Environment, Development and Sustainability
https://doi.org/10.1007/s10668-025-07203-2

Carbon tax, renewable portfolio Standards, or both? Evaluating policy effectiveness in promoting renewable energy and reducing emissions

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Received: 13 June 2024 / Accepted: 10 December 2025
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Abstract
The transition to a low-carbon economy is a critical global challenge. However, the relative effectiveness of renewable portfolio standards (RPS) and carbon tax policies, particularly their potential synergistic effects, remains insufficiently understood. Clarifying this relationship is essential for designing effective policies that enhance renewable energy investment and reduce carbon emissions. We develop an optimization framework in which a monopolistic electricity supplier in China invests in a hybrid energy system of conventional and renewable power. We compare profit-maximizing strategies under four policy scenarios: no policy, a carbon tax, an RPS, and a mixed policy (carbon tax + RPS). The analysis examines how these policies shape production and pricing decisions, investment, emissions, consumer surplus, and social welfare. Three main findings emerge. First, both carbon tax and RPS policies significantly encourage renewable energy investment and reduce carbon emissions. Second, mixed policies consistently outperform single policies, demonstrating the highest potential for renewable energy development and carbon emission reduction. Third, social welfare effects under mixed policies vary depending on the carbon tax and renewable energy quota level, with the highest social welfare achieved under low and medium quotas. Importantly, renewable intermittency does not alter the relative ranking of policies, though consumer environmental awareness shifts investment thresholds. Based on these findings, three recommendations emerge: integrating carbon tax with RPS accelerates renewable deployment, phased emission reduction balances neutrality targets with electricity demand, and incentives linking green electricity with consumer awareness strengthen adoption. These results provide actionable policy guidance for China and offer broader insights for economies pursuing a sustainable low-carbon transition.

Keywords Carbon tax · Renewable portfolio standards · Carbon emission · Renewable energy investment

Abbreviations

RPS	Renewable portfolio standards
GHG	Greenhouse gas
NEA	National Energy Administration

Extended author information available on the last page of the article

Published online: 19 January 2026

CEC	China Electricity Council
NBS	National Bureau of Statistics
TGC	Tradable green certificates
EIA	Energy Information Administration
NDRC	National Development and Reform Commission
FCT	Flat carbon tax
FIT	Feed-in Tariffs
CGE	Computable general equilibrium
ICT	Information and Communication Technology
PTCs	Production Tax Credits
ETS	Emissions trading scheme
CET	Carbon emissions trading
CCS	Carbon capture and storage

1 Introduction

Climate change presents a significant global challenge, driving an increase in the frequency and severity of extreme weather events, primarily due to rising greenhouse gas (GHG) emissions (Adebayo & Özkan, 2024). The power sector, driven by escalating energy demands, is a key source of CO_2 emissions. Thermal power generation, which remains predominantly reliant on non-renewable resources such as coal (Cartelle Barros et al., 2017), continues to dominate energy production in this sector. In China, energy consumption is the largest contributor to CO_2 emissions, accounting for approximately 88% of the country's total emissions. Notably, the power sector alone is responsible for around 41% of energy-related emissions, with power generation as the primary source (NEA, 2021). In 2022, China's thermal power generation reached 5,888,795 million kWh, with an average CO_2 emission intensity of approximately 824 g/kWh. As shown in Fig. 1, based on data from the China Electricity Council (CEC) and the National Bureau of Statistics (NBS), both thermal power generation and associated CO_2 emissions have exhibited an upward trend from 2015 to 2022. Expanding renewable energy capacity and enhancing energy efficiency are essential

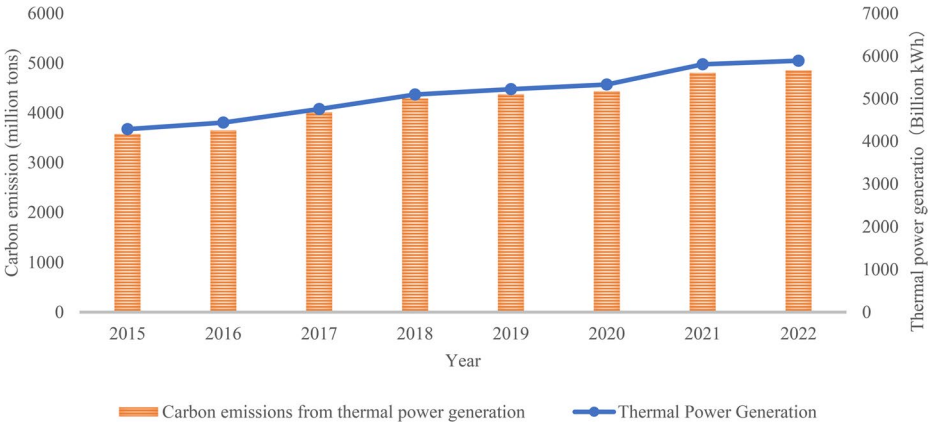

Fig. 1 The amount of thermal power generation and the CO_2 emissions in China from 2015 to 2022

for curbing CO_2 emissions (Adebayo et al., 2024a). Notably, recent evidence by (Adebayo et al., 2025) underscores how media-amplified economic policy uncertainty significantly affects energy asset returns, revealing the vulnerability of renewable energy investment to shifts in macroeconomic expectations. These findings highlight the need for stable and predictable policy environments to foster effective green investment. Thus, enhancing the energy mix by increasing the share of renewable energy is a crucial strategy for achieving net-zero emissions and ensuring long-term sustainability, as renewable energy can substantially reduce carbon emissions and mitigate the power sector's environmental impact (Kirikkaleli & Adebayo, 2021). The outcomes of the recent COP28 summit held in Dubai further emphasized the global consensus on transitioning to renewable energy sources and enhancing carbon mitigation efforts to combat climate change, reinforcing the strategic importance of expanding green energy investments (IRENA, 2024).

To mitigate climate change and achieve net-zero emissions, numerous countries have introduced a range of mandatory and market-based policy instruments, including carbon cap-and-trade systems (Chen et al., 2021; Kuiti et al., 2020), carbon taxes (An et al., 2022; Yu et al., 2022), energy efficiency regulations (Alizamir et al., 2016), and subsidies for renewable energy generation (Nicolini & Tavoni, 2017). Among these measures, carbon taxes are widely regarded as one of the most effective tools for curbing carbon emissions by imposing financial penalties on companies based on their carbon output during production processes (Parker et al., 2019; Zhou et al., 2021). As of the latest reports, carbon taxes have been implemented or are scheduled to be introduced in 37 countries and regions worldwide (Bank, 2022). In recent years, the Chinese government and relevant research institutions have actively explored the feasibility of implementing a carbon tax. A significant milestone was reached in September 2021 with the issuance of the *Guiding Opinions on Achieving Carbon Peak and Carbon Neutrality* by the State Council, which marks a significant step toward the gradual implementation of carbon tax policies. Empirical evidence indicates that carbon tax policies have been effective in reducing emissions in regions such as British Columbia (Kumbhakar et al., 2022). Nevertheless, important limitations remain. Carbon taxes alone may fail to spur large-scale renewable investment, especially in sectors with limited abatement flexibility, while their credibility is vulnerable to political cycles. These challenges highlight the need to complement carbon pricing with broader policy portfolios that foster innovation and long-term market transformation.

Meanwhile, Renewable Portfolio Standards (RPS) play a critical role in achieving the 'dual carbon' target (Song et al., 2021; Wu et al., 2022). In a market-oriented framework, RPS incentivizes utility companies to invest in renewable energy by establishing specific generation targets, often supported by tradable green certificates (TGC) (Zhu et al., 2020). Adopted in over 29 countries, including the United States, the United Kingdom, Japan, and Belgium (Bhattacharya et al., 2017), RPS has significantly contributed to the expansion of renewable energy. In the U.S., for example, 30 states have implemented state-level RPS policies, accounting for approximately 50% of the cumulative growth in renewable electricity generation since 2000 (EIA, 2022). China introduced its first RPS in 2020, and in 2023, the National Development and Reform Commission (NDRC) issued guidelines to expand the coverage of renewable energy green power certificates (NDRC, 2023). Despite these achievements, debates persist regarding the limitations of RPS. Some scholars argue that its focus on quantity-based targets overlooks cost-effectiveness and allocative efficiency, leading to potentially higher compliance costs and hidden burdens on consumers (Carley, 2009;

Yin & Powers, 2010). Others highlight that RPS may distort fair competition by favoring certain renewable technologies while neglecting innovation in others, thereby slowing overall technological progress (Shrimali et al., 2015).

