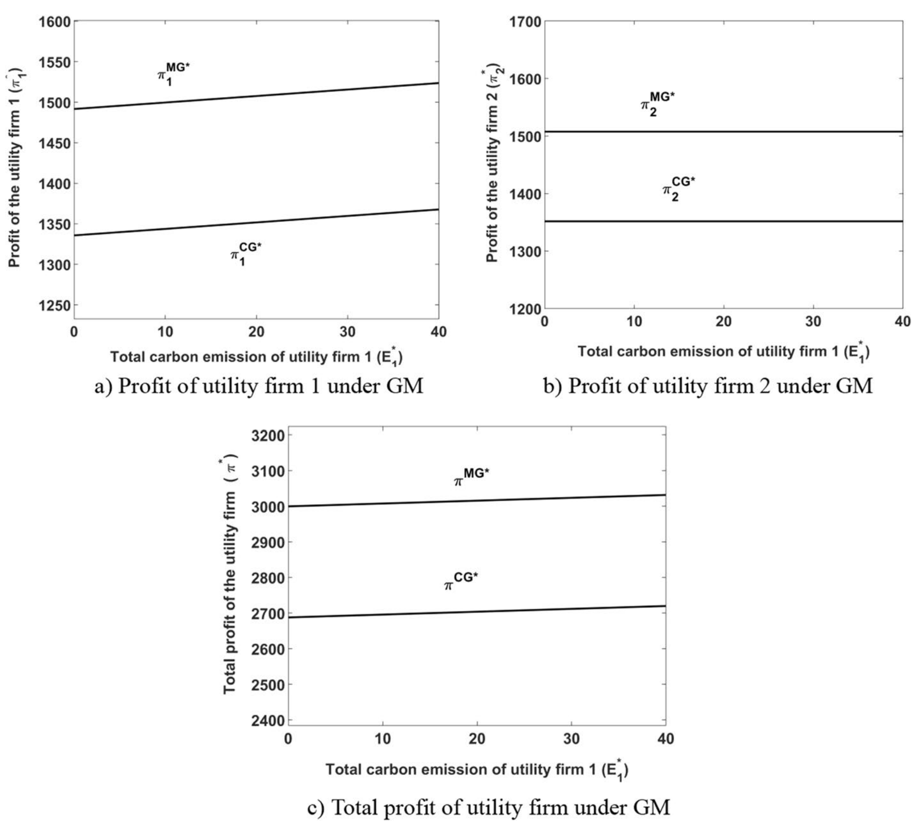

Fig. 7 Total carbon quotas

The profits of utility firms under the BM increase with the unit carbon quota. Because the increase in unit carbon quota will help utility firms to gain more benefits. The profit under the cooperative market is higher than that under the competitive market because the competition results in the losses in profits. Therefore, a competitive market encourages renewable energy investment, but a cooperative market helps to improve profits, implying that the government needs to set an appropriate unit carbon quota between renewable energy investment and profits.

Impact of total carbon quotas

This subsection explores the impacts of a carbon quota on renewable energy investment and utility firm profit using the following, $\mathrm{a} = 100(\mathrm{MW}), \mathrm{b} = 0.8(\$/\mathrm{kWh})$, $c_1 = 0.1(\$/MW), c_2 = 0.1(\$/MW), e_1 = 3(kg/kWh), e_2 = 3(Kg/kWh), d_1 = 0.2(\$/MW)$, $d_2 = 0.2(\$/MW), w = 0.8(\$/kWh), e_0 = 2(Kg/kWh), E_2 = 20(t)$, and $E_1 \in \{0(t), 40(t)\}$. With Fig. 7a–d, we have the following observations.

The total carbon quota is determined based on the historical data of the utility firm. The increase in the total carbon quota would improve the utility firm's own profit. The profit of utility firm 1 would increase, while utility firm 2 remains unchanged. Since the total carbon quotas would encourage the utility firm 1 to invest in renewable energy, the total profits of two utility firms would increase with the total carbon quotas.

Discussions and conclusions

Discussions

This paper discusses the influence of the cap-and-trade mechanisms on renewable energy investment in a competitive market and a cooperative market respectively, to provide managerial insights into the government, utility firms, and consumers.

Let us first take the perspective of the government. Firstly, the government should encourage the utility firms to involve in competitive markets, inducing more investment of renewable energy. Secondly, the government should adopt a BM, as the BM encourages more investment in renewable energy. Therefore, the BM in the competitive market is a more attractive to motivate utility firms to invest in renewable energy. Finally, the increase in the carbon price can lead to more investment in renewable energy, while reducing the demand of electricity in the consumer market. Therefore, setting an appropriate carbon price will induce more investment in renewable energy while maintaining the electricity demand.

