EnPress Publisher

Journal of Infrastructure, Policy and Development 2024, 8(8), 5470.
https://doi.org/10.24294/jipd.v8i8.5470

Article

Do different government policies contribute to electricity suppliers' renewable energy investments?

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CITATION

Wang H, Huang W, Zhang P, et al. (2024). Do different government policies contribute to electricity suppliers' renewable energy investments?. Journal of Infrastructure, Policy and Development. 8(8): 5470. https://doi.org/10.24294/jipd.v8i8.5470

ARTICLE INFO

Received: 27 March 2024
Accepted: 21 May 2024
Available online: 14 August 2024

Abstract: To achieve the energy transition and carbon neutrality targets, governments have implemented multiple policies to incentivize electricity suppliers to invest in renewable energy. Considering different government policies, we construct a renewable energy supply chain consisting of electricity suppliers and electricity retailers. We then explore the impact of four policies on electricity suppliers' renewable energy investments, environmental impacts, and social welfare. We validated the results based on data from Wuxi, Jiangsu Province, China. The results show that government subsidy policies are more effective in promoting electricity suppliers to invest in renewable energy as consumer preferences increase, while no-government policies are the least effective. We also show that electricity suppliers are most profitable under the government subsidy policy and least profitable under the carbon cap-and-trade policy. Besides, our results indicate that social welfare is the worst under the carbon cap-and-trade policy. With the increase in carbon intensity and renewable energy quota, social welfare is the highest under the subsidy policy. However, the social welfare under the renewable energy portfolio standard is optimal when the renewable energy quota is low.

Keywords: renewable energy investment; government policy; environmental impact; social welfare

1. Introduction

As a low-carbon energy source, renewable energy is a crucial component of countries' multi-wheel drive energy supply systems (**Figure 1**) (IEA, 2022). From the current energy structure transformation, renewable energy contributes significantly to improving energy structure, protecting the ecological environment, coping with climate change, and achieving sustainable economic and social development (**Figure 2**). Despite the COVID-19 epidemic, governments have maintained their investments in renewable energy (**Figure 3**). For example, the European Union plans to allocate approximately 30% of the COVID-19 stimulus package to renewable energy. Colombia aims to gather $4.6 million to accelerate the construction of 27 renewable energy projects (Statistical Review of World Energy, 2021).

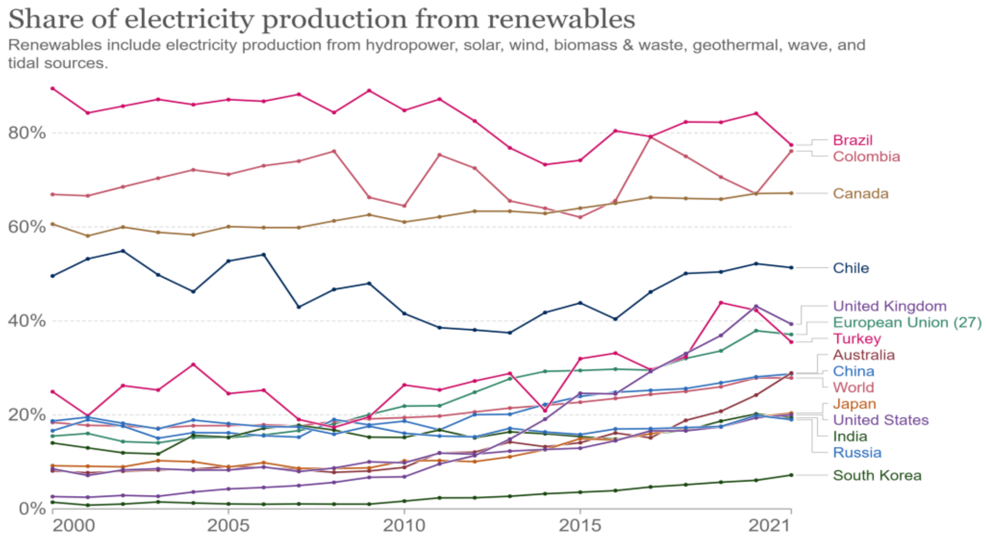


Figure 1. Share of renewable energy generation in total energy.

Source: BP Statistical Review of World Energy. Ember Global Electricity Review (2022). Ember European Electricity Review (2022). Our World in Data.

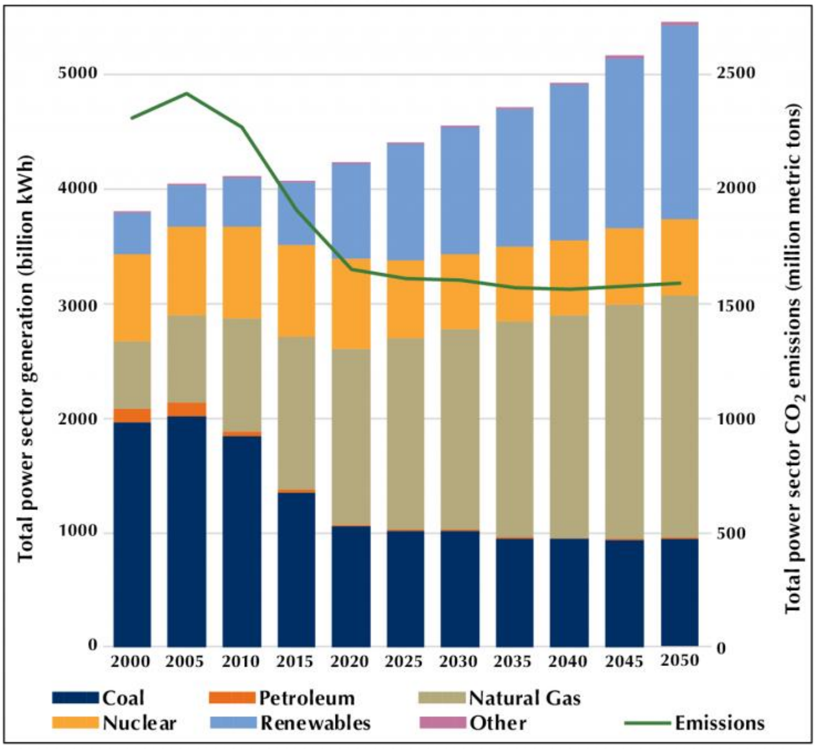


Figure 2. U.S. Renewable energy generation and carbon emissions reduction since 2000.

Note: The rapid growth of renewable energy sources, such as wind and solar, has reduced emissions from the power generation sector by 28% since 2005.

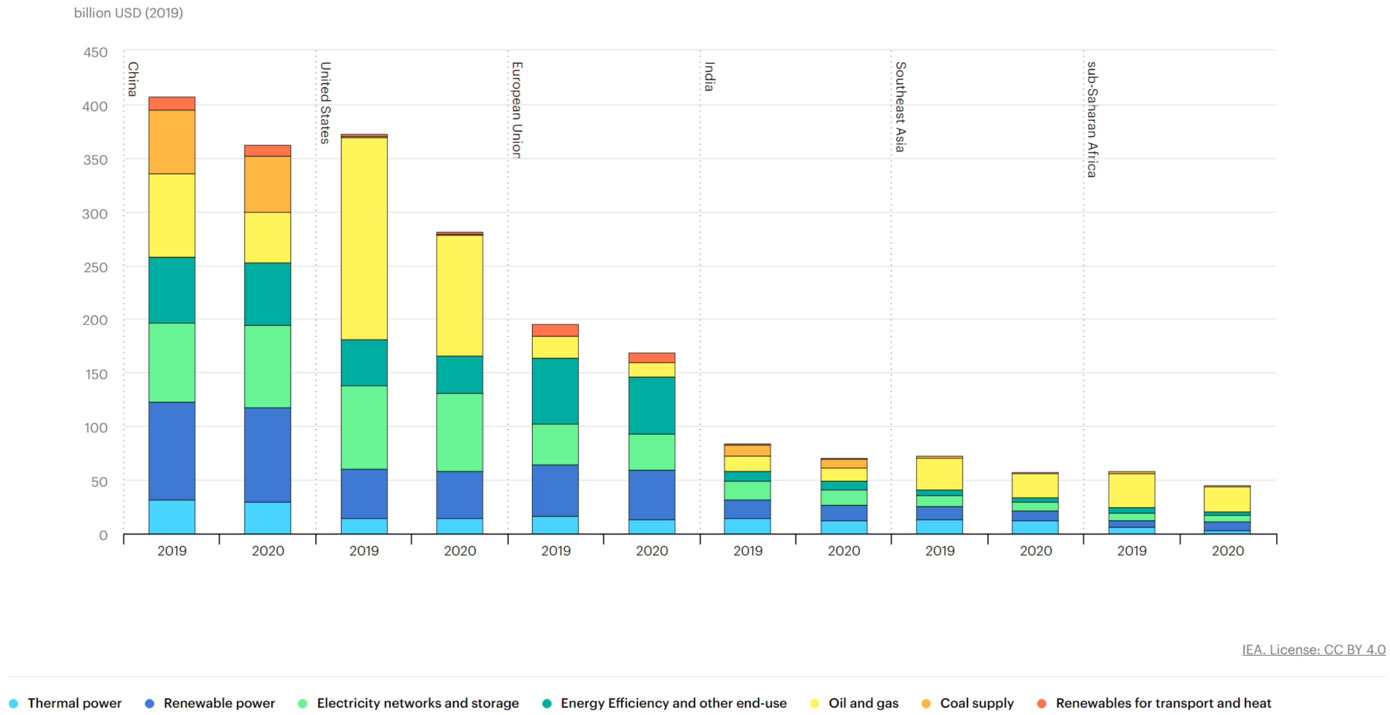


Figure 3. Renewable energy investments in different countries in 2019 and 2020.
(Source: IEA World Energy Investment, 2020).

Furthermore, governments have adopted various policies and regulations to incentivize companies to use and invest in renewable energy to promote renewable energy development. Until 2016, 173 countries have introduced renewable energy policies (Adib et al., 2016). In addition, 146 countries promote renewable energy through subsidy policies (Chen et al., 2020), and 31 countries promote renewable energy through carbon cap-and-trade policy (**Figure 4**). More than 29 countries worldwide, including the United States, the United Kingdom, Japan, and Belgium, have implemented renewable portfolio standard policies (RPS) (Jenny et al., 2019). For example, (RPS) has been adopted by 31 states as a state-level renewable energy policy in the United States (Evensen 2017). China also implemented a renewable energy portfolio standard policy in 2019 (NEA, 2019). While these policies have become widespread, it remains uncertain what impact they have on renewable energy investment in the electricity market. At the same time, it is unclear whether consumer renewable energy preferences have played a role in renewable energy investment. Therefore, this naturally begs the practical question: How do government policies affect renewable energy investment in electricity markets, considering consumer preferences?