While both carbon taxes and RPS are pivotal for decarbonization efforts, their relative effectiveness and potential synergies remain underexplored. Importantly, the interaction between these two instruments is far from straightforward: while some scholars argue that they can complement each other by balancing price and quantity signals, others caution that misaligned policy design may generate redundant costs, weaken incentives, or even create conflicting objectives (Bhattacharya et al., 2017; Zhu et al., 2020). Existing studies predominantly analyze these policies in isolation, leaving unresolved questions about how a combined framework might optimize renewable investment, emissions reduction, consumer surplus, and social welfare. Furthermore, it remains unclear whether policy integration consistently yields superior outcomes compared to unilateral approaches, or how contextual variables such as renewable energy intermittency and consumer environmental awareness interact within hybrid policy scenarios. This study aims to address these gaps by systematically analyzing the renewable energy investment strategies of electricity providers across different policy frameworks and examining the interplay between intermittency and consumer preferences. The findings contribute to both theory and practice, offering a comprehensive understanding of policy effectiveness in promoting renewable energy adoption. Consequently, this study addresses several key questions:

(i) How do electricity suppliers' optimal renewable energy investments and associated carbon emissions vary across different policy scenarios (e.g., carbon tax, renewable portfolio standards, and mixed policies)?
(ii) Which policy maximizes consumer surplus and social welfare, and how do these outcomes quantitatively compare across different policy frameworks?
(iii) What is the quantitative influence of renewable energy intermittency and heterogeneous consumer environmental preferences on suppliers' optimal investments, carbon emissions, and social welfare within the modeled framework?

To address these questions, this study develops a profit-maximizing framework to examine how a monopolistic electricity supplier investing in a hybrid energy system, combining conventional and renewable sources, makes production and pricing decisions under four distinct policy scenarios: no-policy (NOP), carbon tax (TAX), RPS, and mixed policies (MIX). Drawing upon the policy synergy framework proposed by Howlett and Rayner (2007), we posit that the MIX scenario inherently combines the price-based mechanism of carbon taxation (internalizing environmental externalities through cost penalties) with the quantity-based mechanism of RPS (stimulating renewable investment via quota obligations), thereby creating a theoretically superior policy instrument. The models are formulated to obtain optimal solutions, and the resulting equilibria are compared across the four policy scenarios. The findings indicate that both RPS and carbon tax policy effectively promote hybrid renewable energy investment and reduce carbon emissions. Notably, the mixed policy emerges as the most effective mechanism. The trends in consumer surplus and social welfare are similar across the scenarios, but the social welfare of the mixed policy depends on the specific carbon tax rate and renewable energy quota. Additionally, the study extends the model to account for renewable energy intermittency and consumer preferences for

renewable energy. The results suggest that intermittency does not alter the ranking between policy scenarios. However, consumer preferences for renewable energy are found to be directly proportional to the threshold for investment decisions.

The contributions of this study are threefold. First, this paper develops a profit-maximizing framework, to examine how electricity suppliers investing in hybrid energy systems, combining conventional and renewable sources, make capacity and pricing decisions under different policy scenarios, including carbon tax, RPS, and mixed policies. Second, the study analyzes the impact of these policy settings on renewable energy investment, carbon emissions, consumer surplus and social welfare, identifying the conditions under which mixed policies outperform single policies. Finally, the analysis considers the effects of renewable energy intermittency and consumer environmental awareness, showing how these factors influence investment decisions and the relative effectiveness of different policy frameworks. These insights provide a solid foundation for designing more effective renewable energy policies and guiding strategic decisions by electricity suppliers.

The rest of this paper is structured as follows. Section 2 reviews the relevant literature. Section 3 outlines the scenario design and model preliminaries. Section 4 formulates the equilibrium models under four policy scenarios and derives optimal energy investment and pricing strategies. Section 5 examines how emission reduction policies influence hybrid renewable energy investment, carbon emissions, and social welfare. Section 6 conducts a detailed equilibrium analysis through numerical simulations. Section 7 extends the model to account for renewable energy intermittency and consumer preferences. Finally, Sect. 8 discusses policy implications based on the study's findings.

2 Literature review

The existing literature closely related to this paper encompasses three main aspects: (*i*) Mechanism evaluation and impact analysis of carbon tax, (*ii*) Mechanism evaluation and impact analysis of renewable portfolio standards, (*iii*) Policy coordination and interaction.

2.1 Mechanism evaluation and impact analysis of carbon tax

Carbon taxation serves as a key regulatory tool for curbing emissions by imposing levies on specific sources. Its effectiveness depends on how regulated entities adapt to the tax. Electricity suppliers can mitigate emissions through various strategies, including expanding renewable energy adoption, transitioning to alternative fuels, deploying nuclear power, and implementing carbon capture and storage (Fig. 2). Energy efficiency also plays a pivotal role in emission reduction and sustainability. However, determining the optimal tax level remains a challenge, as excessively high rates may hinder industrial activity, while low rates may fail to curb emissions effectively (Zhang & Baranzini, 2004). Alternative models, such as the block carbon tax proposed by Zhou et al. (2019), suggest that progressive tax structures can balance economic and environmental objectives, alleviating the financial burden on manufacturers while promoting low-carbon production.

Extensive research has examined the impact of carbon taxes on the power sector, highlighting their role in shaping energy investment decisions. Carbon pricing has been shown to accelerate renewable energy adoption, as demonstrated by Best and Burke (2018) in

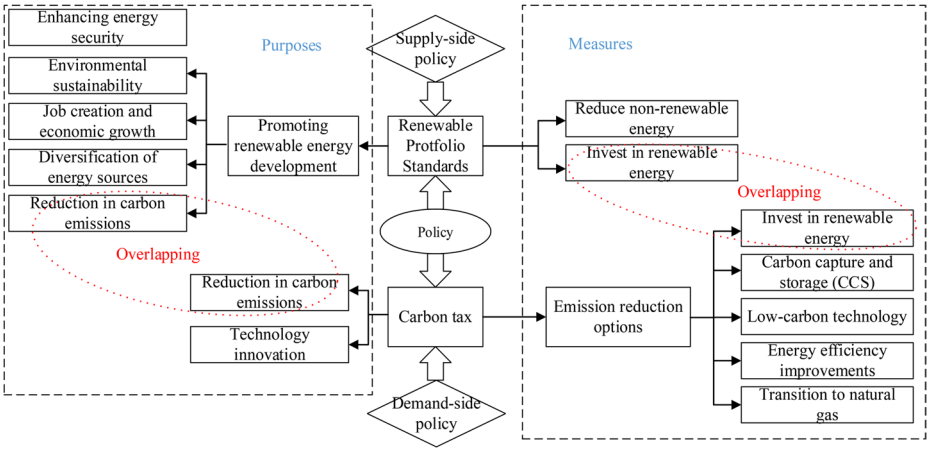

Fig. 2 Distinction and overlapping between RPS and carbon tax. Note: The indirect purpose of carbon tax is not presented, such as environmental effects.

Denmark's wind energy sector. Ding et al. (2019) found that higher carbon taxes discourage high-emission technologies while fostering investor confidence in renewables such as photovoltaics. Moreover, Zhao et al. (2019) identified that a carbon tax exceeding $30/ton effectively incentivizes wind power investment. Empirical studies further suggest that higher carbon taxes improve policy efficiency and enhance the renewable energy mix (Fang et al., 2022; Ratanakuakangwan & Morita, 2022).

Several studies have compared carbon tax with alternative policies. Sun and Yang (2021) found that cap-and-trade is more responsive to consumer environmental awareness than carbon tax. Bian and Zhao (2020) examined carbon tax and subsidies, highlighting their distinct economic, environmental, and social impacts on emission reduction investments. However, limited research explores the comparative effects of carbon tax and renewable portfolio standards (RPS) on electricity suppliers' renewable energy investments and emissions, a gap this study aims to address.

2.2 Mechanism evaluation and impact analysis of RPS

Renewable Portfolio Standards (RPS) mandate progressive targets for renewable energy adoption, a policy that is often complemented by Tradable Green Certificates (TGCs), which provide market-driven incentives to offset environmental costs (Song et al., 2021; Wu et al., 2022). As illustrated in Fig. 2, RPS contribute to reducing reliance on fossil fuels, promoting competition in energy markets, and stimulating technological innovation in renewable energy generation (Aune et al., 2012; Currier, 2013; Sun And Nie, 2015). For instance, California's 33% RPS target achieved cost-effective emissions reductions (Rouhani et al., 2016). However, similar policies in other regions have produced mixed results. In some cases, ambitious targets fail to encourage producers to invest in renewable energy when TGC prices fluctuate unpredictably (Yin And Powers 2010; C. Zhu et al. 2020).

Macro-scale analyses reveal RPS-driven structural shifts, from renewable investments to grid optimization (Raadal et al., 2012). However, micro-level decision-making exposes systemic vulnerabilities. Evolutionary game models demonstrate that producer participa-

tion in TGC markets depends heavily on a combination of regulatory enforcement, market conditions, and producer behavior (Zhao et al., 2018, while ICT integration and solar innovation emerge as unexpected enablers of policy resilience (Adebayo et al., 2024b). Notably, cross-national comparisons highlight context-specific trade-offs: in Japan, renewable policies temporarily offset emissions from globalization-driven growth (Adebayo & Kirikkaleli, 2021), whereas U.S. data caution against overreliance on transitional fuels like natural gas (Adebayo et al., 2023a).

Despite its potential, RPS faces scrutiny. General equilibrium models suggest that increasing RPS allowances may trigger resource booms without concurrent emissions reductions (Bento et al., 2018), which poses a challenge to further optimize the design of the RPS mechanism, especially in terms of balancing environmental effects with emission reductions.