Let us take the perspective of the utility firms. Firstly, they are more likely to cooperate in the market because both are more profitable. Secondly, if the utility firms are encouraged to actively practice the GM, the total carbon quotas increase. Finally, a utility firm's profit increases with the decrease in its own carbon emissions. It is suggested that utility firms should pay attention to reducing their unit carbon emission and provide low-carbon traditional energy.

For the perspective of consumers, they prefer to a BM, because the BM results in a higher consumer surplus. In addition, further educating consumers' knowledge on carbon mechanisms helps to develop the low-carbon economy.

Conclusions

Carbon emissions cause climate change. Governments have implemented carbon mechanisms to regulate the carbon emissions behaviour of firms. In practice, the GM and the BM have been adopted by utility firms, which has encouraged them to invest in renewable energy in many regions such as China and the EU, in either the cooperative or the competitive markets. In our paper, we compare the optimal levels of renewable energy investment and electricity production under the BM and the GM in both the cooperative and the competitive markets to identify which system is more effective in encouraging utility firms to invest in renewable energy. Our study helps firms make decision on the investment in the renewable energy.

We develop a profit maximization model in which two utility firms make decisions on renewable energy investment and electricity production in cooperative or competitive markets. The main results are as follows. (1) As compared to the GM, utility firms will invest more in renewable energy under the BM in both cooperative and competitive markets. Moreover, under both the GM and the BM, utility firms will invest more in renewable energy in a competitive market than in a cooperative market. (2) A competitive market encourages more investment in renewable energy than a cooperation market does. However, the profit of total profits of the two firms in cooperative market is higher than in competitive market. (3) We show that utility firms will have higher electricity production and total carbon emissions under the BM than under the GM. (4) With the increase in one utility firm's unit carbon emission, the other utility firm's renewable energy investment and electricity production will increase.

From the perspective of energy low-carbon transformation, the government can adopt the BM to motivate the utility firms to invest more in renewable energy. The government should encourage market competition, as the competitive market can induce more investment in renewable energy than the cooperative market does. Therefore, competitive market should be encouraged, and BM should be implemented. Furthermore, the government should appropriately raise the carbon price, which also encourages more investment in renewable energy. Finally, increasing the unit carbon quota can increase not only the investment in renewable energy, but also the profits of enterprises. Therefore, the government should appropriately increase the unit carbon quota.

This paper examines the renewable energy investment under cap-and-trade mechanisms in both cooperative and competitive markets. We discuss the influence of different market types on renewable energy investment, which is helpful to achieve the goal of low-energy transformation. The work can be extended to three directions in the future work. Firstly, this paper discusses the relationship between competition and cooperation with the two utility firms. The study can be extended to the setting in which an electricity supply chain has multiple electricity generators and electricity retailers. The research can investigate the influences of the cap-and-trade mechanisms on the renewable energy investment. Secondly, this paper discusses the renewable energy investment under cap-and-trade mechanisms, which can be extended to investigate an electricity generator invest in renewable energy and the low-carbon technology under different carbon mechanisms. Thirdly, this paper studies the impact of the single-cycle cap-and-trade mechanism on the renewable energy investment, which can be extended to examine the renewable energy investment for a two-cycle setting.

Appendix

Proof of Proposition 1

With Lemmas 1–4, we have:

$$q_i^{CB*} - q_i^{CG*} = \frac{we_0(c_i + d_i)\left[2bd_j + c_j\left(2b + d_j\right)\right]}{bd_i\left[3bd_j + c_j\left(3b + 2d_j\right)\right] + c_i\left\{bd_j(3b + 2d_i) + c_j\left[b(3b + 2d_i) + d_j(2b + d_i)\right]\right\}} > 0,$$

$$q_1^{MB*} + q_2^{MB*} - (q_1^{MG*} + q_2^{MG*}) = \frac{we_0\left\{c_2d_1d_2 + c_1[d_1d_2 + c_2(d_1 + d_2)]\right\}}{2bd_1d_2c_2 + c_1\left\{2bd_1d_2 + c_2[2bd_1 + d_2(2b + d_1)]\right\}} > 0,$$