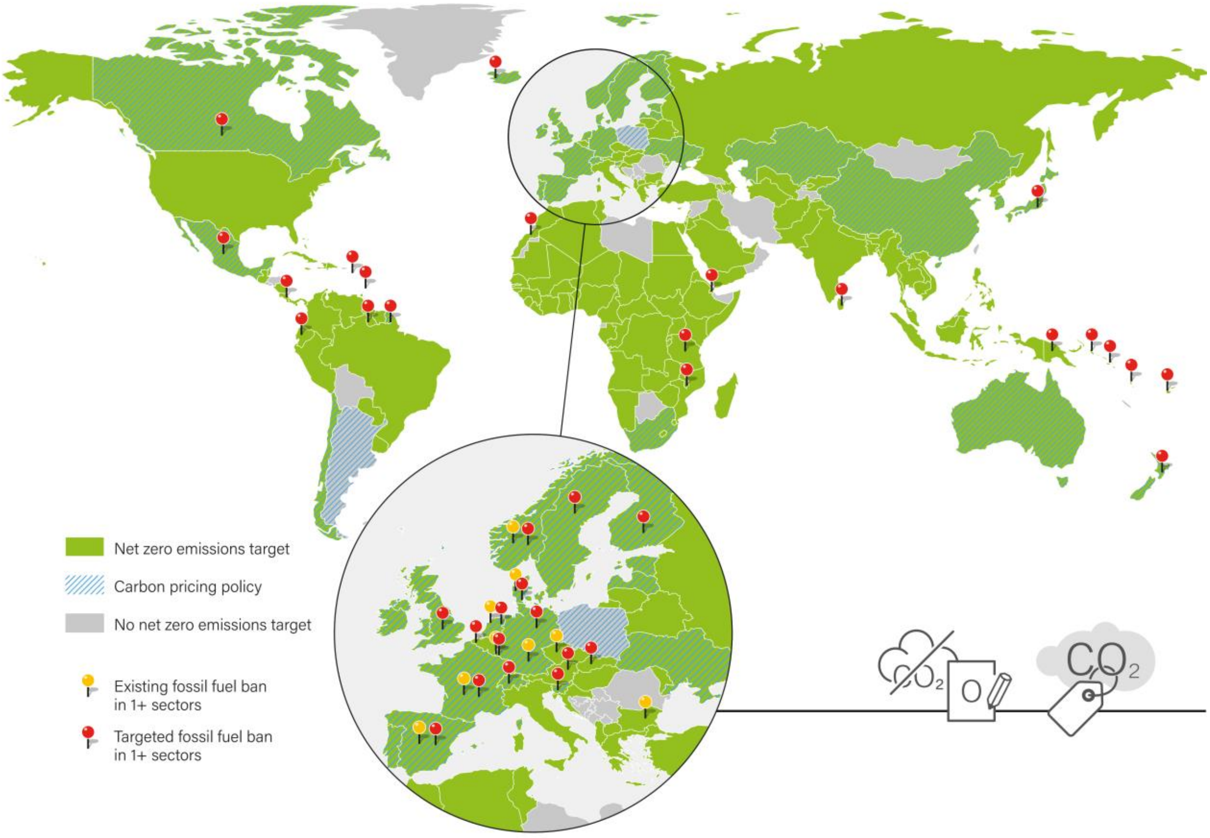


Figure 4. Carbon pricing policies drive the renewable energy development.

Note: Carbon pricing policies include carbon cap-and-trade policies and carbon tax policies.
Source: UN environment program Renewables 2021 Global Status Report.

From the above research motivation, we focus on exploring the impact of different government policies on electricity suppliers' renewable energy investments in the electricity market, considering consumer preferences. Specifically, we address the following research questions: (1) Which policies are conducive to driving electricity suppliers to invest in renewable energy considering consumer preferences? Are consumer preferences favorable to promoting electricity suppliers' renewable energy investments? (2) Which policy is more beneficial to reduce environmental impacts and improve overall social welfare?

To answer the above questions, we construct a renewable energy supply chain consisting of electricity suppliers and electricity retailers. We concentrate on exploring the impact of four government policies on electricity suppliers' renewable energy investments under consumer preferences. Then, we compare the stakeholders' profits under different government policies. Finally, we analyze the impact of different policies on environmental and social welfare under consumer preferences.

The research contributions of this paper are as follows: First, this paper investigates the impact of different policies on renewable energy investments under consumer preferences, which some literature has rarely considered. Second, we consider the impact of electricity suppliers' renewable energy investments on consumer surplus and social welfare under different policies. These results provide managerial insights into the government's choice of reasonable policy to incentivize electricity companies to invest in renewable energy. Finally, we find some interesting findings. For example, the environmental impact and social welfare under the no-government policy scenario may outperform other policies under carbon emissions, renewable energy carbon quotas, and consumer preference constraints.

The remainder of the paper is structured as follows: we present the literature review in Section 2. Section 3 constructs and describes the model consisting of electricity suppliers and electricity retailers under different government policies. Section 4 explores the stakeholders' profits and equilibrium outcomes under different policies. We compare and analyze the equilibrium outcomes, environmental impacts, and social welfare under different scenarios in Section 5. Section 6, we conduct a numerical examination and discussion according to the equilibrium outcomes under different policies. Finally, we summarize the main findings and present management insights in Section 7.

2. Literature review

This paper deals with research on government policy, consumer behavior, and renewable energy investment. Therefore, we focus on exploring the literature related to these three streams in the literature review section. We also summarize the research gaps and theoretical contributions of this paper at the end.

Governments have implemented multiple policies to promote the development and utilization of renewable energy, which is important to improve the energy structure and achieve the goal of carbon neutrality and carbon peaking. As a regular policy instrument implemented by governments, subsidies play an important role in reducing the cost of renewable energy investments by companies (Yang et al., 2016). Yang et al. (2019) explores the impact of government subsidies on investment in renewable energy with a panel threshold effects model. The results show that monetary subsidies and tax incentives can encourage firms to invest in renewable energy. Carbon tax and renewable energy portfolio standard policies have been shown to facilitate increased renewable energy investments (Wall et al., 2018). By constructing an optimization mechanism for renewable energy systems under carbon tax and carbon cap-and-trade policies, Zhang et al. (2016) explores the impact of different policies on the economic efficiency of renewable energy systems. They show that carbon tax and carbon cap-and-trade policies can effectively improve the economic efficiency of renewable energy systems and reduce carbon emissions. Some literature has also explored the impact of carbon cap-and-trade policies and renewable energy portfolio standards on renewable energy investments (Yan et al., 2022; Zhu et al., 2022). Government subsidies can promote renewable energy investment; nevertheless, it may also impose a fiscal burden. In contrast to subsidy policies, renewable portfolio standards are considered to be effective in reducing government expenditures while promoting renewable energy investment (Zhang et al., 2018). Taking the renewable portfolio standard policy (RPS) as the research object, Wang et al. (2022) investigate the impact of RPS on PV power investment at the micro level, and the results show that phased investment is the best choice. The carbon neutrality target drives the implementation of renewable energy portfolio standard policies. Based on a two-level decision model, the findings show that the renewable portfolio standard policy contributes to achieving carbon emission reduction targets and maximizing social welfare (Wang and Li, 2022). Renewable energy portfolio standard policies are crucial means to promote the energy transition, but the trade-off between their effectiveness and cost remains a challenge. Therefore, Zhao et al. (2022) investigate the incentive mechanism under the renewable energy portfolio standard policy to improve effectiveness and reduce costs.

Consumers' low-carbon awareness and growing concern about the climate environment have changed consumer behavior and attitudes, which stimulates consumers more inclined to consume renewable energy (Colasante et al., 2021; Itaoka et al., 2022; Niamir et al., 2020). For example, Kesari et al. (2018) utilizes structural equation modeling to analyze consumer decision-making behavior for renewable energy. They show that environmental responsibility, environmental attitudes contribute to the consumer's adoption of renewable energy. Similar to Kesari et al. (2018), according to consumer data results, Venugopal and Shukla (2018) show that consumer indifference to environmental issues increases the negative impact of consumer purchases of renewable energy. Bae et al. (2021) investigates heterogeneous consumer preferences with different estimation models. They show that consumers prefer solar energy and a higher share of renewable energy electricity. In addition, considering consumer preferences, Amin et al. (2020) explores novel schemes for energy pricing and energy allocation, and the results show that the novel schemes contribute to reducing consumer energy costs and improving energy market fairness. Promoting the use of renewable energy is becoming a policy strategy for achieving carbon neutrality goals in some countries. The achievement of carbon neutrality targets needs to consider consumers' willingness to pay and purchase behavior for renewable energy (Chaikumbung, 2021). Energy consumption ties closely to consumer behavior characteristics, and Masrahi et al. (2021) attempts to understand the impact of consumer behavior on willingness to use renewable energy. The results show that consumer perceived behavioral control exert positive impact on increasing willingness to use renewable energy. With the help of a complex network evolution model, Fan et al. (2022) show that consumer preferences and carbon cap-and-trade policies exhibit duality in driving the R&D diffusion of new energy vehicles. Besides, according to social surveys in 22 European countries, Umit et al. (2019) shows that consumer energy-saving behavior is influenced by education level and income.

High fossil fuel prices and energy security issues highlight the urgent necessity to accelerate the transition to renewable energy. As a result, some electricity generation companies are committed to investing in renewable energy to shift energy risks and achieve sustainable development (Al-Barakati et al., 2022; Atakan et al., 2022). Using retrospective policy changes as a research perspective, Sendstad et al. (2022) builds difference-in-difference regression models with time series data from the EU. They show that retrospective subsidies reduce the rate of renewable energy investment. However, a stable policy environment is conducive for firms to increase their renewable energy investments. Due to the potential risks associated with renewable energy investments, electric companies are more inclined to invest in renewable energy if credit banks offer low-interest rate loans and reduced financing terms (Tsao et al., 2021). Considering marketing efforts in the electricity market, Chen et al. (2022) investigates the impact of carbon cap-and-trade policies on electricity generation companies' renewable energy investments. Renewable energy system construction requires long-term investments and is influenced by multiple factors. Therefore, renewable energy investment decision-makers need to fully consider economic, social, and environmental indicators to establish a robust decision-making framework (Koponen and Net, 2021). In addition, focusing on the intermittent and volatile character of renewable energy, Kök et al. (2018) analyzes renewable energy investments under different pricing policies, and its results show that uniform pricing increases the level of investment in renewable energy and reduces carbon emissions. Similarly, to deal with the volatility, indirectness, and high-risk characteristics of renewable energy, governments will adopt subsidy policies to increase the rate and economic viability of renewable energy investments (Williams, 2001). For example, Babich et al. (2020) shows that government subsidies can eliminate investment delays and price variability. Subsidies play a vital role in promoting renewable energy investments, but some controversy remains. Moreover, some studies suggest that subsidies can reduce renewable energy investment (Kök et al., 2020).

Research gaps

Similar to some of the literature, we consider renewable energy investments under renewable energy portfolio standard policies, but based on this, we further analyze and discuss the combined effects of different government policies (subsidies, carbon cap policies) and market expansion (i.e., additional markets due to consumer preferences) on electricity suppliers' investments, which have been less considered in the previous literature. In addition, we analyze the impact of consumer preferences on electricity suppliers' investment strategies. We focus on the combined impact of four government policies on electricity suppliers' investments under consumer preferences, which is something that has not been emphasized in the analysis in some of the literature. In addition, we analyze social welfare under different government policies. To the best of our knowledge, this is the first paper to consider the combined effects of four different policies, costs, and market expansion on social welfare and electricity suppliers' investment strategies under consumer preferences.

- Our contribution to the field of theoretical literature:

We provide an efficient methodology to study the promotion of electricity supplier investment under government policies, while maintaining the computability of the model. Our contributions to the literature on different government policies, electricity supplier investment and renewable energy utilization are:

- We explore the combined effects of four different government policies, investment costs, and market expansion (i.e., additional markets due to consumer preferences) in our model.
- We capture not only the effects of different government policies on electricity supplier investment, but also the effects of investment costs, market expansion on electricity supplier investment and social welfare.
- To the best of our knowledge, this is the first time that different government policies, investment costs, and market expansions have been incorporated into a game model, and some interesting conclusions have

been drawn that provide managerial insights for firms and electricity suppliers' renewable energy investments and improved social welfare.

3. Model

This paper considers a supply chain system consisting of electricity suppliers and electricity retailers under different government policies. Electricity suppliers generate electricity by using conventional energy sources (e.g., natural gas, oil) and renewable energy sources (e.g., building hydroelectric plants, solar and biomass power). The government implements different policy measures to incentivize electricity suppliers to invest in renewable energy. Under the same conditions, we assume that stakeholders are rational and stakeholders pursue the option that is most beneficial to them. Under different policy backgrounds and with the above supply chain structure, we mainly consider the following scenarios.