2.3 Policy coordination & interaction

Increasing interest in the interaction and coordination of climate and renewable energy policies has been seen in recent years. Numerous studies have explored policy combinations, including carbon tax and trading schemes (Zhang et al., 2022), RPS and emissions trading (Yi et al., 2019), and FIT and RPS (Kwon, 2020; Sun & Nie, 2015). These studies primarily evaluate how policy mixes influence electricity market dynamics, renewable energy adoption, and carbon mitigation. Understanding these interactions is crucial for designing effective, cost-efficient strategies to achieve sustainable energy transitions and climate goals.

Quantitative methods have been central to policy evaluation. Computable general equilibrium (CGE) models, for example, suggest that combining carbon taxes with emissions trading achieves peak emissions at lower economic cost (Zhang et al., 2022), while system dynamics models indicate that integrating RPS with trading enhances market efficiency and accelerates renewable deployment (Bao & Zhao, 2023). Empirical analyses further show that hybrid instruments, such as Korea's FIT–RPS mix, can offset the weaknesses of individual policies (Kwon, 2020), and under uncertainty, renewable subsidies are found to complement emissions trading by improving both economic and environmental outcomes (Lecuyer & Quirion, 2019). Yet these methods face clear limitations: CGE models rely on aggregated structures and static equilibria, constraining their ability to capture firm-level strategic adjustments under overlapping mandates; system dynamics approaches, while valuable for tracing feedback loops, typically abstract from heterogeneous firms' competitive behaviors. By contrast, optimization frameworks grounded in game theory allow explicit modeling of micro-level decisions on production, pricing, and investment, as well as firms' responses to policy instruments. While a growing literature applies such models to single instruments, such as carbon taxes or RPS, few extend this approach to dual-policy settings, where interacting instruments generate multidimensional incentives and strategic trade-offs.

Moreover, existing research highlights potential pitfalls of policy coordination. Excessive or poorly designed regulation may generate unintended consequences: dual regulation can inflate administrative costs (Currier, 2016), and interactions between carbon taxes and production tax credits (PTCs) may distort dispatch decisions and undermine emission-reduction efforts (Bhandari et al., 2017). While the interplay between RPS and emissions trading has received substantial attention (Bao & Zhao, 2023; Wu et al., 2022), studies

on the combined impact of RPS and carbon taxation remain scarce. Importantly, there is little analytical exploration of how firms' investment strategies and market equilibria evolve when these policies are jointly implemented.

As illustrated in Fig. 2, Renewable Portfolio Standards (RPS) and carbon taxation pursue similar environmental goals but operate through distinct mechanisms. RPS restricts fossil-based generation and mandates renewable expansion, thereby enhancing energy security and supporting broader sustainability objectives, while carbon taxation incentivizes continuous emission reductions and technological upgrading. Their coexistence creates a multi-dimensional decision environment for electricity providers, who may respond by investing in renewables, adopting carbon capture and storage (CCS), or improving efficiency. A rigorous, game-theoretic analysis of these interactions is thus essential for understanding how firms navigate dual mandates and for designing policies that balance environmental effectiveness with economic efficiency. Recent studies highlight the relevance of such hybrid approaches in diverse contexts. For instance, Inzunza et al. (2021) show that combined instruments provide risk mitigation benefits in Chile's power sector, while evidence from the EU and U.S. demonstrates that layering renewable obligations onto carbon pricing can enhance renewable penetration without compromising market stability. Yet, despite these insights, the joint impact of RPS and carbon taxation on firm-level investment strategies, emissions reduction, and welfare outcomes remains insufficiently understood.

2.4 Research gaps

Table 1 provides a comprehensive review of relevant studies on energy management and highlights three critical research gaps. First, prior work has largely examined energy management under either no-policy conditions or a single low-carbon instrument, such as a carbon tax or a renewable portfolio standard (RPS). The comparative effectiveness and potential complementarities of these policies remain underexplored. Notably, most existing game-theoretic studies focus on single-policy settings and adopt simplifying assumptions about firm behavior, thereby overlooking the strategic trade-offs and equilibrium interactions that emerge when multiple instruments coexist. Second, while existing research has extensively investigated renewable energy investments, it typically treats investment and technology adoption as exogenous or deterministic variables. Furthermore, it fails to sufficiently analyze how different policy mechanisms can optimize investment decisions, emission reduction outcomes, consumer surplus, and social welfare. A more integrated analytical approach is required to assess policy interactions and their broader economic and environmental implications. Third, the influence of renewable intermittency and consumer environmental awareness on policy effectiveness is not well understood. Many studies abstract from these factors, despite their central role in shaping firm responses and regulatory outcomes. This study addresses these gaps by systematically analyzing the renewable energy investment strategies of electricity providers across different policy frameworks, derives closed-form equilibrium conditions and comparative results across different allocation rules, and explicitly incorporates intermittency and consumer heterogeneity. The findings contribute to both analytical form and equilibrium insights, providing a more comprehensive understanding of how mixed policies can promote renewable adoption and decarbonization.

Table 1 Differences between this paper and existing studies

Authors	Carbon policy	Energy policy	Methods	Renewable energy	Conventional energy	Hybrid energy	CS	SW	Intermittence	Consumer preference
Aflaki and Netessine (2017)	Carbon tax		The newsvendor framework	√	√	√			√	√
Kök et al. (2018)	Carbon tax and subsidy policy		The profit maximization model	√	√	√	√	√	√	
Wei et al. (2021)	Cap-and trade mechanisms		The game theory	√	√	√	√			
Zhu et al. (2022)		Renewable electricity standard and Renewable energy certificates	An analytical model	√	√	√			√	
Rui et al. (2023)	Carbon cap-and-trade policy		An analytical framework	√	√	√				
Adebayo et al. (2023a, b)			A novel time-frequency (WLMC) approach	√	√	√		√		
Chen et al. (2024)	Carbon quota policy		The game model	√	√	√	√			√
Adebayo et al. (2024b)			The novel Quantile on Quantile Kernel Based Regularized Least Squares (QQKRLS) approach	√				√		
Adebayo and Kirikkaleli (2021)			The wavelet approach	√		√				
This paper	Carbon tax	RPS	A profit-maximizing equilibrium model	√	√	√	√	√	√	√

CS: Consumer surplus; SW: Social welfare; WLMC: Wavelet local multiple local; QQKRLS: The novel Quantile on Quantile Kernel Based Regularized Least Squares; RPS: Renewable Portfolio Standard

3 Scenario design and model preliminaries

This study develops a profit-maximizing framework to analyze how a monopolistic electricity supplier makes investment and pricing decisions in a hybrid energy system under four policy scenarios: no policy (NOP), carbon tax (TAX), RPS, and mixed policies (MIX).

3.1 Scenario design

This study systematically evaluates the effects of different policy mechanisms on carbon emission reduction and renewable energy investment. Table 2 outlines the four policy scenarios:

By comparing these scenarios, this study provides insights into how different regulatory approaches influence green investment and emissions mitigation.

3.2 Model preliminaries

This study is based on several key assumptions. First, the electricity supplier invests in existing energy infrastructure, with carbon emissions subject to taxation. Additionally, the supplier can trade renewable energy certificates and may operate as an independent electricity provider. To simplify the model, we assume suppliers can adjust electricity tariffs within predefined limits. Decision-makers are rational and seek to maximize individual benefits. Unlike Yan et al. (2022), our model considers a combined policy environment of carbon tax and renewable portfolio standards while extending the intermittency of renewable energy sources and consumers' environmental awareness. This dual perspective enhances both the realism and applicability of our framework. All symbols and their units are summarized in Table 3.

Demand. Following Bao et al. (2019), Bhattacharya et al. (2017), Chen et al. (2021), we assume that electricity demand responds linearly to price changes, given by $Q = a - bp$, where a denotes the market size and b represents the sensitivity coefficient ($0 < b < 1$). Lower prices stimulate higher demand. Consistent with Yan et al. (2022), Krass et al. (2013) and Rui et al. (2023), we assume uniform pricing for electricity from conventional and renewable sources, as the focus is on hybrid energy investment strategies rather than price differentiation. This abstraction enables us to focus on the comparative dynamics of policy instruments and green investment strategies without introducing the added complexity of technology-specific pricing.

Table 2 Description of the four policy scenarios

Scenario	Abbreviation	Description
No policy	NOP	No government intervention; electricity suppliers make decisions independently.
Carbon tax	TAX	A tax is levied on carbon emissions, incentivizing investment in renewable energy.
Renewable portfolio standards	RPS	A minimum renewable energy share (β) is mandated. If unmet, suppliers buy green certificates at f; excess quotas can be sold at f.
Mixed policies	MIX	A combination of TAX and RPS, reflecting real-world policy frameworks.