$$q_1^{CB*} + q_2^{CB*} - q_1^{CG*} - q_2^{CG*} = \frac{w\left\{e_0c_1[(2b + d_1)d_2 + c_2(2b + d_1 + d_2)] + d_1[2bd_2 + c_2(2b + d_2)]\right\}}{\left\{\begin{array}{c} bd_1[3bd_2 + c_2(3b + 2d_2)] \\ +c_1\left\{bd_2(3b + 2d_1) + c_2[b(3b + 2d_1) + d_2(2b + d_1)]\right\} \end{array}\right\}} > 0,$$

$$p^{MB*} - p^{MG*} = -\frac{bwe_0\left\{c_2d_1d_2 + c_1[d_1d_2 + c_2(d_1 + d_2)]\right\}}{bd_1[3bd_2 + c_2(3b + 2d_2)] + c_1\left\{bd_2(3b + 2d_1) + c_2[b(3b + 2d_1) + d_2(2b + d_1)]\right\}} < 0, \text{and}$$

$$p^{CB*} - p^{CG*} = -\frac{bwe_0\left\{d_1[2bd_2 + c_2(2b + d_2)] + c_1[d_2(2b + d_1) + c_2(2b + d_1 + d_2)]\right\}}{bd_1[3bd_2 + c_2(3b + 2d_2)] + c_1\left\{bd_2(3b + 2d_1) + c_2[b(3b + 2d_1) + d_2(2b + d_1)]\right\}} < 0.$$

Proof of Proposition 2

With Lemmas 1–4, we have:

$$k_1^{MB*} + k_2^{MB*} - (k_1^{MG*} + k_2^{MG*}) = \frac{we_0c_1c_2(d_1 + d_2)}{2bd_1d_2c_2 + c_1\left\{2bd_1d_2 + c_2[2bd_1 + d_2(2b + d_1)]\right\}} > 0,$$

$$k_1^{CB*} - k_1^{CG*} = \frac{wc_1e_0[bd_2 + c_2(b + d_2)]}{bd_1[3bd_2 + c_2(3b + 2d_2)] + c_1\left\{bd_2(3b + 2d_1) + c_2[b(3b + 2d_1) + d_2(2b + d_1)]\right\}} < 0, \text{and}$$

$$k_1^{CB*} + k_2^{CB*} - k_1^{CG*} - k_2^{CG*} = \frac{we_0\left\{bc_2d_1 + c_1[bd_2 + c_2(2b + d_1 + d_2)]\right\}}{\left\{\begin{array}{c} bd_1[3bd_2 + c_2(3b + 2d_2)] + c_1\{bd_2(3b + 2d_1) \\ +c_2[b(3b + 2d_1) + d_2(2b + d_1)]\} \end{array}\right\}} > 0.$$

Proof of Proposition 3

With Lemmas 2–3, we have:

$$E_1^{MB*} + E_2^{MB*} - (E_1^{MG*} + E_2^{MG*}) = \frac{we_0d_1d_2(e_1c_2 + c_1e_2)}{2bd_1d_2c_2 + c_1\left\{2bd_1d_2 + c_2[2bd_1 + d_2(2b + d_1)]\right\}} > 0,$$

$$E_i^{CB*} - E_i^{CG*} = \frac{wd_i\left[bd_j + c_je_0e_i\left(b + d_j\right)\right]}{bd_i\left[3bd_j + c_j\left(3b + 2d_j\right)\right] + c_i\left\{bd_j(3b + 2d_i) + c_j\left[b(3b + 2d_i) + d_j(2b + d_i)\right]\right\}} > 0, \text{and}$$