(1) No government policy (Scenario NON), i.e., the government does not implement any government policy. The electricity suppliers are not constrained or incentivized by government policies, which means that the electricity suppliers' renewable energy investments only depend on environmental awareness and renewable energy technologies of the electricity suppliers. It is worth noting that this scenario is too idealistic, i.e., it does not exist in practice. Therefore, we set the non-government policy as a base situation (benchmark model) to compare and analyze the impact of other policies on renewable energy investments by electricity suppliers.

(2) Government subsidy policy (Scenario SUB). To motivate electricity suppliers to invest in renewable energy, the government provides subsidies to electricity suppliers who invest in renewable energy. As a result, when electricity suppliers invest in renewable energy, they receive a unit subsidy (r).

(3) Carbon cap-and-trade policy (Scenario CAP). Under the carbon cap-and-trade policy, the government sets carbon quotas (G). The electricity suppliers may face a surplus or shortage of carbon quotas under the carbon quota constraint. In this case, the electricity supplier can sell or purchase additional carbon quotas in the carbon trading market to match the production demand. The carbon trading market determines the carbon quota trading price g (Liu et al., 2021).

(4) Renewable energy portfolio standard policy (Scenario RPS). In order to encourage electricity suppliers to invest in renewable energy, the government sets unit renewable energy quotas $\theta\ (0 < \theta < 1)$ for electricity suppliers (Yan et al., 2022). If the electricity supplier's renewable energy use percentage is lower than the renewable energy quota (θ) (Yan et al., 2022), it has to buy green certificates in the trading market to avoid severe penalties from the government. Conversely, if the electricity supplier's renewable energy use is higher than the renewable energy quota (θ), the supplier can sell the renewable energy quota for an additional profit. Besides, the renewable energy quota trading market determines the trading price (t) of green certificates.

To better explore the impact of different government policies on renewable energy investments by electricity suppliers, we make the following assumptions.

Market demand: Consumer market demand varies linearly with price and consumers' renewable energy preferences (Liuet al., 2012; Yenipazarli, 2019), i.e., $q = a - p + \gamma s$. Where a denotes the basic market demand, p represents the retail price in the electricity market, γ $(0 < \gamma < 1)$ indicates the consumer's renewable energy preference coefficient, and s means the electricity supplier's renewable energy investment quantity. The consumer preference that measures through the extent of consumers' preference on factors such as product characteristics, price, and service quality. In this paper, we explore the impact of consumer preferences on electricity suppliers' renewable energy investments via a game model that quantifies consumer preferences for renewable energy. For example, consumer preferences bring additional markets and increase the market expectations of electricity suppliers. Moreover, there are different levels of consumer preferences that have different impacts on electricity suppliers' renewable energy investments.

Supply: The electricity supplier usually generates electricity from conventional energy sources, supplemented by renewable energy sources. Therefore, the electricity supplier has two energy options: conventional and renewable energy. Electricity suppliers entrust electricity resources to electricity retailers at a wholesale price (w) and eventually sell them to consumers. In addition, the electricity supplier needs to shoulder additional investment costs to invest in renewable energy.

Cost: The electricity supplier needs to undertake additional investment costs to invest in renewable energy, i.e., $\frac{1}{2}ks^2$, where k is the renewable energy investment cost coefficient (Kök et al., 2016). In the fields of resource economics and climate change, the quadratic cost function serves to model and measure the cost of resource investment. As an intuitive and easy-to-understand loss function, the quadratic cost function is more robust and tolerant to some noise or disturbances, and has some advantages in game modeling. Within the game model, the quadratic cost function represents the cost or utility of the participants and can easily interpret the model results to improve stability and understanding. The evaluation of renewable energy investment costs and benefits through the development of a model that includes a quadratic cost function facilitates the analysis of the impact of investment costs on the renewable energy investment of electricity suppliers. Besides, electricity suppliers using conventional energy sources face a unit production cost of c.

Carbon emissions: We assume that the carbon emissions intensity of electricity suppliers using conventional energy to generate electricity is e (i.e., unit carbon emissions). The conventional energy sources, such as fossil energy sources like coal, oil and natural gas, are one of the major sources of energy. When these fossil energy sources are burned, large quantities of greenhouse gases, such as carbon dioxide, are released into the atmosphere, resulting in carbon emissions. Carbon intensity e is the amount of carbon dioxide emissions per unit of energy consumption or output, usually expressed as carbon emissions per unit of energy consumption. In the analysis in the field of environmental economics and climate change, assuming that the use of conventional energy produces carbon intensity e is a simplification that facilitates the study and modeling of carbon emissions and their impacts. This assumption allows researchers to estimate and compare the contribution of different energy sources to carbon emissions, to assess the costs and benefits of mitigation measures for carbon emissions, and so on. Besides, renewable energy, as a clean energy source, does not consume any fossil fuels in the process of generating electricity, so the carbon emissions intensity of renewable energy is 0. To facilitate reading and illustration, we have summarized the symbols in this paper in **Table 1**.

Table 1. Description of relevant symbols in the paper.

Parameters	**Description**
a	Basic market demand
q	The market demand of consumers
γ	Consumer's renewable energy preference coefficient
s	Electricity supplier's renewable energy investment quantity
k	Renewable energy investment cost factor
e	Carbon emission intensity of conventional energy sources
t	Green certificate prices for renewable energy
g	Carbon quota trading price
c	Unit operating cost of the port
r	Unit government subsidies for renewable energy
G	carbon quotas
θ	Unit renewable energy quota
ϕ	Environmental impact coefficient
w	wholesale price
p	Electricity retailer's retail prices

4. Equilibrium results under different policies

This section focuses on the optimal profits for stakeholders and renewable energy investments by electricity suppliers under different policies. The electricity suppliers use conventional and renewable energy to generate electricity. We first analyze the equilibrium outcomes of the stakeholders under the basic model. Then, we analyze the optimal profits of electricity suppliers and the renewable energy investments under the other three policies.

4.1. No government policy (Scenario *NON*)

To better analyze and compare renewable energy investments under different policies. We first analyze the equilibrium results under scenario NON (benchmark model). In the benchmark model, the government does not implement any policy measures to constrain or incentivize electricity suppliers to invest in renewable energy. The electricity suppliers capture optimal profits by setting wholesale prices and investing in renewable energy. The electricity retailer sells electricity to consumers at the retail price of p. Therefore, we can capture the electricity suppliers' and electricity retailers' profit functions as follows.

$$\pi_{ES}^{NON} = \left(wq - c(q - s)\right) - \frac{1}{2}ks^2$$

$$= \left(w(a - p + \gamma s) - c\left((a - p + \gamma s) - s\right)\right) - \frac{1}{2}ks^2$$

$$\pi_{ER}^{NON} = (p - w)(a - p + \gamma s),$$

where the superscript NON denotes no government policy scenario, and the subscripts ER, ES denote electricity retailers and electricity supplier, respectively.

According to the stakeholder's profit function, we derive the equilibrium outcomes for the stakeholders under scenario NON. The main results are summarized in Proposition 1.

Proposition 1. *The equilibrium outcomes and renewable energy investments of electricity suppliers under scenario NON are as follows.*

$$w^{NON*}=\frac{2ak+2ck+2c\gamma-c\gamma^2}{4k-\gamma^2},\ s^{NON*}=\frac{a\gamma+c(4-\gamma)}{4k-\gamma^2},\ p^{NON*}=\frac{3ak+c(k+(3-\gamma)\gamma)}{4k-\gamma^2},$$

$$q^{NON*}=\frac{ak-ck+c\gamma}{4k-\gamma^2},\pi_{ER}^{NON*}=\frac{(ak+c(-k+\gamma))^2}{(-4k+\gamma^2)^2},\ \pi_{ES}^{NON*}=\frac{a^2k+c^2(4+k-2\gamma)+2ac(-k+\gamma)}{8k-2\gamma^2}.$$

(See Appendix for proof).

4.2. Government subsidy policy (Scenario *SUB*)

Under scenario SUB, the government gives unit subsidies to electricity suppliers who invest in renewable energy, which is a popular policy measure in practice (see China National Energy Administration: http://www.nea.gov.cn/). In Model SUB, the government stimulates electricity suppliers to invest in renewable energy with a subsidy policy. The electricity supplier uses conventional and renewable energy sources to generate electricity and incurs additional renewable energy investment costs. The electricity retailer sells the electricity to the final consumer. Therefore, we can derive the profit function of stakeholders under scenario SUB.

$$\pi_{ES}^{SUB}=\big(wq-c(q-s)\big)+sr-\frac{1}{2}ks^2$$

$$=\big(w(a-p+\gamma s)-c((a-p+\gamma s)-s)\big)+sr-\frac{1}{2}ks^2$$

$$\pi_{ER}^{SUB}=(p-w)(a-p+\gamma s)$$

where the superscript SUB denotes government subsidy policy scenario, and the subscripts ER, ES denote electricity retailers and electricity supplier, respectively.

According to the inverse derivation of the Stackelberg model, we can obtain the equilibrium outcomes of the stakeholders under the government subsidy policy (see Proposition 2).

Proposition 2. *The equilibrium outcomes and renewable energy investments of electricity suppliers under scenario SUB are as follows.*

$$w^{SUB*}=\frac{8ak+8ck+c(8-7\gamma)\gamma-2e(-4+\gamma)\gamma\phi}{16k-7\gamma^2}$$

$$s^{SUB*}=\frac{c(16-7\gamma)+7a\gamma-4e(-4+\gamma)\phi}{16k-7\gamma^2}$$

$$p^{SUB*}=\frac{12ak+4ck+c(12-7\gamma)\gamma-3e(-4+\gamma)\gamma\phi}{16k-7\gamma^2}$$

$$q^{SUB*}=\frac{4ak+4c(-k+\gamma)-e(-4+\gamma)\gamma\phi}{16k-7\gamma^2}$$

$$\pi_{ER}^{S*}=\frac{(4ak+4c(-k+\gamma)-e(-4+\gamma)\gamma\phi)^2}{(16k-7\gamma^2)^2}$$

$$\pi_{ES}^{SUB*}=$$

$$\frac{\begin{gathered}(a^2k(64k-7\gamma^2)+2ac(-64k^2-28\gamma^3+7k\gamma(16+\gamma))+c^2(64k^2+8\gamma^2(-8+7\gamma)+k(256-7\gamma(32+\gamma)))+\\14ae(-4+\gamma)\gamma(-4k+\gamma^2)\phi-2ce(-4+\gamma)(-16+7\gamma)(-4k+\gamma^2)\phi-4e^2(-4+\gamma)^2(-4k+\gamma^2)\phi^2)\end{gathered}}{2(16k-7\gamma^2)^2}$$

4.3. Carbon cap-and-trade policy (Scenario *CAP*)

Under Scenario CAP, the government constrains the carbon emissions of electricity suppliers through the carbon cap-and-trade policy. In other words, the government sets carbon quotas G to control the level of carbon emissions of electricity suppliers to incentivize them to invest in renewable energy. This implies that the renewable energy investments of electricity suppliers are influenced by the carbon quota and carbon emission levels. Therefore, we derive the profit function of stakeholders under the carbon cap-and-trade policy as follows.

$$\pi_{ES}^{CAP} = \big(wq - c(q-s)\big) + g(G - e(q-s)) - \frac{1}{2}ks^2$$

$$\pi_{ER}^{CAP} = (p-w)(a-p+\gamma s)$$

where the superscript CAP denotes carbon cap-and-trade policy scenario, and the subscripts ER, ES denote electricity retailers and electricity supplier, respectively.

According to the profit function of stakeholders, we obtain the equilibrium outcomes of stakeholders under the carbon cap-and-trade policy (see Proposition 3).