Table 3 Model parameters and decision variables

Parameters	Description
F	Index of carbon scenarios (F= {N, T, R, M}), representing No policy, Carbon tax, Renewable portfolio standard, respectively
*	Indicate the optimal solutions
e	Unit carbon emissions from conventional energy (kg/kWh)
t	Unit carbon tax (yuan/kg)
f	Unit TGC price (yuan/kWh)
β	Renewable energy quota
d	The impact factor of conventional energy on ecological environment (yuan per kg CO_2)
r_1	Unit production cost of photovoltaic renewable energy (yuan/kWh)
r_2	Unit production cost of wind renewable energy (yuan/kWh)
a	Potential electricity demand for electricity(kWh)
b	Sensitivity coefficient of electricity price
Q^F	Electricity demand in the market under the policy scenario F (kWh)
π^F	Profits of the electricity company under the policy scenario F (yuan)
E^F	Total carbon emissions of policy scenario F (yuan)
CS^F	Consumer surplus under the policy scenario F (yuan)
SW^F	Social welfare (yuan)
Decision Variables	Description
p^F	Unit electricity price under the policy scenario F (yuan/kWh)
g^F	Conventional energy production/investment (kWh) under policy F
k_1^F	PV production/investment (kWh) under policy F
k_2^F	Wind production/investment (kWh) under policy F

Costs. Following Chen et al. (2023), we integrate investment and production costs into a single cost framework using a quadratic function. The unit production cost of conventional energy is modeled as $Z_c^F = \frac{1}{2}c\left(g^F\right)^2$, where c is the cost coefficient and g^F represents conventional energy production. Similarly, the unit cost for photovoltaic or wind energy is $Z_i^F = \frac{1}{2}r_i\left(k_i^F\right)^2$ ($i = 1,2$), where r_i is the cost coefficient and k_i denotes the supplier's investment in renewable energy (Chen et al., 2021; Yenipazarli, 2016). For comparative analysis, we assume $r_i > c$. Empirical evidence shows non-linear escalation of both conventional and renewable costs, supporting this convex specification (Mendes et al., 2024)[1].

[1] Economically, the coefficients c and r_i represent the marginal cost scaling factors, reflecting the technological maturity and efficiency of conventional production and renewable investment, respectively. In the subsequent equilibrium analysis, these fundamental parameters are aggregated into composite positive constants to bridge mathematical compactness with economic intuition.

The total energy balance is constrained by demand, such that $g^F + k_1^F + k_2^F = Q^F$, consistent with standard assumptions in the literature (Yenipazarli, 2019).

Carbon Emissions. The carbon intensity of conventional energy is denoted by e, while renewable energy has zero emissions. Total carbon emissions are calculated as:

$$E^F = eg^F \tag{1}$$

Consumer surplus. Consumer surplus is the difference between the maximum amount consumers are willing to pay, given by $\int_0^{q^*} Q^{F^{-1}}(p)\,dq$, and the actual expenditure p^*q^*, where q^* is the optimal demand at price p^*. Following Krass et al. (2013), it is expressed as:

$$CS^F = \int_0^{q^*} Q^{F^{-1}}(p)\,dq - p^*q^* = \frac{(a - bp^*)^2}{2b} \tag{2}$$

Tax revenue. Tax revenue applies only under a carbon tax policy and is calculated as: $te(Q^F - k_1^F - k_2^F)$, where revenue is assumed to enhance social welfare.

Social welfare. Social welfare is the sum of consumer surplus, electricity suppliers' profits, and tax revenue, minus the external costs of carbon emissions. Each component's contribution is weighted by x_i, commonly assumed to be equal (Linghu et al., 2022). When a carbon tax is imposed, $x_4 = 1$; otherwise, $x_4 = 0$. Social welfare is given by:

$$SW^F = x_1\pi^F + x_2CS^F - x_3E^Fd + x_4te(Q^F - k_1^F - k_2^F) \tag{3}$$

Where d $(0 < d < 1)$ represents the environmental damage factor of conventional energy.

4 Models and equilibrium analysis

This section examines an electricity supplier's capacity investment and pricing decisions under four policy scenarios: no policy, carbon tax, renewable portfolio standard, and mixed policies. The analysis assumes rational decision-making, aligning with prior studies (Chen et al., 2021; Yan et al., 2022), to optimize profits and renewable energy investments.

4.1 No-policy scenario

In this scenario, the government does not enforce any mandatory low-carbon policies. This setup enables a better comparison of the impact of the other three policy scenarios outlined in Table 2 on renewable energy investment and total carbon emissions. The electricity supplier's profit maximization involves adjusting the electricity price and investing in renewable energy. The profit function for the electricity supplier is formulated as following:

$$\pi^N = p^NQ^N - \frac{1}{2}c(Q^N - k_1^N - k_2^N)^2 - \frac{1}{2}r_1k_1^{N2} - \frac{1}{2}r_2k_2^{N2} \tag{4}$$

The terms in Eq. (4) represent the electricity sales income, production costs of power generation from conventional, photovoltaic and wind renewable energy, respectively. In Eq. (4),

the electricity supplier makes two renewable energy investment decisions and a pricing decision. Hence, the supplier's sequential decisions regarding k_1^N, k_2^N and p^N can be regarded as simultaneous.

By substituting $Q^N = a - bp^N$ into Eq. (4) and applying an inverse induction approach, we consider the first-order conditions for profit maximization:

$$\frac{\partial \pi^N}{\partial k_1^N} = 0, \ \frac{\partial \pi^N}{\partial k_2^N} = 0, \ \frac{\partial \pi^N}{\partial p^N} = 0$$

Solving these equations yields the optimal renewable investment strategies k_1^{N*}, k_2^{N*}, and the optimal electricity price p^{N*} as follows:

$$\begin{aligned} k_1^{N*} &= \frac{acr_2}{2cr_2+2r_1r_2+cr_1(2+br_2)} \\ k_2^{N*} &= \frac{acr_1}{2cr_2+2r_1r_2+cr_1(2+br_2)} \\ p^{N*} &= \frac{a(r_1r_2+c(r_1+r_2+br_1r_2))}{b(2cr_2+2r_1r_2+cr_1(2+br_2))} \end{aligned} \tag{5}$$

By substituting the optimal strategies from Eq. (5) into Eqs. (1) and (2), we obtain the total carbon emissions E^{N*}, consumer surplus CS^{N*}, and social welfare SW^{N*} under the optimal solution, as shown in Table 4.

4.2 Carbon tax scenario

In this scenario, the government controls the carbon emissions of the electricity supplier by implementing the carbon tax (t). Consequently, the electricity supplier's decision-making is influenced by the tax. The profit function for the electricity supplier in this scenario is expressed as:

$$\begin{aligned} \pi^T = p^T Q^T - \tfrac{1}{2}c(Q^T - k_1^T - k_2^T)^2 - \\ \tfrac{1}{2}r_1 k_1^{T2} - \tfrac{1}{2}r_2 k_2^{T2} - te(Q^T - k_1^T - k_2^T) \end{aligned} \tag{6}$$

The terms in Eq. (6) represent the electricity sales income, production costs of power generation from conventional, photovoltaic and wind renewable energy, and the potential additional cost of carbon emissions. Economically, the carbon cost acts as a price signal that raises the marginal cost of fossil-based generation, encouraging suppliers to shift investment toward cleaner energy sources. The calculation procedure follows a similar approach to that of the no-policy scenario, and the corresponding outcomes are presented in Table 4. Leveraging this information, we can deduce the trajectory of equilibrium decisions of the electricity supplier concerning the carbon tax rate, as expounded in *Corollary* 1.

Corollary 1 The optimal decisions with carbon tax scenario have the following properties:

i) $\frac{\partial k_1^{T*}}{\partial t} > 0$, $\frac{\partial k_2^{T*}}{\partial t} > 0$

As shown in *Corollary* 1 i), the electricity supplier increases investments in renewable energy as the carbon tax rises, aiming to mitigate its financial impact. Meanwhile, as shown in *Corollary* 1 iii), investments in conventional energy decrease to further reduce emissions. This theoretical result is consistent with European experience: Sweden's long-standing car-

Table 4 Optimal electricity price p^{F*}, renewable energy investments k^{F*}, profit, carbon emissions, consumer surplus, social welfare

Scenarios	p^{F*}	k_i^{F*}
NOP	$\frac{Z_1+abcr_1r_2}{bA_1}$	$\frac{acr_{3-i}}{A_1}$
TAX	$\frac{Z_1+abcr_1r_2+ber_1r_2t}{bA_1}$	$\frac{r_{3-i}(ac+2et)}{A_1}$
RPS	$\frac{Z_1+abcr_1r_2+bf(c(r_1+r_2)(\beta-1)+r_1r_2\beta)}{bA_1}$	$\frac{r_{3-i}(ac+f(2+b(c-c\beta)))}{A_1}$
MIX	$\frac{Z_1+abcr_1r_2+bcf(r_1+r_2)(\beta-1)+br_1r_2(et+f\beta)}{bA_1}$	$\frac{r_{3-i}(ac+2et+f(2+bc-bc\beta))}{A_1}$
Scenarios	π^{F*}	
NOP	$\frac{aZ_1}{2bA_1}$	
TAX	$\frac{aZ_1-2aber_1r_2t+be^2(2r_2+r_1(2+br_2))t^2}{2bA_1}$	
RPS	$\frac{aZ_1-2abfA_5+bf^2A_6}{2bA_1}$	
MIX	$\frac{aZ_1-2abA_8+bA_9}{2bA_1}$	
Scenarios	E^{F*}	CS^{F*}
NOP	$\frac{aer_1r_2}{A_1}$	$\frac{(Z_1)^2}{2b(A_1)^2}$
TAX	$\frac{e(ar_1r_2-e(2r_2+r_1(2+br_2))t)}{A_1}$	$\frac{(Z_1-ber_1r_2t)^2}{2b(A_1)^2}$
RPS	$\frac{eA_7}{A_1}$	$\frac{(Z_1-bfA_5)^2}{2b(A_1)^2}$
MIX	$-\frac{eA_{10}}{A_1}$	$\frac{(Z_1-bA_8)^2}{2b(A_1)^2}$
Scenarios	SW^{F*}	
NOP	$\frac{aZ_1A_2-2abder_1r_2A_1}{2b(A_1)^2}$	
TAX	$\frac{aZ_1A_2+be^2tA_3-2aber_1r_2A_4}{2b(A_1)^2}$	
RPS	$\frac{(Z_1-bfA_5)^2-2bdeA_1A_7+(aZ_1-2abfA_5+bf^2A_6)A_1}{2b(A_1)^2}$	
MIX	$\frac{(Z_1-bA_8)^2+(d-t)A_1A_{10}+(aZ_1-2abA_8+bA_9)A_1}{2b(A_1)^2}$	