Table 1 The optimal profits under the two mechanisms and types of markets

	π^*
MG	$\dfrac{\left\{\begin{array}{c} 4B^2\widetilde{E}_1 w - A_1^2 c_1 - A_2^2 c_2 + 2A_1(C - Bwe_1 + c_1F_1) \\ +F_1[2Bwe_1 - (c_1 + d_1)F_1] + 2Bwe_2F_2 - c_2F_2^2 + 2A_2(C - Bwe_2 + c_2F_2) \end{array}\right\}}{2B^2}$
MB	$\dfrac{\left\{\begin{array}{c} d_2(F_2 + c_1d_1e_0wc_2)^2 + d_1(F_1 + c_1d_2e_0wc_2)^2 + c_1(A_1 - F_1 + d_1d_2e_0wc_2)^2 - 2B(F_1 + c_1d_2e_0wc_2)we_0 - \\ 2\left\{C - bwe_0\left\{c_2d_1d_2 + c_1\left[c_2d_1 + (c_2 + d_1)d_2\right]\right\}\right\}\left\{A_1 + A_2 + we_0\left\{c_1c_2d_1 + d_2\left[c_1c_2 + (c_1 + c_2)d_1\right]\right\}\right\} + \\ 2Bw(-e_0 + e_1)\left\{A_1 - F_1 + d_2\left[-c_1e_0wc_2 + c_2(c_1 + d_1)we_0\right]\right\} \\ -2Bw(e_0 - e_2)\left\{-A_2 + F_2 + c_1d_1\left[e_0wc_2 - (c_2 + d_2)we_0\right]\right\} + c_2\left\{A_2 - F_2 + c_1d_1\left[-e_0wc_2 + (c_2 + d_2)we_0\right]\right\}^2 \end{array}\right\}}{2B^2}$
CG	$\pi_1^{CG*} = \frac{2D^2Rw - d_1G_1^2 + 2Dwe_1(G_1 - T_1) - c_1(G_1 - T_1)^2 + 2JT_1}{2D^2}$; $\pi_2^{CG*} = \frac{2D^2Rw - d_2G_2^2 + 2Dwe_2(G_2 - T_2) - c_2(G_2 - T_2)^2 + 2JT_2}{2D^2}$
CB	$\pi_1^{CB} = \dfrac{\left\{\begin{array}{c} 2Dwe_0\left\{G_1 + c_1we_0\left[bd_2 + c_2(b + d_2)\right]\right\} - 2Dw(e_0 - e_1)\left\{G_1 - T_1 - d_1we_0\left[bd_2 + c_2(b + d_2)\right]\right\} \\ +c_1\left\{-G_1 + T_1 + d_1we_0\left[bd_2 + c_2(b + d_2)\right]\right\}^2 \\ +2(J - Me_0)\left\{T_1 + we_0(c_1 + d_1)\left[bd_2 + c_2(b + d_2)\right]\right\} + d_1\left\{G_1 + c_1we_0\left[bd_2 + c_2(b + d_2)\right]\right\}^2 \end{array}\right\}}{2D^2}$; $\pi_2^{CB} = \dfrac{\left\{\begin{array}{c} 2Dwe_0\left\{G_2 + c_2we_0\left[bd_1 + c_1(b + d_1)\right]\right\} \\ -d_2\left\{G_2 + c_2we_0\left[bd_1 + c_1(b + d_1)\right]\right\}^2 + 2Dw(e_0 - e_1)\left\{G_2 - T_2 - d_2we_0\left[bd_1 + c_1(b + d_1)\right]\right\} \\ -c_2\left\{-G_2 + T_2 + d_2we_0\left[bd_1 + c_1(b + d_1)\right]\right\}^2 - 2(J - Me_0)\left\{T_2 + we_0\left[bd_1 + c_1(b + d_1)\right](c_2 + d_2)\right\} \end{array}\right\}}{2D^2}$

$$E_1^{CB*}+E_2^{CB*}-E_1^{CG*}-E_2^{CG*}=\frac{we_0\left\{d_1e_1[bd_2+c_2(b+d_2)]+d_2e_2[bd_1+c_1(b+d_1)]\right\}}{\left\{\begin{array}{c} bd_1[3bd_2+c_2(3b+2d_2)]+c_1\{bd_2(3b+2d_1) \\ +c_2[b(3b+2d_1)+d_2(2b+d_1)]\} \end{array}\right\}}>0.$$

Proof of Lemma 5

With Lemmas 1–4 and the customer surplus function $Cs^*=\frac{(q_1^*+q_2^*)^2}{2b}$, we can easily obtain the results presented in Lemma 5.

Proof of Proposition 4

We firstly define:

$$A_i=d_j(c_i+d_i)\left(ac_j+2bwe_j\right)-wd_ie_i\left[2bd_j+c_j\left(2b+d_j\right)\right],$$

$$B=2bd_1d_2c_2+c_1\left\{2bd_1d_2+c_2[2bd_1+d_2(2b+d_1)]\right\},$$

$$C=bc_2d_1d_2(a+we_1)+c_1\left\{ac_2[bd_1+d_2(b+d_1)]+bd_1d_2(a+we_2)\right\},$$

$$D=bd_1[3bd_2+c_2(3b+2d_2)]+c_1\left\{bd_2(3b+2d_1)+c_2[b(3b+2d_1)+d_2(2b+d_1)]\right\},$$