Proposition 3. *The equilibrium outcomes and renewable energy investments of electricity suppliers under scenario* CAP *are as follows*.

$$w^{CAP*} = \frac{2ak + 2ck + 2egk + 2c\gamma + 2g\gamma - c\gamma^2 - eg\gamma^2}{4k - \gamma^2}$$

$$s^{CAP*} = \frac{-4(c+g) + (-a+c+eg)\gamma}{-4k + \gamma^2}$$

$$p^{CAP*} = \frac{3ak + ck + 3g\gamma - c(-3+\gamma)\gamma + eg(k - \gamma^2)}{4k - \gamma^2}$$

$$q^{CAP*} = \frac{ak - (c+eg)k + (c+g)\gamma}{4k - \gamma^2}$$

$$\pi_{ER}^{CAP*} = \frac{(ak - (c+eg)k + (c+g)\gamma)^2}{(-4k + \gamma^2)^2}$$

$$\pi_{ES}^{CAP*} = \frac{a^2k+c^2(4+k-2\gamma)+2c(eg(4+k-2\gamma)+a(-k+\gamma))+g(8Gk+g(-4+e(8+e(k-2\gamma)))-2G\gamma^2+2ae(-k+\gamma))}{8k-2\gamma^2}$$

4.4. Renewable energy portfolio standard policy (Scenario *RPS*)

Under scenario RPS, the government sets mandatory renewable energy quota targets and develops a renewable energy portfolio standard model, which improves the energy structure and protects the environment. Under the renewable energy portfolio standard, the government stimulates electricity suppliers to invest in renewable energy by setting renewable energy quotas. Thus, we yield the profit function of stakeholders under scenario RPS.

$$\pi_{ES}^{RPS} = \big(wq - c(q-s)\big) + t(s - \theta q) - \tfrac{1}{2}ks^2,\ \pi_{ER}^{RPS} = (p-w)(a-p+\gamma s)$$

where the superscript RPS denotes renewable energy portfolio standard policy scenario, and the subscripts ER, ES denote electricity retailers and electricity supplier, respectively.

Based on the profit function of stakeholders under the renewable energy portfolio standard constraint, we derive the equilibrium results under scenario RPS (see Proposition 4).

Proposition 4. *Under the renewable energy quota constraint, we have the optimal outcome for stakeholders and electricity suppliers' renewable energy investments.*

$$w^{RPS*} = \frac{2ak + 2ck + 2c\gamma + 2t\gamma - c\gamma^2 + 2tk\theta - t\gamma^2\theta}{4k - \gamma^2}$$

$$s^{RPS*} = \frac{c(-4+\gamma) - a\gamma + t(-4+\gamma\theta)}{-4k+\gamma^2}$$

$$p^{RPS*} = \frac{3ak + ck - c(-3+\gamma)\gamma + tk\theta + t\gamma(3-\gamma\theta)}{4k-\gamma^2}$$

$$q^{RPS*} = \frac{ak - ck + c\gamma + t\gamma - tk\theta}{4k-\gamma^2}$$

$$\pi_{ER}^{RPS*} = \frac{(ak + c(-k+\gamma) + t(\gamma - k\theta))^2}{(-4k+\gamma^2)^2}$$

$$\pi_{ES}^{RPS*} = \frac{a^2k + c^2(4+k-2\gamma) + 2ac(-k+\gamma) + 2at(\gamma - k\theta) - 2ct(-4+\gamma-k\theta+\gamma\theta) + t^2(4-2\gamma\theta+k\theta^2)}{8k-2\gamma^2}$$

5. Comparison and analysis

In this section, we compare and analyze the renewable energy investments of electricity suppliers in different scenarios and analyze the profits of electricity suppliers in different policy backgrounds. Moreover, we explore the environmental impacts and social welfare in different scenarios.

By comparing the renewable energy investments of electricity suppliers under different policies, we can obtain Lemma 1.

Lemma 1. *When* $0 < \gamma \leq \gamma_1$, $s^{CAP*} \geq s^{RPS*} \geq s^{SUB*} \geq s^{NON*}$; *When* $\gamma_1 < \gamma \leq \gamma_2$, $s^{RPS*} \geq s^{CAP*} \geq s^{SUB*} \geq s^{NON*}$; *When* $\gamma_2 < \gamma \leq \gamma_3$, $s^{RPS*} \geq s^{SUB*} \geq s^{CAP*} \geq s^{NON*}$; *When* $\gamma_3 < \gamma < 1$, $s^{SUB*} > s^{RPS*} > s^{CAP*} > s^{NON*}$.

(See Appendix for proof).

With the increase in consumers' environmental awareness, consumers prefer to consume renewable energy to protect the environment. Lemma 1 shows the impact of consumer renewable energy preferences on renewable energy investments by electricity suppliers under different policies. We find that as consumer renewable energy preferences increase, electricity suppliers under no-government policies always perform the worst in terms of renewable energy investments. When consumer renewable energy preferences are moderate, carbon cap-and-trade policies and renewable portfolio standard policies are more favorable to incentivize electricity suppliers to invest in renewable energy. When consumer renewable energy preferences are high, government subsidy policies dominate in promoting electricity suppliers to invest in renewable energy. In other words, the incentive effect of government subsidy policy is better than other policies.

Comparing the profits of electricity suppliers under different policies, we obtain the results in Lemma 2.

Lemma 2. *When* $\gamma \leq \frac{-8c-4t+2ak\theta-2ck\theta-kt\theta^2}{2(a-c-c\theta-t\theta)}$ ($\theta \leq \theta_1$), $\pi_{ES}^{SUB*} > \pi_{ES}^{NON*} >$

$\pi_{ES}^{RPS*} > \pi_{ES}^{CAP*}$; *When* $\gamma \geq \frac{-8c-4t+2ak\theta-2ck\theta-kt\theta^2}{2(a-c-c\theta-t\theta)}$ $(\theta \geq \theta_1)$, $\pi_{ES}^{SUB*} > \pi_{ES}^{RPS*} > \pi_{ES}^{NON*} > \pi_{ES}^{CAP*}$

where $\theta_1 = \frac{2ak-2ck+2c\gamma+2t\gamma-\sqrt{4kt(-8c-4t-2a\gamma+2c\gamma)+(2ak-2ck+2c\gamma+2t\gamma)^2}}{2kt}$.

(See Appendix for proof).

Lemma 2 shows that government subsidy policies contribute to achieving optimal profits for electricity suppliers, which implies that electricity suppliers are more inclined to invest in renewable energy under subsidy policies. Besides, electricity suppliers' renewable energy investment strategies are combined influenced by consumers' renewable energy preferences and renewable energy quotas. However, something counter-intuitive is that electricity suppliers are less profitable under the carbon cap-and-trade policy than under other scenarios. This result implies that carbon cap-and-trade policies are not always conducive to promoting electricity suppliers' investment in renewables.

Furthermore, we explore consumer surplus, environmental impacts, and social welfare under different policy scenarios in this section.

Following the equilibrium results in Sections 4.1–4.4 and the consumer surplus function $CS^* = \int_{p_{minx}}^{p_{max}} q dp = \frac{q^2}{2}$, we can obtain the consumer surplus under different policy scenarios.

$$CS^{NON*} = \frac{(ak + c(-k+\gamma))^2}{2(-4k+\gamma^2)^2}$$

$$CS^{SUN*} = \frac{(4ak + 4c(-k+\gamma) - e(-4+\gamma)\gamma\phi)^2}{2(16k-7\gamma^2)^2}$$

$$CS^{CAP*} = \frac{(ak - (c+eg)k + (c+g)\gamma)^2}{2(-4k+\gamma^2)^2}$$

$$CS^{RPS*} = \frac{(ak + c(-k+\gamma) + t(\gamma - k\theta))^2}{2(-4k+\gamma^2)^2}$$

Lemma 3. *Comparing consumer surplus in different scenarios, we obtain the impact of different policies on consumer surplus*

(see Appendix for specific results).

We can see from Lemma 3 that the carbon cap-and-trade policy and the renewable energy portfolio standard policy are the combined conditions that affect consumer surplus. Furthermore, we find that consumers' renewable energy preferences play a positive role in increasing consumer surplus. Moreover, Lemma 3 shows that government subsidy policies are more likely to increase consumer surplus overall. Therefore, the government needs to develop reasonable policies to improve consumer surplus to increase the proportion of renewable energy consumption by consumers.

Similarly, following Krass et al. (2013), we measure the environmental impact of carbon emissions of electricity suppliers with ϕ $(0 < \phi < 1)$. According to the environmental impact function $EI^* = \phi e(q - s)$, we have the environmental impact of renewable energy investments of electricity suppliers under different scenarios.

$$EI^{NON*} = \frac{(a(k-\gamma)) - \big(c(4+k-2\gamma)\big)\phi e}{4k-\gamma^2}$$

$$EI^{SUB*}=\frac{e\phi(-4c(4+k)+a(4k-7\gamma)+11c\gamma-e(-4+\gamma)^2\phi)}{16k-7\gamma^2}$$

$$EI^{CAP*}=\frac{e(-c(4+k-2\gamma)+a(k-\gamma)+g(-4-ek+\gamma+e\gamma))\phi}{4k-\gamma^2}$$

$$EI^{RPS*}=\frac{e(-c(4+k-2\gamma)+a(k-\gamma)+t(-4+\gamma-k\theta+\gamma\theta))\phi}{4k-\gamma^2}$$

Government policies influence electricity suppliers' production and renewable energy investment decisions. Social welfare as a standard for measuring and evaluating the effectiveness of policy implementation presents the impact of government policies on electricity suppliers, consumers, and the environment. Drawing on Krass et al. (2013) and Yan et al. (2022), we define social welfare as consisting of the following components.

Social welfare = Electricity supplier's profit + Electricity retailer's profit + Consumer surplus − Environmental impact.

According to the above social welfare function, we can obtain social welfare in different scenarios.

$$SW^{NON*}=\frac{3(ak+c(-k+\gamma))^2}{2(-4k+\gamma^2)^2}+\frac{a^2k+c^2(4+k-2\gamma)+2ac(-k+\gamma)}{8k-2\gamma^2}+\frac{(c(4+k-2\gamma)+a(-k+\gamma))\phi e}{4k-\gamma^2}$$

$$SW^{SUB*}=\frac{7a^2k+c^2(16+7k-14\gamma)+2c(7a(-k+\gamma)+e(16+4k-11\gamma)\phi)+e\phi(a(-8k+14\gamma)+e(-4+\gamma)^2\phi)}{32k-14\gamma^2}$$

$$SW^{CAP*}=\frac{a^2k+c^2(4+k-2\gamma)+2c(eg(4+k-2\gamma)+a(-k+\gamma))+g(8Gk+g(-4+e(8+e(k-2\gamma)))-2G\gamma^2+2ae(-k+\gamma))}{8k-2\gamma^2}+\frac{3(ak-(c+eg)k+(c+g)\gamma)^2}{2(4k-\gamma^2)^2}+\frac{e(c(4+k-2\gamma)+a(-k+\gamma)+g(4+ek-(1+e)\gamma))\phi}{4k-\gamma^2}$$

$$SW^{RPS*}=\frac{3(ak+c(-k+\gamma)+t(\gamma-k\theta))^2}{2(-4k+\gamma^2)^2}+\frac{e(c(4+k-2\gamma)+a(-k+\gamma)-t(-4+\gamma-k\theta+\gamma\theta))\phi}{4k-\gamma^2}+\frac{a^2k+c^2(4+k-2\gamma)+2ac(-k+\gamma)+2at(\gamma-k\theta)-2ct(-4+\gamma-k\theta+\gamma\theta)+t^2(4-2\gamma\theta+k\theta^2)}{8k-2\gamma^2}$$

6. Simulation and discussion

6.1. Data

The city of Wuxi is one of the economically developed regions in China, with a large number of industrial and commercial enterprises, and with a large amount of energy consumption. While analyzing the electricity consumption data of Wuxi, we can better capture the energy consumption of the region and provide a reference and basis for investing in renewable energy projects in the region. In addition, Jiangsu Province has more mature policies and development in the field of renewable energy. Therefore, the selection of Wuxi City in Jiangsu Province as the parameter data is conducive to a more accurate assessment of the potential and prospect of renewable energy investment. In addition, Wuxi is located in the Yangtze River Delta Economic Zone, and its electricity consumption data can also indirectly reflect the country's level of economic development and energy consumption.