$Z_1 = a\,(r_1r_2 + c\,(r_1+r_2))$

$A_1 = 2cr_2 + 2r_1r_2 + cr_1\,(2 + br_2)$

$A_2 = 3cr_2 + 3r_1r_2 + cr_1\,(3 + br_2)$

$A_3 = c(2r_2 + r_1(2 + br_2))^2(2d - t) + r_1r_2(8dr_2 + 4dr_1(2 + br_2) - 4r_2t - r_1(4 + br_2)t)$

$A_4 = cd(2r_2 + r_1(2 + br_2)) + c(r_1 + r_2)t + r_1r_2(2d + t)$

$A_5 = c(r_1 + r_2)(-1 + \beta) + r_1r_2\beta$

$A_6 = r_2(2 + bc(-1 + \beta)^2) + r_1(2 + b(c - 2c\beta + (c + r_2)\beta^2))$

$A_7 = ar_1r_2 - f\,(2(r_1 + r_2) + br_1r_2\beta)$

$A_8 = cf(r_1 + r_2)(-1 + \beta) + r_1r_2(et + f\beta)$

$A_9 = e^2\,(2r_1+2r_2+br_1r_1)\,t^2 + 2eft(2(r_1 + r_2) + br_1r_2\beta) + f^2((2 + bc) - (r_1 + r_2) - 2bc(r_1 + r_2)\,\beta + b(cr_1 + (c + r_1)r_2)\beta^2)$

$A_{10} = -ar_1r_2 + 2f(r_1 + r_2) + e(2r_1 + 2r_2 + br_1r_2)t + bfr_1r_2\beta$

bon tax has sharply curtailed fossil fuel use and accelerated bioenergy adoption (Shmelev & Speck, 2018). *Corollary 1* ii) further reveals that the transition towards renewable energy raises production costs, prompting suppliers to adjust electricity prices. This mechanism has

also been observed in practice. For instance, empirical studies on Germany's Energiewende suggest that rising renewable shares initially increased retail electricity tariffs, though these adjustments helped stabilize long-term investment incentives (Klessmann et al., 2008). As a result, demand for conventional energy falls, leading to lower carbon emissions, as demonstrated in *Corollary 1* iv), which is consistent with the carbon tax's goal of promoting sustainable practices. Additionally, *Corollary* 1 4 v) shows that higher carbon taxes reduce consumer demand, causing a corresponding decline in consumer surplus. The proof of *Corollary* 1 can be seen in Appendix A1.

4.3 Renewable portfolio standards scenario

In the context of renewable portfolio standards scenario, the government encourages electricity supplier to invest in photovoltaic and wind renewable energy by setting the renewable energy quota β. Decisions made by the electricity supplier is therefore influenced by β. The profit function in this case is thus expressed as:

$$\begin{aligned}\pi^2 = p^R Q^R - \tfrac{1}{2}c\left(Q^R - k_1^R - k_2^R\right)^2 - \\ \tfrac{1}{2}r_1 k_1^{R2} - \tfrac{1}{2}r_2 k_2^{R2} + f\left(k_1^R + k_2^R - \beta Q^R\right)\end{aligned} \tag{7}$$

There are four items on the right of Eq. (7), which include the supplier's electricity sales revenue, production costs of conventional energy, photovoltaic and wind renewable energy correspondingly. The last one is the additional cost that companies may incur by investing in renewable energy to generate electricity. Q^R is the total power generation in this scenario, whiles $\beta Q^R$is the total renewable energy consumption allocated according to the renewable energy consumption quota. If $\beta Q^R > k_1^R + k_2^R$, it indicates the renewable power generation invested by the electricity supplier does not meet the standard, hence there is a need to buy additional renewable energy generation quota in the green certificate market. Conversely, the electricity supplier can obtain an over fulfilled task of renewable energy consumption and can as well gain profits in the market if $\beta Q^R < k_1^R + k_2^R$.The calculation procedure follows a similar approach to that of the no-policy scenario, and the corresponding outcomes are presented in Table 4. Similarly, we can deduce the trajectory of equilibrium decisions of the electricity supplier concerning the RPS quota, as expounded in *Corollary* 2.

Corollary 2 The optimal decisions with renewable portfolio standards scenario have the following properties:

i) $\frac{\partial k_1^{R*}}{\partial \beta} > 0,\ \frac{\partial k_2^{R*}}{\partial \beta} > 0$

In *Corollary* 2 *i*), the electricity supplier's investment in renewable energy declines as the RPS quota increases; nevertheless, RPS remains an effective incentive when quotas are appropriately calibrated, as shown in Sect. 5.1. This aligns with empirical evidence: well-designed RPS schemes in the U.S. and EU have significantly expanded renewable generation even under initial investment constraints (Carley, 2009). Higher renewable penetration increases production costs, prompting suppliers to adjust tariffs (*Corollary* 2 *ii*) and reduce conventional energy investment (*Corollary* 2 *iii*), which in turn lowers fossil energy demand and carbon emissions (*Corollary* 2 *iv*). Similar patterns are observed in the EU, where ambitious RPS targets in Denmark and Spain drove a sharp decline in coal generation during

2010–2020. Finally, rising quotas reduce consumer demand, leading to lower consumer surplus and social welfare (*Corollary* 2 *v*). The formal proof is provided in Appendix A1.

4.4 Mixed policies scenario

In the mixed policies scenario, the government simultaneously implements a carbon tax and a renewable energy portfolio standard. The electricity supplier's pricing and renewable energy investments are jointly constrained by the carbon tax (t) and the renewable energy quota (β). The profit function for the electricity supplier in this scenario is formulated as follows:

$$\begin{aligned}\pi^M = p^M Q^M - \tfrac{1}{2}c\left(Q^M - k_1^M - k_2^M\right)^2 - \tfrac{1}{2}r_1 k_1^{M2} - \\ \tfrac{1}{2}r_2 k_2^{M2} - te\left(Q^M - k_1^M - k_2^M\right) + f\left(k_1^M + k_2^M - \beta Q^M\right)\end{aligned} \tag{8}$$

The terms in Eq. (8) represent the electricity sales income, production costs of power generation from conventional energy, photovoltaic and wind renewable energy, the carbon costs associated with electricity generation, and the possible additional costs related to investing in renewable energy generation. The calculation procedure follows a similar approach to that of the no-policy scenario, and the corresponding outcomes are presented in Table 4. *Corollary* 3 is obtained.

Corollary 3 The optimal decisions with renewable portfolio standards scenario have the following properties:

i) $\frac{\partial k_1^{M*}}{\partial t} > 0$; $\frac{\partial k_2^{M*}}{\partial t} > 0$; $\frac{\partial p^{M*}}{\partial t} > 0$; $\frac{\partial (Q-k_1-k_2)^{M*}}{\partial t} < 0$; $\frac{\partial E^{M*}}{\partial t} < 0$; $\frac{\partial CS^{M*}}{\partial t} < 0$

ii) $\frac{\partial k_1^{M*}}{\partial \beta} > 0$; $\frac{\partial k_2^{M*}}{\partial \beta} > 0$; $\frac{\partial p^{M*}}{\partial \beta} > 0$; $\frac{\partial (Q-k_1-k_2)^{M*}}{\partial \beta} < 0$; $\frac{\partial E^{M*}}{\partial \beta} < 0$; $\frac{\partial CS^{M*}}{\partial \beta} < 0$

Similarly, the logic behind *Corollary* 3 is identical to that of *Corollary* 1 and *Corollary* 2. Therefore, we omit the details for brevity. The proof of *Corollary* 3 can be seen in Appendix A1.

5 Comparison analysis

This section focuses on the effects of emission reduction requirements under different policy scenarios on renewable energy investments, carbon emissions, profits, consumer surplus, and social welfare, using the electricity supplier model presented in Sect. 4. The assumptions and corollaries in this section are provided in Appendix to establish the theoretical foundation.

Before discussing the effects, we first introduce the following assumptions:

Assumption 1

$$r_1 \geqslant \max\left\{\frac{2er_2t}{ar_2 - e\left(2+br_2\right)t}, \frac{2fr_2}{ar_2 - f\left(2+br_2\beta\right)}, \frac{2r_2\left(f+et\right)}{ar_2 - e\left(2+br_2\right)t - f\left(2+br_2\beta\right)}\right\}$$

Assumption 1 ensures that the production cost of renewable energy generation is sufficiently high at the current stage. Thus, the generation from conventional energy should never be less than 0. This assumption aligns with the data provided in Sect. 6.