$$T_i=(c_i+d_i)\left[ac_j\left(b+d_j\right)+bd_j\left(a+we_j\right)\right]-wd_ie_i\left[2b\left(c_j+d_j\right)+c_jd_j\right],$$

$$F_i=d_j\left[2bwe_ic_j+c_i\left(ac_j+2bwe_j\right)\right],$$

$$G_i=bwe_i\left[3bd_j+c_j\left(3b+2d_j\right)\right]+c_i\left[ac_j\left(b+d_j\right)+bd_j\left(a+we_j\right)\right],$$

$$H_i=e_i\left\{c_j\left[ad_1d_2-we_i\left(2bd_j+2bd_i+d_1d_2\right)\right]+2bwd_1d_2\left(e_j-e_i\right)\right\},$$

$$I_i=e_i\left\{\begin{array}{c} c_j\{ad_i(b+d_j)-w[d_i(2b+d_j)+be_i(3b+2d_j)]\} \\ +bd_j[-bwe_i+d_j(a-2we_i+we_j)] \end{array}\right\},$$

$$J=[bd_2+c_2(b+d_2)][ac_1(b+d_1)+bd_1(a+we_1)]+bwd_2e_2[bd_1+c_1(b+d_1)],$$

$$M=bw\left\{d_1[2bd_2+c_2(2b+d_2)]+c_1[(2b+d_1)d_2+c_2(2b+d_1+d_2)]\right\},$$

$$\begin{aligned}\bar{E}=&A_1^2c_1+A_2^2c_2-2A_1(C-Bwe_1+c_1F_1)-2Bwe_2F_2+c_2F_2^2-2A_2(C-Bwe_2+c_2F_2)\\ &-d_2(F_2+c_1d_1e_0wc_2)^2+d_1(F_1+c_1d_2e_0wc_2)^2+c_1(A_1-F_1+d_1d_2e_0wc_2)^2\\ &+2B(F_1+c_1d_2e_0wc_2)we_0+2\left\{C-bwe_0[c_2d_1d_2+c_1(d_1c_2+d_2(c_2+d_1))]\right\}\\ &\left\{A_1+A_2+we_0[c_1c_2d_1+d_2(c_1c_2+(c_1+c_2)d_1)]\right\}+2Bw(e_0-e_1)\\ &\left\{A_1-F_1+d_2[-c_1e_0wc_2+c_2we_0(c_1+d_1)]\right\}-F_1[2Bwe_1-(c_1+d_1)F_1]2Bw(e_0-e_2)\\ &\left\{-A_2+F_2+c_1d_1[e_0wc_2-we_0(c_2+d_2)]\right\}-c_2\left\{A_2-F_2+c_1d_1[-e_0wc_2+(c_2+d_2)we_0]\right\}^2;\end{aligned}$$

$$\begin{aligned}\bar{\bar{E}} =& d_1G_1^2 - 2Dwe_1(G_1 - T_1) + c_1(G_1 - T_1)^2 - 2JT_1 + 2Dwe_0\{G_1 + c_1we_0[bd_2 + c_2(b + d_2)]\}\\ &- 2Dw(e_0 - e_1)\{G_1 - T_1 - d_1we_0[bd_2 + c_2(b + d_2)]\} + c_1\{-G_1 + T_1 + d_1we_0[bd_2 + c_2(b + d_2)]\}^2\\ &+ 2e_0\{J - bw\{d_1[2bd_2 + c_2(2b + d_2)] + c_1[(2b + d_1)d_2 + c_2(2b + d_1 + d_2)]\}\}\\ &\{T_1 + we_0(c_1 + d_1)[bd_2 + c_2(b + d_2)]\} - d_1\{G_1 + c_1we_0[bd_2 + c_2(b + d_2)]\}^2, \text{and}\end{aligned}$$

$$\begin{aligned}\bar{\bar{\bar{E}}} =& d_2G_2^2 + c_2(G_2 - T_2)^2 - 2Dwe_0\{G_2 + c_2we_0[bd_1 + c_1(b + d_1)]\} + d_2\{G_2 + c_2we_0[bd_1 + c_1(b + d_1)]\}^2\\ &+ 2Dwe_2(-G_2 + T_2) + 2Dw(e_0 - e_1)\{G_2 - T_2 - d_2we_0[bd_1 + c_1(b + d_1)]\}\\ &+ c_2\{-G_2 + T_2 + d_2we_0[bd_1 + c_1(b + d_1)]\}^2 - 2JT_2\\ &- 2e_0\{J - bw\{d_1[2bd_2 + c_2(2b + d_2)] + c_1[(2b + d_1)d_2 + c_2(2b + d_1 + d_2)]\}\}\\ &\{T_2 + we_0[bd_1 + c_1(b + d_1)](c_2 + d_2)\}.\end{aligned}$$

The we can summarize optimal profits under the two mechanisms and types of markets in We have Table 1.