Consider data from the China Carbon Cap-and-Trade Market (China Carbon Cap-and-Trade Market., n.d.), the National Energy Information Platform (National Energy Information Platform, n.d.), and the National Energy Network (National

Energy Network., n.d.), as well as the carbon emission levels of the energy sector (CPG, n.d.). Therefore, we set the parameter data based on the electricity consumer volume in Wuxi City, Jiangsu Province. Combining the literature of Yan et al. (2022) and the National Bureau of Statistics on electricity consumption in Jiangsu province by city, we set some parameters as follows: $a = 839, c = 30$, $k = 2$, $e = 2.49$, $g = 60$, $t = 50$, $G = 20$.

6.2. Sensitivity analysis

Figure 5 illustrates the impact of different policies on electricity suppliers' renewable energy investments. We can find that **Figure 5** verifies the results of Lemma 1. We find that electricity suppliers are more inclined to invest in renewable energy under the subsidy policy as the consumer preference for renewable energy increases. The main reason is that government subsidies compensate the cost of electricity suppliers to invest in renewable energy. As a direct incentive policy, government subsidies are more beneficial to increase the incentive of electricity suppliers to invest in renewable energy. Besides, we can observe that the renewable portfolio standard is more likely to be the sub-optimal choice for electricity suppliers to invest in renewable energy.

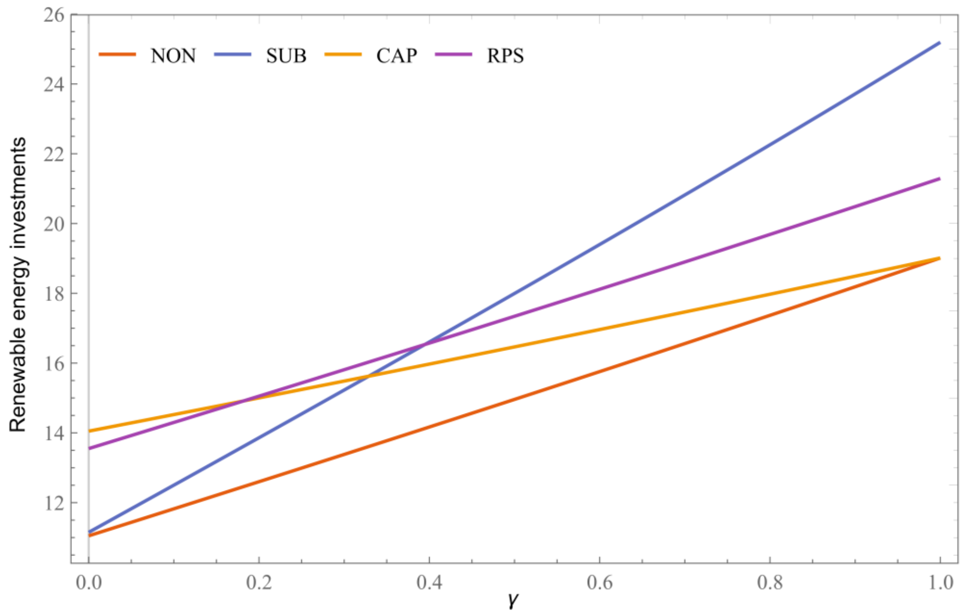


Figure 5. Renewable energy investments under different policies.

Figure 6 shows that electricity supplier profits increase with consumers' renewable energy preferences. We find that electricity suppliers are more easily to capture optimal profits under the subsidy policy, which indicates that electricity suppliers are more inclined to invest in renewable energy with government subsidies. This suggests that government subsidies and consumer preferences are conducive to increasing electricity suppliers' profits. Noticeably, **Figure 6** shows that the carbon cap-and-trade policy plays the worst role in increasing the profits of electricity suppliers. This result shows that cap-and-trade policies do not always promote carbon emission reductions for electricity suppliers to sell carbon quotas for additional profits. Besides, the profits of electricity suppliers under the cap-and-trade policy are lower than those under the no-government policy and renewable portfolio standard policy scenarios. The profitability of electricity suppliers under the no-government policy and renewable energy portfolio standard policy depends on the level of renewable energy quotas.

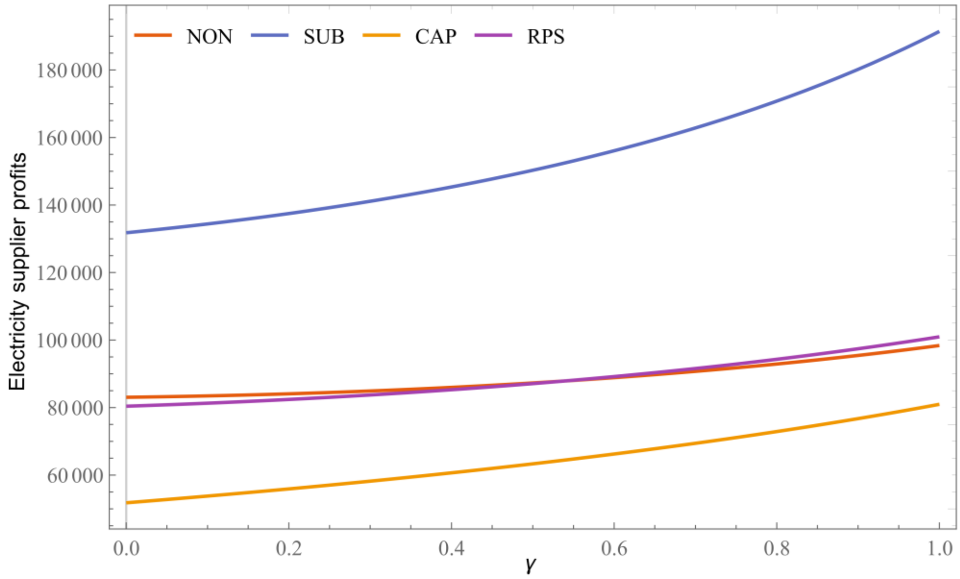
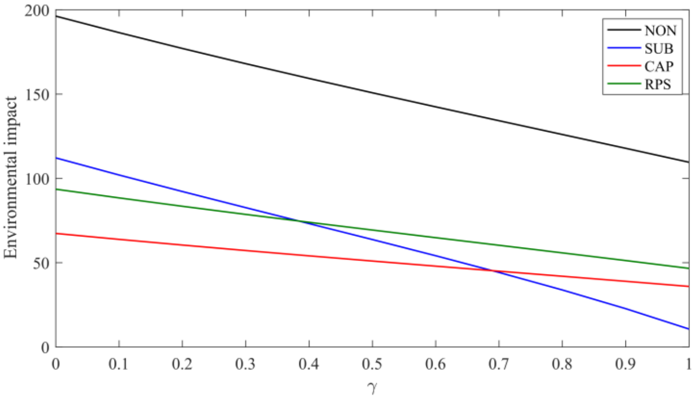


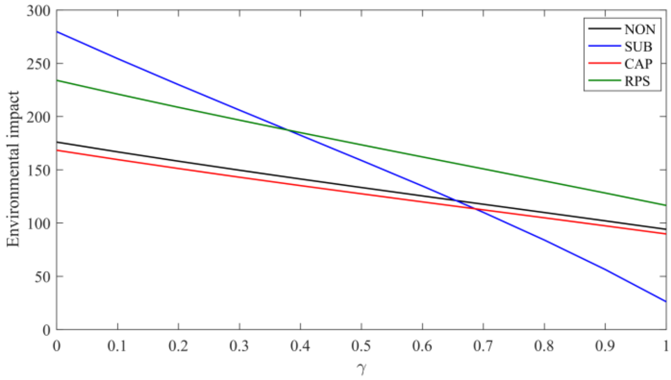
Figure 6. Electricity supplier profits under different policies.

6.2.1. Environmental impact analysis under different policies

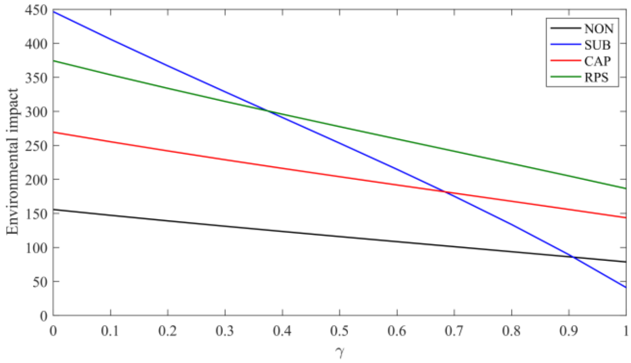
Figure 7 illustrates the environmental impacts of consumer preferences (γ), carbon emission levels (e), and environmental impact coefficients (ϕ) under different policies. We can find from **Figure 7** that the environmental impact under the four policies decreases with the increase in consumer preference for renewable energy. This result indicates that the increase in consumer renewable energy preference is beneficial to reduce the environmental impact. **Figure 7a–c** show that the environmental impact of NON decreases with the increase of ϕ when e is higher. Moreover, **Figure 7a–c** shows that SUB, CAP, and RPS policies have a positive role and outperform NON in reducing environmental impacts when ϕ is low. However, SUB, CAP, and RPS policies do not always better than NON in reducing environmental impacts as ϕ increases. Besides, **Figure 7a–c** shows that the SUB policy works better in reducing environmental impacts as γ increases. When e is moderate, **Figure 7d–f** show that when ϕ is low (moderate), the NON has a higher environmental impact than the other policies. It is worth noting that the NON outperforms other policies in reducing environmental impacts as ϕ increases. However, the SUB policy is superior to NON as γ increases. In addition, **Figure 7g–i** show that when e is low, the environmental impact of the NON exceeds that of the other policies regardless of the change in ϕ. When γ is low, the environmental impact of CAP policy is lower than other policies, but as γ increases, SUB policy dominates in reducing the environmental impact.