5.1 Renewable energy investment

This section examines the impact of emission reduction policies on the level of renewable energy investment. We assume that the coefficient of the promotional effort satisfies $\tilde{t}_1 = \frac{f(2+b(c-c\beta))}{2e}$ for model feasibility (see Appendix A2).

Proposition 1 The comparative results regarding renewable energy investment under the four scenarios are given as follows:

(i) $k_1^{N*} < k_1^{R*} \leqslant k_1^{T*} < k_1^{M*}$ and $k_2^{N*} < k_2^{R*} \leqslant k_2^{T*} < k_2^{M*}$ if and only if $t \geqslant \tilde{t}_1$;
(ii) $k_1^{N*} < k_1^{T*} < k_1^{R*} < k_1^{M*}$ and $k_2^{N*} < k_2^{T*} < k_2^{R*} < k_2^{M*}$ if and only if $t < \tilde{t}_1$.

Proposition 1 shows that electricity supplier's investment in two types of renewable energy remains consistent across four policy scenarios. First, policies involving a carbon tax (TAX), renewable portfolio standards (RPS), or a combination (MIX) more effectively promote photovoltaic energy generation compared to no policy (NOP), highlighting the critical role of government intervention. TAX policies primarily aim to reduce emissions. When the carbon tax is low, suppliers may prefer paying the tax rather than incurring high renewable generation costs, leading to lower renewable investment. In this case, TAX is less effective than RPS and MIX. RPS, in contrast, mandates a fixed share of renewable generation. When the carbon tax is high, reducing non-renewable output alone cannot satisfy demand, forcing suppliers to invest in renewables. Under these conditions, TAX becomes more effective than RPS. MIX integrates the strengths of both approaches, simultaneously lowering carbon intensity and securing renewable quotas, making it consistently the most effective strategy across tax levels. Thus, MIX yields the best outcomes for renewable promotion, while NOP performs worst. Moreover, RPS outperforms TAX when the carbon tax is low, whereas TAX exceeds RPS when the tax is high. Proposition 1 therefore identifies MIX as the optimal mechanism for accelerating the transition toward renewable energy. Coordinated implementation of carbon taxes and renewable quotas is essential to reshape the energy structure and advance decarbonization.

The proof of Proposition 1 can be seen in Appendix A2.

5.2 Carbon emissions

This section analyzes the impact of different policies on total carbon emissions. Let us assume $\tilde{t}_2 = \frac{f(2(r_1+r_2)+br_1r_2\beta)}{e(2r_2+r_1(2+br_2))}$.

Proposition 2 The comparative results regarding carbon emissions under the four scenarios are given as follows:

(i) $E^{M*} < E^{T*} \leqslant E^{R*} < E^{N*}$ if and only if $t \geqslant \tilde{t}_2$;
(ii) $E^{M*} < E^{R*} < E^{T*} < E^{N*}$ if and only if $t < \tilde{t}_2$

Proposition 2 indicates that MIX effectively controls carbon emissions compared to any single policy scenario, while NOP has the least effective control. The MIX promotes renewable energy and aims to reducing carbon emissions. A higher carbon tax signifies that the

government imposes stricter penalties on carbon emissions, resulting in strict control over carbon emissions from electricity production and a reduction in the share of electricity generated by non-renewable energy. Therefore, MIX exhibits the lowest total emissions. Conversely, NOP has the highest total emissions due to the absence of carbon emission control measures. When carbon tax is high ($t \geqslant \tilde{t}_2$), regardless of the value of β, the carbon emissions under the carbon tax scenario are lower than those under the RPS. When carbon tax is low ($t < \tilde{t}_2$), TAX is considered to have a poorer reduction effect, while RPS is more effective than TAX. This is because a lower carbon tax implies less stringent control over carbon emissions, resulting in higher total carbon emissions under TAX. Nevertheless, RPS is primarily influenced by renewable energy allowances. Even with a lower carbon tax, RPS still aims to achieve the goal of generating a quantified amount of green electricity. As renewable energy generation has no carbon emissions, the total emissions under RPS are lower. Therefore, Proposition 2 suggests that carbon emissions can only be effectively controlled through rationalized carbon tax.

The proof of Proposition 2 can be seen in Appendix A2.

5.3 Consumer surplus

This section explores the effects of the four scenarios on consumer surplus.

Proposition 3 The comparative results regarding consumer surplus under the four scenarios are given as follows:

(i) $CS^{T*} < CS^{N*} < CS^{M*} < CS^{R*}$ if and only if $\beta < \tilde{\beta}_1$ and $t < \tilde{t}_3$;
(ii) $CS^{T*} < CS^{M*} < CS^{N*} < CS^{R*}$ if and only if $\beta < \tilde{\beta}_1$ and $t > \tilde{t}_3$;
(iii) $CS^{M*} < CS^{R*} < CS^{T*} < CS^{N*}$ if and only if $\beta > \tilde{\beta}_1$ and $t < \min\left(\tilde{t}_4, \tilde{t}_5\right)$;
(iv) $CS^{T*} < CS^{M*} < CS^{R*} < CS^{N*}$ if and only if $\beta > \tilde{\beta}_1$ and $t > \max\left(\tilde{t}_4, \tilde{t}_5\right)$;
(v) $CS^{M*} < CS^{T*} < CS^{R*} < CS^{N*}$ if and only if $\tilde{\beta}_1 < \beta < \tilde{\beta}_2$ and $\min\left(\tilde{t}_4, \tilde{t}_5\right) < t < \max\left(\tilde{t}_4, \tilde{t}_5\right)$.

Where, $\tilde{\beta}_1 = \frac{c(r_1+r_2)}{r_1r_2+c(r_1+r_2)}$, $\tilde{\beta}_2 = \frac{2a}{bf} + \frac{c(r_1+r_2)}{r_1r_2+c(r_1+r_2)}$, $\tilde{t}_3 = \frac{f(c(r_1+r_2)(1-\beta)-r_1r_2\beta)}{er_1r_2}$, $\tilde{t}_4 = \frac{f(c(r_1+r_2)(1-\beta)+r_1r_2\beta)}{er_1r_2}$ and $\tilde{t}_5 = \frac{2a(r_1r_2+c(r_1+r_2))-bf(c(r_1+r_2)(\beta-1)+r_1r_2\beta)}{2ber_1r_2}$.

Proposition 3 reveals that the impact of RPS and carbon tax (TAX) policies on consumer surplus depends critically on the renewable quota and carbon tax levels. Specifically, when $\beta > \widetilde{\beta}_1$, if the carbon tax is less than $\max\left(\widetilde{t}_4, \widetilde{t}_5\right)$, the no-policy (NOP) scenario yields the highest consumer surplus, while MIX produces the lowest. In intermediate ranges ($\min\left(\widetilde{t}_4, \widetilde{t}_5\right) < t < \max\left(\widetilde{t}_4, \widetilde{t}_5\right)$), consumer surplus under TAX exceeds that under RPS, as suppliers reduce output and raise prices, decreasing overall costs. When the carbon tax is lower ($t < \min\left(\widetilde{t}_4, \widetilde{t}_5\right)$), RPS leads to greater consumer surplus, driven by the green certificate system, which boosts renewable investments without substantially increasing electricity prices. When $\beta > \widetilde{\beta}_1$, if the carbon tax is high ($t > \max\left(\widetilde{t}_4, \widetilde{t}_5\right)$), the consumer surplus is lowest under TAX. This is because, under low carbon tax conditions,

the impact on electricity prices is minimal, and renewable energy investments are one-time, resulting in higher consumer surplus under TAX compared to RPS. Additionally, when $\beta < \widetilde{\beta}_1$, RPS consistently yields the highest consumer surplus, while TAX produces the lowest. When $t < \widetilde{t}_3$, MIX results in greater consumer surplus. Conversely, when $t > \widetilde{t}_3$, NOP prevails. Importantly, while renewable quotas stimulate low-carbon transitions, excessively high quotas can suppress consumer surplus, highlighting the need for careful policy design to balance environmental goals and consumer welfare.

The proof of Proposition 3 can be found in Appendix A2.

5.4 Social welfare

As regulators of the electricity supplier, government exerts significant influence on production and investment decisions (Barazza & Strachan, 2020). In evaluating the effectiveness of policy interventions, social welfare represents an appropriate criterion (Rustico & Dimitrov, 2022). This metric considers the interests of the three key stakeholders, namely the government, electricity supplier, and consumers, as well as the negative environmental externalities arising from electricity generation (Li et al., 2023). The specific formula is Eq. (3). Due to the complexity of parameter expression, we introduced case data to effectively compare the social welfare of the four scenarios, as shown in Sect. 6.