With Table 1, we have:

$\pi^{MG*} - \pi^{MB*} = 2\widetilde{E}w - \frac{\bar{E}}{2B^2}, \pi_1^{CG*} - \pi_1^{CB*} = \widetilde{E}w - \frac{\bar{\bar{E}}}{2D^2}$, and $\pi_2^{CG*} - \pi_2^{CB*} = \widetilde{E}w - \frac{\bar{\bar{\bar{E}}}}{2D^2}$. Thus, (1) when $\widetilde{E} < \frac{w\bar{E}}{4B^2}$, then $\pi^{MG*} < \pi^{MB*}$ and $\pi^{MG*} \geq \pi^{MB*}$ otherwise; (2) when $\widetilde{E} < \frac{\bar{\bar{E}}}{2wD^2}$, then $\pi_1^{CG*} < \pi_1^{CB*}$ and $\pi_1^{CG*} \geq \pi_1^{CB*}$ otherwise; (3) when $\widetilde{E} < \frac{\bar{\bar{\bar{E}}}}{2wD^2}$, then $\pi_2^{CG*} < \pi_2^{CB*}$ and $\pi_2^{CG*} \geq \pi_2^{CB*}$ otherwise.

Proof of Lemma 7

$Fs^{CG*} - Fs^{CB*} = \widetilde{E} - \widehat{E}$ gives when $\widetilde{E} < \widehat{E}$, then $Fs^{CG*} < Fs^{CB*}$ and $Fs^{CG*} \geq Fs^{CB*}$ otherwise.$Fs^{MG*} - Fs^{MB*} = \widetilde{E} - \widehat{\widehat{E}}$ gives when $\widetilde{E} < \widehat{\widehat{E}}$, then $Fs^{MG*} < Fs^{MB*}$ and $Fs^{MG*} \geq Fs^{MB*}$ otherwise, where

$$\widehat{E} = \frac{we_0\left\{\begin{array}{c} we_0(c + d)\{(3 + 4b^2)d + c[3 + 2b(2b + d)]\}\\ +4[a(c + d) - dwe]\{d + 2b^2d + c[1 + b(2b + d)]\}\end{array}\right\}}{4b\{cd + 3b(c + d)\}^2} \text{and}$$

$$\widehat{\widehat{E}} = \left\{\begin{array}{c} \frac{4[(c+d)(a+we_0)-dwe]^2}{b[cd+4b(c+d)]^2} - \frac{-2(c+d)(a+we_0)^2+4dw(a+we_0)e-2(4b+d)w^2e_2^2}{cd+4b(c+d)}\\ -\frac{4[ac+d(a-we)]^2}{b[4bd+c(4b+d)]^2} - \frac{2[a^2c+4bw^2e^2+d(a-we)^2]}{4bd+c(4b+d)}\end{array}\right\}.$$

Proof of Proposition 5

With Table 1, we have:

$$\pi^{MG*} - \pi_1^{CG*} - \pi_2^{CG*} = \frac{(c + d)[abc + bd(a - we)]^2}{[3bd + c(3b + d)]^2[4bd + c(4b + d)]} > 0\text{and}$$

$$\pi^{MB*} - \pi_1^{CB*} - \pi_2^{CB*} = \frac{(c + d)[b(c + d)(a + we_0) - bwde]^2}{[3bd + c(3b + d)]^2[4bd + c(4b + d)]} > 0.$$

List of symbols

a	Potential electricity demand
b	Sensitivity coefficient of electricity production
w	Carbon price
c_i	Cost coefficient of conventional energy of utility firm i
D_i	Electricity production of conventional energy of utility firm i
d_i	Cost coefficient of renewable energy investment of utility firm i
e_0	Unit carbon quota
$\tilde{E}_i$	Total carbon quota
e_i	Carbon emissions of utility firm i
π_i	Profit of utility firm i

Decision variables

q_i	Electricity production of utility firm i
k_i	Renewable electricity investment of utility firm i

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Authors' contributions
All authors read and approved the final manuscript.

Declarations

Competing interests
The authors declare that they have no competing interests.

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