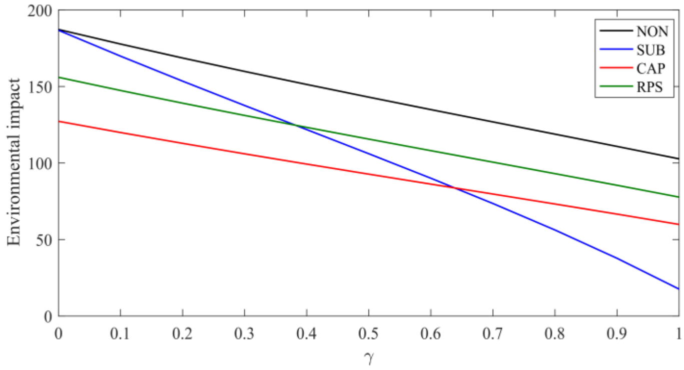
(a) $e = 3,\ \phi = 0.2$



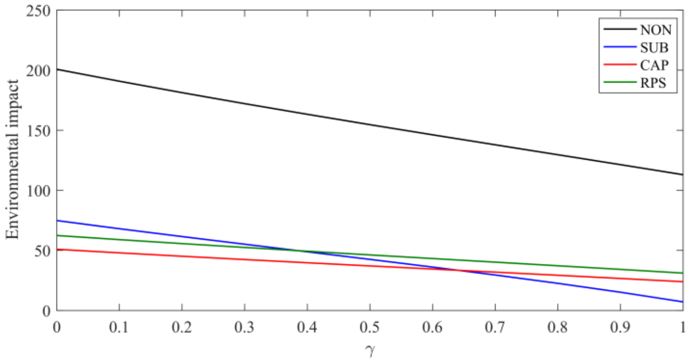
(b) $e = 3,\ \phi = 0.5$



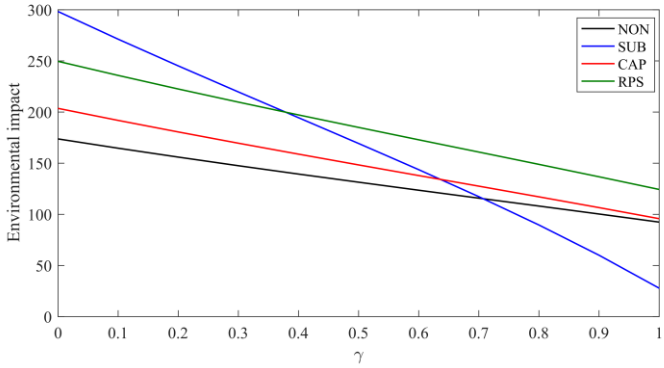
(c) $e = 3,\ \phi = 0.8$



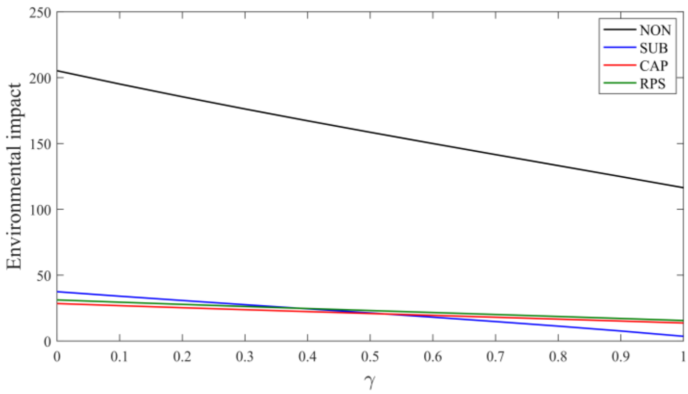
(d) $e = 2,\ \phi = 0.2$



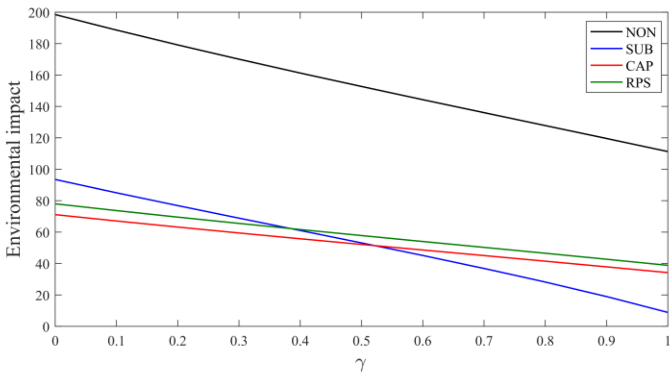
(e) $e = 2,\ \phi = 0.5$



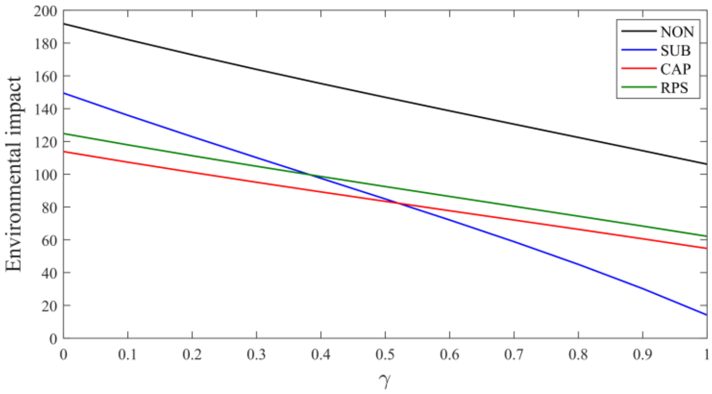
(f) $e = 2,\ \phi = 0.8$



(g) $e = 1,\ \phi = 0.2$



(h) $e = 1,\ \phi = 0.5$



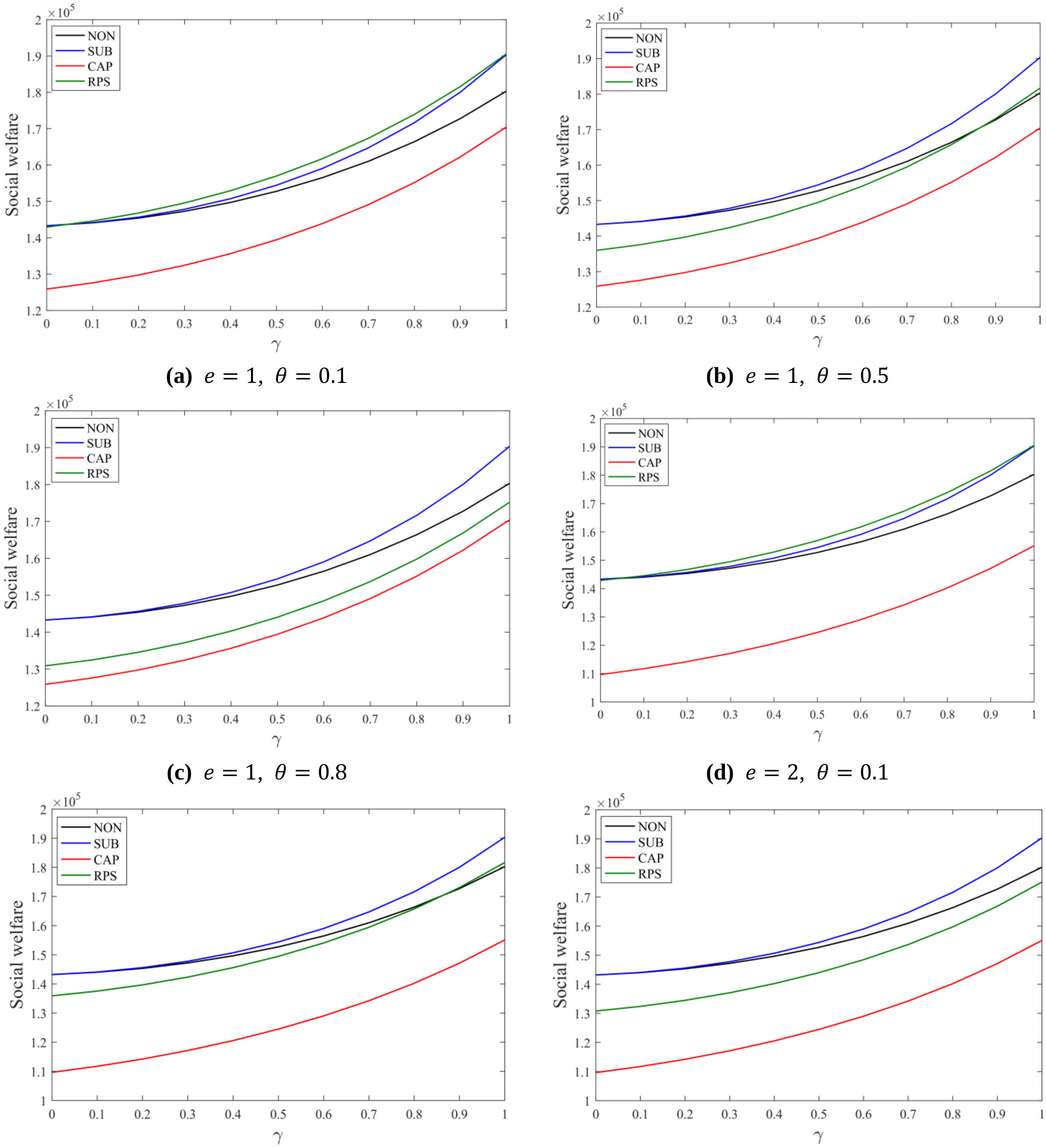
(i) $e = 1,\ \phi = 0.8$

Figure 7. Environmental impact under different policies.

Figure 7a,d,g illustrate that the environmental impact of the NON is higher than that of the other policies. With the decrease of e, SUB, CAP, and RPS provide obvious effects in reducing environmental impacts. Comparing **Figure 7b,e,h**, we find that the environmental impact of CAP is lower than the other policies, especially when γ is low. This result implies that the CAP plays a vital role in reducing environmental impacts when consumer renewable energy preferences are low. With the increase of γ, the environmental impacts under SUB are lower than other policies. From **Figure 7c,f,i**, we find that SUB, CAP, and RPS are not always reducing environmental impacts as e increases. Moreover, NON is more likely to become a policy choice for electricity suppliers to reduce environmental impacts. However, considering the impact of consumer preferences, the SUB policy will eventually be the optimal choice for electricity suppliers.

6.2.2. Social welfare analysis under different policies

Figure 8 illustrates the impact of consumer preferences, carbon emission levels, and renewable energy quotas on social welfare under different policies. From **Figure 8**, we can find that social welfare increases with the increase in consumers' renewable energy preference (γ). By observing **Figure 8**, we can see that the social welfare under the carbon cap-and-trade policy (CAP) is evidently lower than the other policies. Comparing **Figure 8a–c**, we can observe that the social welfare of the RPS decreases with the increase of the renewable energy quota (e). However, when θ is moderate (higher), we find that the social welfare under the government subsidy policy (SUB) is better than the other policies. We can find similar results in **Figure 8d–f** and **Figure 8g–i**. Moreover, when θ is moderate, we find that the magnitude of social welfare under NON and RPS depends on consumer renewable energy preferences (γ) (see **Figure 8b,e,h**). Besides, when γ is low (high), the social welfare of the RPS is lower (higher) than that of the NON.