6 Simulation and discussion

This section conducts numerical analysis to compare the effects of different policy scenarios on renewable energy investment, carbon emissions, electricity supplier profits, consumer surplus, and social welfare. The simulations are grounded in the Chinese electricity market, selected as a representative case given its rich data availability and global relevance. In China, power generation accounts for a substantial share of coal use, driving more than 40% of national CO_2 emissions, primarily from coal-fired plants (Yan et al., 2019; Yuan et al., 2018). To mitigate this challenge, the Renewable Portfolio Standard (RPS) was officially implemented in 2019, accelerating the transition toward low-carbon energy and advancing the "carbon neutrality" agenda. The set of carbon tax refers to Fu et al. (2022) and Meng and Yu (2023). Additionally, our approach has been informed by the implementation standards observed in various other nations for the establishment of carbon tax brackets.

6.1 Numerical analysis

While analytical results highlight the underlying mechanisms, numerical simulations are necessary to quantify the impacts of carbon tax and renewable portfolio standards (RPS) policies. To this end, baseline parameter values are calibrated from official statistics and prior studies, ensuring both empirical plausibility and internal consistency with the model. For instance, the electricity demand elasticity in 2021 is reported as 1.27, with Shandong Province recording total consumption of 7,383 GWh (NBS, 2021). Data from the National Green Power Certificate Subscription Trading Platform provide the renewable certificate price (f=0.33 yuan/kWh). Other key parameters include renewable generation cost (r=0.65 yuan/kWh), conventional generation cost (c=0.40 yuan/kWh), and unit carbon emissions

(e=0.96 kg/kWh), based on industry data and empirical studies (Li et al., 2023; Qi et al., 2023 and Yan et al., 2022).

To capture policy heterogeneity across regions, both the renewable quotas (β) and carbon tax (t) are varied systematically across low, medium, and high standards. This design allows us to compare policy effects under alternative regulatory intensities, thereby enhancing the robustness of the analysis. For computational convenience, all variables are normalized without altering their structural relationships or economic interpretation. This approach ensures numerical stability while preserving the validity of comparative results.

6.2 Sensitivity analysis

As demonstrated in Sect. 5, renewable energy investment, carbon emissions, supplier profits, consumer surplus, and social welfare are jointly influenced by the renewable quota (β) and carbon tax (t). To evaluate the robustness of simulation results, sensitivity analyses are conducted by varying these two parameters independently. The ecological impact of fossil-based generation is represented by the externality coefficient d, where $0 < d < 1$. Following Yan et al. (2022), we set d=0.1 and simulate the effects of alternative carbon tax and quota levels on equilibrium outcomes across four policy scenarios.

To capture the responsiveness of results to renewable targets, three quota levels are adopted based on prior research (Yan et al., 2022; Young & Bistline, 2018). Specifically, β=15% represents a low standard, β=25% a medium standard, and β=45% a high standard. Similarly, to examine the role of carbon taxation, three levels are designed with reference to global practices reported in the World Bank's Carbon Pricing Dashboard. Many countries, such as Japan, Estonia, Mexico, Singapore, and Baja California, impose relatively low taxes not exceeding 8.32 USD/ton, while Denmark and Iceland fall into a mid-range bracket with 28.14 and 34.83 USD/ton, respectively. In contrast, Nordic countries including Norway, Sweden, and Finland have introduced substantially higher levels, with rates up to 129 USD/ton. For alignment with the unit conventions of this study, these benchmarks are converted into three representative cases: a low tax of 0.05 yuan/kg, a standard tax of 0.3 yuan/kg, and a high tax of 0.6 yuan/kg. This design enables systematic assessment of how incremental adjustments in β and t shape investment incentives, emissions reduction, and welfare outcomes, thereby highlighting the resilience of equilibrium results under varying policy intensities.

6.2.1 Impact of carbon tax t

This section examines the effects of changes in the carbon tax on renewable energy investment, carbon emissions, consumer surplus, and social welfare.

Figure 3(a1–a3) show that investment increases as carbon taxes rise in both MIX and TAX scenarios, regardless of quota intensity. However, lower quotas consistently yield higher investment, indicating that stringent quotas constrain the generation capacity of thermal power firms and reduce their ability to expand renewables. These results align with Ozkan et al. (2024), who found that uncertainties in carbon pricing and related climate policies strongly shape the dynamics of clean and sustainable energy markets.

Figure 4(b1)–4(b3) demonstrates that higher carbon taxes effectively reduce emissions across all scenarios, and the MIX policy consistently outperforms RPS, TAX, and NOP. Our calculated threshold tax rate t_2 in Sect. 5.2 falls within the range of effective carbon prices

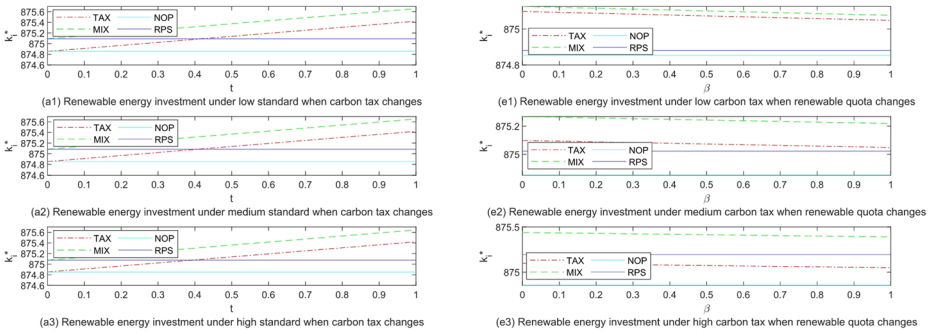

Fig. 3 Renewable energy investments under NOP, TAX, RPS and MIX

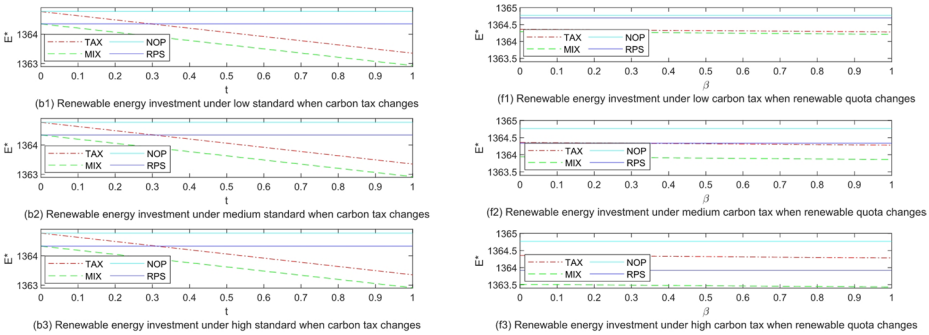

Fig. 4 Carbon emissions under NOP, TAX, RPS and MIX

observed in jurisdictions with successful decarbonization, such as the Nordic countries (Andersson, 2019; World Bank, 2022). This empirical consistency enhances the practical value and policy relevance of the derived thresholds.

The impact of carbon tax on consumer surplus is reflected in the slope of the curves in Fig. 5(c1)-(c3). Steeper slopes in TAX and MIX indicate a sharper decline in surplus as the tax rises. At low quota levels, TAX yields a higher consumer surplus than MIX; as quotas increase, their values converge, and beyond a threshold, MIX surpasses TAX. These

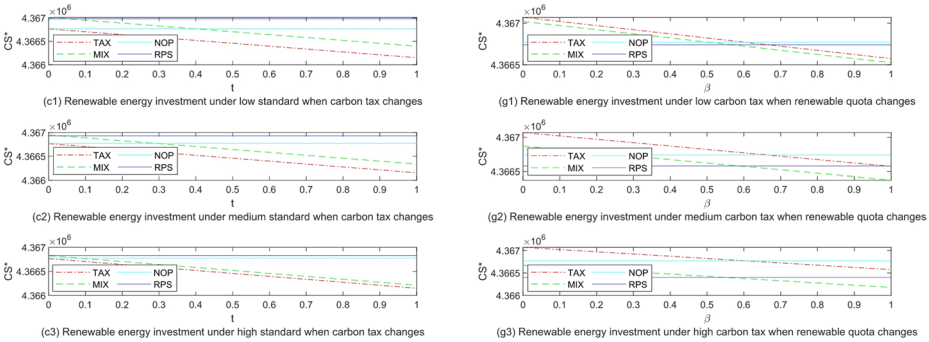

Fig. 5 Consumer surplus under NOP, TAX, RPS and MIX

results suggest that early-stage policies should prioritize raising renewable energy quotas to cushion market demand, while carbon taxes can be gradually intensified in later phases of regulation.

Figure 6(d1)−6(d3) illustrate the variation in social welfare with carbon tax (t) across different policy scenarios and quota levels. Under low quotas (β =15%), the MIX scenario yields higher social welfare than the TAX scenario, as the electricity supplier benefits from participating in the green certificate market rather than relying solely on carbon pricing. This is consistent with previous findings that renewable energy investment enhances environmental outcomes (Adebayo et al., 2023b). As quotas rise to a medium level (β =25%), the profitability from green certificates diminishes, narrowing the welfare gap between MIX and TAX. At high quotas (β =45%), constraints on green certificate sales and reduced consumer surplus cause MIX's social welfare to fall below that of TAX. These results highlight the importance of calibrating quotas to balance market incentives and welfare, reinforcing that tailored policy design is essential for advancing sustainability goals.