(a) $e = 1, \ \theta = 0.1$

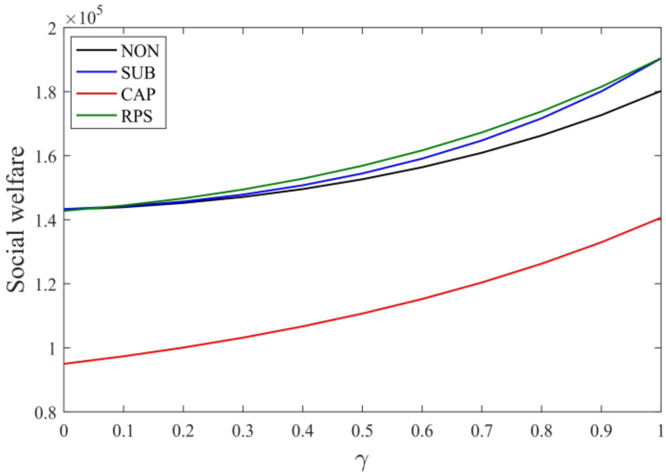
(b) $e = 1, \ \theta = 0.5$

(c) $e = 1, \ \theta = 0.8$

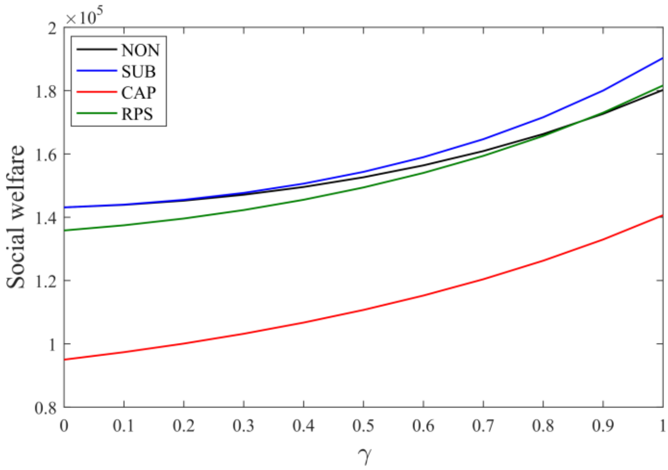
(d) $e = 2, \ \theta = 0.1$

(e) $e = 2, \ \theta = 0.5$

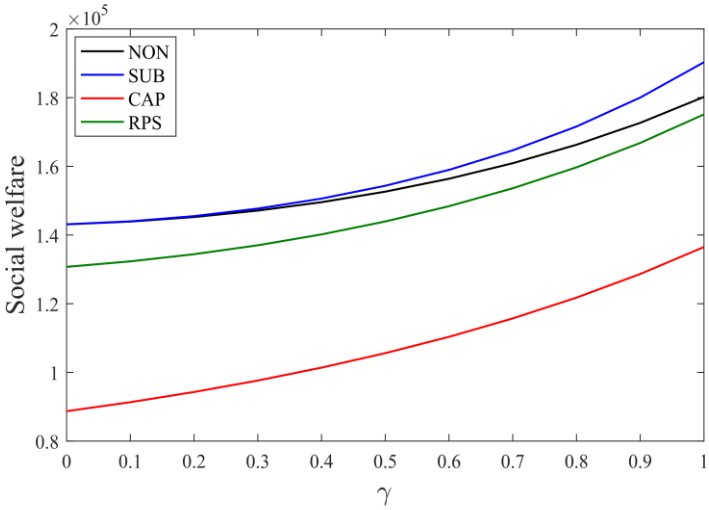
(f) $e = 2, \ \theta = 0.8$



(g) $e = 3,\ \theta = 0.1$



(h) $e = 3,\ \theta = 0.5$



(i) $e = 3,\ \theta = 0.8$

Figure 8. Social welfare under NON, SUB, CAP and RPS.

Figure 8a,d,g show that the social welfare of CAP decreases with the increase of e, which implies that the increase in the carbon emission level (e) of electricity suppliers is not beneficial to improve social welfare. The main reason is that the increase in carbon emission level reduces the electricity suppliers' profit and consumer surplus and increases the negative environmental impact, which decreases the overall social welfare. We can find similar results in **Figure 8b,e,h** and **Figure 8c,f,i.**

Based on the above results, considering carbon emissions, renewable energy quotas, and consumer preferences, government implementation of subsidy policies or renewable energy portfolio standard policies may capture higher social welfare. Moreover, policymakers fully consider consumer preferences when incentivizing electricity suppliers to invest in renewable energy. In addition, if the government wants to capture higher social welfare when implementing policies, it can choose a direct incentive policy (SUB) to encourage electricity suppliers to invest in renewable energy.

7. Conclusion and management insights

7.1. Concluding remarks

We construct a renewable energy generation supply chain with electricity suppliers and electricity retailers as the research objects. Considering the impact of policy policies and carbon neutral targets on renewable energy investments, we construct a game model under four policies to explore the impact of government policies on electricity suppliers' renewable energy investments. Then, we analyze and compare the electricity suppliers' profits under the four policies. We then explore the impact of different policies on consumer surplus, environmental impacts, and social welfare. Finally, we utilize numerical simulations to compare the impact of different policies on stakeholder profits and social welfare. We draw the following main conclusions.

(1) The government subsidy policy (SUB) facilitates electricity suppliers to invest in renewable energy and increases the electricity suppliers' profits. In terms of renewable energy investment, the no-government policy (NON) has the worst effect. In addition, no matter which policy is implemented, consumer preferences contribute to increasing the effect of electricity suppliers' renewable energy investments.

(2) The electricity suppliers' profit is the highest under the government subsidy policy (SUB), whereas that under the carbon cap-and-trade policy (CAP) is the worst. In addition, when θ is high (low), electricity supplier profits under the renewable portfolio standard policy (RPS) are higher (lower) than those under the no government policy (NON).

(3) Regarding the environmental impact, NON has the worst effect on controlling the environmental impact when e and θ are low. When e or θ is moderate, NON is not always the worst for controlling environmental impacts. On the other hand, when e or θ is high, NON becomes more effective in controlling environmental impacts as e or θ increases. And which policy is best for controlling environmental impacts is influenced by consumer renewable energy preferences. Besides, consumer renewable energy preferences have a positive effect on controlling environmental impacts. Moreover, the environmental impact under different policies decreases with consumer renewable energy preferences.

(4) For social welfare, the social welfare is the lowest under CAP. When θ is low, social welfare under RPS is better than other policies, whatever the electricity supplier's carbon emission level changes. With the increase of θ or e, the social welfare under SUB is the highest. When θ is moderate, the magnitude of social welfare under RPS and NON depends on consumer renewable energy preferences. In addition, social welfare under different policies increases with consumer renewable energy preferences.

7.2. Management insights

First, government policies are one of the important measures to promote the renewable energy investments in China. Therefore, the government should formulate effective policy measures to promote the renewable energy investments according to the practical situation. Besides, policy makers should fully consider the impact of consumer preferences and carbon emission levels and establish reasonable renewable energy quotas. Our results demonstrate the importance of renewable energy in energy transition and environmental protection, and help policymakers realize the importance of increasing support and investment in renewable energy. Policymakers should adjust their policy frameworks and optimize supportive policies to promote the development and utilization of renewable energy. In addition, while giving full play to the role of government policies, electricity suppliers should also consider the impact of their own carbon emission reduction on renewable energy investments.

Second, when θ is low (moderate) (or e is low), electricity suppliers are more inclined to control environmental impacts under CAP. This provides an effective approach for the government to formulate renewable energy quotas and policy policies. Furthermore, considering consumer preferences, we show that SUB has the best effect in controlling environmental impacts as consumer preferences increase. Therefore, it is necessary for the government to consider the electricity suppliers' carbon emission levels, renewable energy quotas and consumer preferences in controlling environmental impacts. In addition, our results support electricity suppliers with integration options for renewable energy under different policy measures, helping them to increase the share of clean energy in their energy mix. Further, through exploring renewable energy investments in the context of consumer preferences, our results assist electricity suppliers in reducing the production costs of renewable energy and building a more stable and reliable energy supply system.

Finally, when the renewable energy quota (θ) is low, it is easier for the government to implement RPS to capture the optimal social welfare. Moreover, considering the combined effects of e and θ, subsidy policies are more likely to achieve the government's target of capturing optimal social welfare. Therefore, the government should give direct incentive policies to electricity suppliers to reduce the cost of renewable energy investment for electricity suppliers and increase their motivation to invest in renewable energy.

In this paper, we consider the impact of different policies on electricity suppliers' renewable energy investments, environmental impacts and social welfare. We capture some valuable conclusions, but this research could also expand some interesting future research directions. First, the natural environment constrains the sustainability of renewable energy, which means that renewable energy is intermittent and volatile. Therefore, considering the impact of indirectness and volatility on renewable energy investments may capture different conclusions. Second, considering the impact of stochastic consumer demand on electricity suppliers' renewable energy investments may yield some interesting results. For example, consider the impact of consumer electricity demand on electricity suppliers' renewable energy investments under COVID-19. Finally, it is worth exploring the question of renewable energy investment under multiple electricity supplier competition.

Author contributions: Conceptualization, methodology, HW, PZ, YX, YJ, WH and CW; software, HW and PZ; validation, YX, YJ, WH and CW; formal analysis, HW, PZ, WH and CW; investigation, HW and PZ; resources, WH and CW; writing—original draft preparation, HW, PZ; writing—review and editing, YX;

supervision, WH and CW. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

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Appendix

Proof of Proposition 1. Under scenario *NON*, we have $\pi_{ES}^{NON} = \left(wq - c(q - s)\right) - \frac{1}{2}ks^2, \pi_{ER}^{NON} = (p - w)(a - p + \gamma s)$. It is easily shown that the Hessian matrix is negative definite for the equilibrium. Therefore, according to the first-order conditions $\frac{\partial \pi_{ER}^{NON}}{\partial p} = a - 2p + w + s\gamma = 0$, $\frac{\partial \pi_{ES}^{NON}}{\partial w} = \frac{c}{2} - \frac{w}{2} + \frac{1}{2}(a - w + s\gamma)$, $\frac{\partial \pi_{ES}^{NON}}{\partial s} = -ks - c(-1 + \frac{\gamma}{2}) + \frac{w\gamma}{2}$), we get the retail prices, wholesale prices, and renewable energy investment levels of the stakeholders under scenario *NON*, i.e., $w^{NON*} = \frac{2ak+2ck+2c\gamma-c\gamma^2}{4k-\gamma^2}, s^{NON*} = \frac{a\gamma+c(4-\gamma)}{4k-\gamma^2}$, $p^{NON*} = \frac{3ak+c(k+(3-\gamma)\gamma)}{4k-\gamma^2}$ and $q^{NON*} = \frac{ak-ck+c\gamma}{4k-\gamma^2}$. Therefore, according to the profit function of stakeholders, we obtain the equilibrium profit under scenario *NON*: $\pi_{ER}^{NON*} = \frac{(ak+c(-k+\gamma))^2}{(-4k+\gamma^2)^2}$, $\pi_{ES}^{NON*} = \frac{a^2k+c^2(4+k-2\gamma)+2ac(-k+\gamma)}{8k-2\gamma^2}$. □

Proof of Proposition 2. Under scenario *SUB*, we have the profit function of stakeholders.

$$\pi_{ES}^{SUB} = \left(wq - c(q - s)\right) + sr - \frac{1}{2}ks^2,\ \pi_{ER}^{SUB} = (p - w)(a - p + \gamma s)$$

Similar to the solution of Proposition 1, we derive the equilibrium results under scenario *SUB*:

$$w = \frac{2ak+2ck+2c\gamma+2t\gamma-c\gamma^2}{4k-\gamma^2},\ s = \frac{4c+4t+a\gamma-c\gamma}{4k-\gamma^2},\ p = \frac{3ak+3t\gamma+c(k-(-3+\gamma)\gamma)}{4k-\gamma^2},\ q = \frac{ak-ck+(c+t)\gamma}{4k-\gamma^2}$$

$$\pi_{ER} = \frac{(ak-ck+(c+t)\gamma)^2}{(-4k+\gamma^2)^2},\ \pi_{ES} = \frac{4c^2+a^2k-2ack+c^2k+8ct+4t^2+2(a-c)(c+t)\gamma}{8k-2\gamma^2}$$

Thus, we have the consumer surplus, environmental impact, government expenditures (*EXP*) and social welfare under the scenario *SUB* as follows.

$$CS^{SUB} = \frac{(ak-ck+(c+t)\gamma)^2}{2(-4k+\gamma^2)^2},\ EI^{SUB} = \frac{e(-c(4+k-2\gamma)+a(k-\gamma)+t(-4+\gamma))\phi}{4k-\gamma^2},\ EXP^{SUB} = \frac{-4t(c+t)+(-a+c)t\gamma}{-4k+\gamma^2},$$

$$SW^{SUB} = \frac{4c^2+a^2k-2ack+c^2k+8ct+4t^2+2(a-c)(c+t)\gamma}{8k-2\gamma^2} + \frac{3(ak-ck+(c+t)\gamma)^2}{2(-4k+\gamma^2)^2} + \frac{t(4t-c(-4+\gamma)+a\gamma)}{-4k+\gamma^2} + \frac{e(c(4+k-2\gamma)-t(-4+\gamma)+a(-k+\gamma))\phi}{4k-\gamma^2}$$

According to the first-order conditions ($\frac{\partial SW^{SUB}}{\partial t}$), we have the optimal subsidy level $t^* = \frac{3ak\gamma+3c\gamma(-k+\gamma)+e(-4+\gamma)(-4k+\gamma^2)\phi}{16k-7\gamma^2}$. Substituting the optimal subsidy level into the above equilibrium results, we obtain the optimal results under government subsidies.

$$w^{SUB*} = \frac{8ak+8ck+c(8-7\gamma)\gamma-2e(-4+\gamma)\gamma\phi}{16k-7\gamma^2}, s^{SUB*} = \frac{c(16-7\gamma)+7a\gamma-4e(-4+\gamma)\phi}{16k-7\gamma^2},$$

$$p^{SUB*} = \frac{12ak+4ck+c(12-7\gamma)\gamma-3e(-4+\gamma)\gamma\phi}{16k-7\gamma^2},\ q^{SUB*} = \frac{4ak+4c(-k+\gamma)-e(-4+\gamma)\gamma\phi}{16k-7\gamma^2},$$

$$\pi_{ER}^{S*} = \frac{(4ak+4c(-k+\gamma)-e(-4+\gamma)\gamma\phi)^2}{(16k-7\gamma^2)^2},$$

$$\pi_{ES}^{SUB*} = \frac{\begin{array}{c}(a^2k(64k-7\gamma^2)+2ac(-64k^2-28\gamma^3+7k\gamma(16+\gamma))+c^2(64k^2+8\gamma^2(-8+7\gamma)+k(256-7\gamma(32+\gamma)))+ \\ 14ae(-4+\gamma)\gamma(-4k+\gamma^2)\phi-2ce(-4+\gamma)(-16+7\gamma)(-4k+\gamma^2)\phi-4e^2(-4+\gamma)^2(-4k+\gamma^2)\phi^2)\end{array}}{2(16k-7\gamma^2)^2}.\ □$$

Proof of Proposition 3. Under the scenario *CAP*, we have the profit function of stakeholders.

$$\pi_{ES}^{CAP} = \left(wq - c(q - s)\right) + g(G - e(q - s)) - \frac{1}{2}ks^2,\ \pi_{ER}^{CAP} = (p - w)(a - p + \gamma s).$$

Similar to the proof of Proposition 1, we can obtain the equilibrium results under the scenario *CAP*. The proof we do not elaborate here. □

Proof of Proposition 4. The solution of Proposition 3 is similar to the proof of Proposition 1, which we omit here. □

Proof of Lemma 1. According to the equilibrium results of stakeholders under different policy scenarios, we compare the renewable energy investments under scenario *NON* with other scenarios. Thus, we have

$s^{SUB*} - s^{NON*} = \frac{4\left(3ak\gamma+3c\gamma(-k+\gamma)+e(-4+\gamma)\left(-4k+\gamma^2\right)\phi\right)}{64k^2-44k\gamma^2+7\gamma^4} > 0, s^{CAP*} - s^{NON*} = \frac{g(4-e\gamma)}{4k-\gamma^2} > 0$, $s^{RPS*} - s^{NON*} =$

$\frac{t(4-\gamma\theta)}{4k-\gamma^2} > 0$.

Then, by comparing the renewable energy investments under scenario *SUB*, scenario *CAP* and scenario *RPS*, we have $s^{SUB*} - s^{CAP*} = \frac{4(c+g)+(a-c-eg)\gamma}{-4k+\gamma^2} + \frac{c(16-7\gamma)+7a\gamma-4e(-4+\gamma)\phi}{16k-7\gamma^2}$, $s^{SUB*} - s^{RPS*} = \frac{-c(-4+\gamma)+a\gamma+t(4-\gamma\theta)}{-4k+\gamma^2} + \frac{c(16-7\gamma)+7a\gamma-4e(-4+\gamma)\phi}{16k-7\gamma^2}$, $s^{CAP*} - s^{RPS*} \frac{g(-4+e\gamma)+t(4-\gamma\theta)}{-4k+\gamma^2}$.

By solving for $s^{SUB*} - s^{CAP*} > 0$, we have

$$\gamma_2 > -\frac{4(3c+7g-4e\phi)}{3(-7eg+4e\phi)} - (2^{1/3}(X))/(3(-7eg+4e\phi)(Y+\sqrt{(Y)^2+4(X)^3})^{1/3}) + \frac{1}{3\times 2^{1/3}(-7eg+4e\phi)}(Y+\sqrt{(Y)^2+4(X)^3})^{1/3}$$

Next, solving for $s^{SUB*} - s^{RPS*} > 0$, we have:

$\gamma_3 > -\frac{4(3c+7t-4e\phi)}{3(-7t\theta+4e\phi)} - (2^{1/3}(H))/(3(-7t\theta+4e\phi)(Z+\sqrt{(Z)^2+4(H)^3}))^{1/3}) + \frac{(Z+\sqrt{(Z)^2+4(H)^3}))^{1/3}}{32^{1/3}(-7t\theta+4e\phi)}$. Similarly, we have $s^{CAP*} - s^{RPS*} > 0$ if $\gamma_1 < \frac{4(g-t)}{eg-t\theta}$. Comparing the thresholds in different scenarios, we have $\gamma_1 < \gamma_2 < \gamma_3$.

where $X = -16(3c+7g-4e\phi)^2 + 12(-7eg+4e\phi)(3ak-3ck+4egk-4ek\phi)$

$Y = -3456c^3 - 24192c^2g - 56448cg^2 - 43904g^3 - 9072acegk + 9072c^2egk - 21168aeg^2k + 21168ceg^2k - 12096ce^2g^2k + 56448e^2g^3k + 13824c^2e\phi + 64512ceg\phi + 75264eg^2\phi + 5184acek\phi - 5184c^2ek\phi + 12096aegk\phi - 12096cegk\phi + 12096ae^2gk\phi + 6912ce^2gk\phi - 52416e^2g^2k\phi - 68544e^3g^2k\phi - 18432ce^2\phi^2 - 43008e^2g\phi^2 - 6912ae^2k\phi^2 + 11520e^2gk\phi^2 + 71424e^3gk\phi^2 + 8192e^3\phi^3 - 18432e^3k\phi^3$, $H = -16(3c+7t-4e\phi)^2 + 12(-7t\theta+4e\phi)(3ak-3ck+4kt\theta-4ek\phi)$

$Z = (-3456c^3 - 24192c^2t - 56448ct^2 - 43904t^3 - 9072ackt\theta + 9072c^2kt\theta - 21168akt^2\theta + 21168ckt^2\theta - 12096ckt^2\theta^2 + 56448kt^3\theta^2 + 13824c^2e\phi + 5184acek\phi - 5184c^2ek\phi + 64512cet\phi + 12096aekt\phi - 12096cekt\phi + 75264et^2\phi + 12096aekt\theta\phi + 6912cekt\theta\phi - 52416ekt^2\theta\phi - 68544ekt^2\theta^2\phi - 18432ce^2\phi^2 - 6912ae^2k\phi^2 - 43008e^2t\phi^2 + 11520e^2kt\phi^2 + 71424e^2kt\theta\phi^2 + 8192e^3\phi^3 - 18432e^3k\phi^3$. □

Proof of Lemma 2. Similar to the proof of Lemma 1, according to the optimal equilibrium results for stakeholders, we compare the profits of electricity suppliers under different policies, and we have $\pi_{ES}^{SUB*} > \pi_{ES}^{CAP*}$, $\pi_{ES}^{NON*} > \pi_{ES}^{CAP*}$, $\pi_{ES}^{RPS*} > \pi_{ES}^{CAP*}$. Comparing electricity supplier profits under scenario *NON*, scenario *RPS* and scenario *SUB*, we have $\pi_{ES}^{SUB*} > \pi_{ES}^{RPS*}$, $\pi_{ES}^{SUB*} > \pi_{ES}^{NON*}$. We then compare the electricity supplier profits under scenario *NON* with scenario *RPS*, so we have $\pi_{ES}^{NON*} > \pi_{ES}^{RPS*}$ if $\gamma \leq \frac{-8c-4t+2ak\theta-2ck\theta-kt\theta^2}{2(a-c-c\theta-t\theta)}$ and $\theta \leq \theta_1$, otherwise, $\pi_{ES}^{NON*} < \pi_{ES}^{RPS*}$ where $\theta_1 = \frac{2ak-2ck+2c\gamma+2t\gamma-\sqrt{4kt(-8c-4t-2a\gamma+2c\gamma)+(2ak-2ck+2c\gamma+2t\gamma)^2}}{2kt}$. □

Proof of Lemma 3. Similar to the proofs of Lemma 1 and Lemma 2, we can obtain comparative results for consumer surplus (see **Table A1**).

Table A1. Comparison of consumer surplus under different policy scenarios.

$\gamma < \gamma_4$ and $\theta < \theta_2$	$0 < e < e_1$ $CS^{CAP*} > CS^{RPS*} > CS^{SUN*} > CS^{NON*}$	$e_1 < e < e_2$ $CS^{RPS*} > CS^{CAP*} > CS^{SUN*} > CS^{NON*}$	$e_2 < e < e_3$ $CS^{RPS*} > CS^{SUN*} > CS^{CAP*} > CS^{NON*}$	$e > e_3$ $CS^{RPS*} > CS^{SUN*} > CS^{NON*} > CS^{CAP*}$
	$0 < e < e_2$ $CS^{CAP*} > CS^{SUN*} > CS^{RPS*} > CS^{NON*}$	$e_2 < e < e_1$ $CS^{SUN*} > CS^{CAP*} > CS^{RPS*} > CS^{NON*}$	$e_1 < e < e_3$ $CS^{SUN*} > CS^{RPS*} > CS^{CAP*} > CS^{NON*}$	$e > e_3$ $CS^{SUN*} > CS^{RPS*} > CS^{NON*} > CS^{CAP*}$
	$0 < e < e_2$ $CS^{CAP*} > CS^{SUN*} > CS^{NON*} > CS^{RPS*}$	$e_2 < e < e_3$ $CS^{SUN*} > CS^{CAP*} > CS^{NON*} > CS^{RPS*}$	$e_3 < e < e_1$ $CS^{SUN*} > CS^{NON*} > CS^{CAP*} > CS^{RPS*}$	$e > e_1$ $CS^{SUN*} > CS^{NON*} > CS^{RPS*} > CS^{CAP*}$
$\gamma_4 < \gamma <1$ and $\theta < \theta_2$	$0 < e < e_1$ $CS^{SUN*} > CS^{CAP*} > CS^{RPS*} > CS^{NON*}$	$e_1 < e < e_3$ $CS^{SUN*} > CS^{RPS*} > CS^{CAP*} > CS^{NON*}$	$e > e_3$ $CS^{SUN*} > CS^{RPS*} > CS^{NON*} > CS^{CAP*}$	
	$0 < e < e_3$ $CS^{SUN*} > CS^{CAP*} > CS^{NON*} > CS^{RPS*}$	$e_3 < e < e_1$ $CS^{SUN*} > CS^{NON*} > CS^{CAP*} > CS^{RPS*}$	$e > e_1$ $CS^{SUN*} > CS^{NON*} > CS^{RPS*} > CS^{CAP*}$	

$\gamma_4 = \frac{-3ak+3ck+\sqrt{-64(-3c-7g)gk+(-3ak+3ck)^2}}{2(3c+7g)}$, $e_1 = \frac{g\gamma-t\gamma+kt\theta}{gk}$, $e_2 = \frac{16gk\gamma-3ak\gamma^2+3ck\gamma^2-3c\gamma^3-7g\gamma^3}{16gk^2-7gk\gamma^2+16k\gamma\phi-4k\gamma^2\phi-4\gamma^3\phi+\gamma^4\phi}$, $e_3 = \frac{\gamma}{k}$,

$\theta_2 = \frac{egk-g\gamma+t\gamma}{kt}$. □