6.2.2 Impact of quota β

We analyze how the renewable energy quota (β) shapes renewable investment, emissions, consumer surplus, and social welfare. As shown in Fig. 3(e1–e3), higher β systematically increases renewable investment under both RPS and MIX, with the effect more pronounced under RPS. This indicates that RPS provides stronger and more direct incentives for green investment. By contrast, higher carbon taxes tend to suppress investment, as the additional production costs deter suppliers. Overall, β is an effective driver of renewable expansion, while the performance of carbon taxation is highly sensitive to policy design and enforcement stringency.

Carbon emissions display a clear inverse relationship with β (Fig. 4(f1–f3). As the renewable share rises, emissions decline, consistent with the lower carbon intensity of renewables relative to conventional sources. This pattern reinforces findings by Andrew et al. (2024), underscoring the central role of renewables in reducing emissions. Across all tax levels, RPS consistently achieves lower emissions than NOP, while MIX yields intermediate outcomes. Although the combination of renewable and conventional energy can reduce emissions, purely renewable-based obligations deliver the most substantial reductions, with carbon taxes amplifying this trend when effectively implemented.

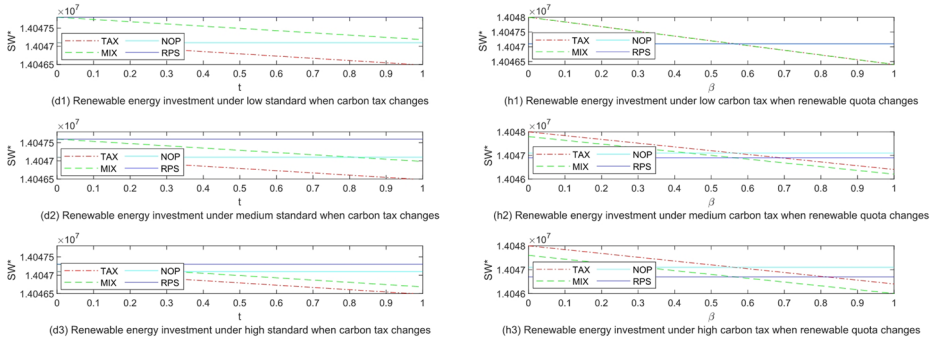

Fig. 6 Social welfare under NOP, TAX, RPS and MIX

The impact on consumer surplus is less favorable. As shown in Fig. 5(g1–g3), higher β reduces consumer surplus, primarily due to higher generation costs and retail electricity prices. Under low carbon taxation, TAX can initially generate a higher surplus than RPS and MIX at certain β levels. However, as t increases, the consumer surplus under TAX and MIX falls below that of RPS.

Social welfare outcomes are more complex (Fig. 6($h1$–$h3$)). Higher quotas increase the burden on suppliers, raising costs and electricity prices while reducing profits, which in turn depresses social welfare. At low tax levels (t=0.05), MIX achieves welfare comparable to RPS. Yet under medium (t=0.3) and high (t=0.6) taxation, MIX underperforms due to escalating fines and environmental penalties. Over time, persistently high costs and declining profits could weaken incentives for renewable investment under MIX, further reducing welfare relative to RPS.

A cross-sectional comparison of Fig. 6(d1)−6(d3) and Fig. 6(h1)−6(h3) shows that quota changes induce larger welfare shifts. This reflects the direct role of quota changes in shaping green certificate trading, which strongly affects firm profitability. Given the direct influence of supply and demand on certificate prices, firms should accelerate renewable investment to enhance competitiveness in the evolving green certificate market.

7 Extensions

7.1 Intermittency

In previous model analyzing electricity market policies, the assumption of stable output from renewable energy sources does not accurately reflect their intermittent nature in practice. Recent studies, such as the one conducted by Li et al. (2021), have demonstrated that the intermittency of renewables, along with the high emissions and operating costs associated with backup energy, can significantly impact investment decisions in distributed renewables. To account for this intermittency, we introduce the random variable μ as the intermittency factor of renewable energy sources. To maintain tractability in the model, we assume a two-point distribution for μ as follows:

$$\mu = \begin{cases} 1 & The\ probability\ of\ generating\ electricity\ is\ \theta \\ 0 & The\ probability\ of\ not\ generating\ electricity\ is\ 1-\theta \end{cases}$$

The probability when the renewable energy source generates electricity is θ and the probability when it does not generate electricity is $1-\theta$. It should be noted that the intermittency of renewable energy sources taken in this way has been widely used, e.g., Kök et al. (2018). The subscript θ signifies the analysis considering the intermittency of power generation.

In the no-policy scenario,

$$\pi^{\theta N} = p^{\theta N} Q^{\theta N} - \frac{1}{2} c \left(Q^{\theta N} - \mu k_1^{\theta N} - \mu k_2^{\theta N} \right) - \frac{1}{2} r_1 k_1^{\theta N 2} - \frac{1}{2} r_2 k_2^{\theta N 2} \tag{9}$$

In the carbon tax scenario,

$$\pi^{\theta T} = p^{\theta T} Q^{\theta T} - \frac{1}{2} c \left(Q^{\theta T} - \mu k_1^{\theta T} - \mu k_2^{\theta T}\right)^2 - \frac{1}{2} r_1 k_1^{\theta T 2} - \frac{1}{2} r_2 k_2^{\theta T 2} - te \left(Q^{\theta T} - \mu k_1^{\theta T} - \mu k_2^{\theta T}\right) \tag{10}$$

In the renewable portfolio standards scenario,

$$\pi^{\theta R} = p^{\theta R} Q^{\theta R} - \frac{1}{2} c \left(Q^{\theta R} - \mu k_1^{\theta R} - \mu k_2^{\theta R}\right)^2 - \frac{1}{2} r_1 k_1^{\theta R 2} - \frac{1}{2} r_2 k_2^{\theta R 2} + f \left(\mu k_1^{\theta R} + \mu k_2^{\theta R} - \beta Q^{\theta R}\right) \tag{11}$$

In the mixed policies scenario,

$$\pi^{\theta M} = p^{\theta M} Q^{\theta M} - \frac{1}{2} c \left(Q^{\theta M} - \mu k_1^{\theta M} - \mu k_2^{\theta M}\right)^2 - \frac{1}{2} r_1 k_1^{\theta M 2} - \frac{1}{2} r_2 k_2^{\theta M 2} - te \left(Q^{\theta M} - \mu k_1^{\theta M} - \mu k_2^{\theta M}\right) + f \left(\mu k_1^{\theta M} + \mu k_2^{\theta M} - \beta Q^{\theta M}\right) \tag{12}$$

According to the reverse induction method, the equilibrium hybrid renewable energy capacity investments and carbon emissions of conventional energy sources of the solvable model above, by comparing them, have the following conclusions, see Proposition 4 . Let's first assume $\tilde{t}_6 = \frac{f(2+b(c-c\beta))}{2e}$.

Proposition 4 When considering the intermittent nature of renewable energy, the results are:
i) The equilibrium $k_1^{\theta N*}$ and $k_2^{\theta N*}$ is maximum under MIX and minimum under NOP.
ii) if $t \geqslant t_6^{\%}$, then $k_1^{\theta R*} \leqslant k_1^{\theta T*}$ and $k_2^{\theta R*} \leqslant k_2^{\theta T*}$;
iii) if $t < t_6^{\%}$, then $k_1^{\theta R*} > k_1^{\theta T*}$ and $k_2^{\theta R*} > k_2^{\theta T*}$.

Proposition 4 provides insights into the comparison of hybrid renewable energy capacity investment levels among different policy scenarios, considering the intermittency of renewable energy sources. It confirms that intermittency affects the investment decisions of electricity supplier but does not alter the relative effectiveness ranking of each policy in promoting renewable energy. MIX is found to be the most effective, while NOP is the least effective. Moreover, a threshold $\tilde{t}_6$ determines whether TAX or RPS is more effective, depending on the carbon tax.

Please refer to Appendix A3 for the proof of Proposition 4.

7.2 Consumer preferences

Moving on to consumer preferences, it is recognized that consumer demand for electricity is influenced not only by price but also by preferences for renewable energy investment. Studies such as Du et al. (2015) and Niu et al. (2023) have identified the existence of consumer preferences that lead to changes in market demand and incentivize electricity supplier to invest in renewable energy. For simplicity, we adopt the demand function constructed by Ghosh et al. (2020) and Xu et al. (2016), which is expressed as:

$$Q = a - bp + \delta \left(k_1 + k_2\right) \tag{13}$$

This demand function is integrated into the model Eqs. (4), (6), (7), and (8) to calculate the equilibrium renewable energy investment under different policy scenarios. Proposition 5 is derived through comparisons, assuming a threshold $\tilde{t}_7 = \frac{f(2+bc(1-\beta)-\beta\delta)}{e(2-\delta)}$.

Proposition 5 When considering consumer preferences for renewable energy, the results are:

i) The equilibrium $k_1^{\delta N*}$ and $k_2^{\delta N*}$ is maximum under MIX and minimum under NOP;
ii) $k_1^{\delta R*} \leqslant k_1^{\delta T*}$ and $k_2^{\delta R*} \leqslant k_2^{\delta T*}$, if $t \geqslant \tilde{t}_7$;
iii) $k_1^{\delta R*} > k_1^{\delta T*}$ and $k_2^{\delta R*} > k_2^{\delta T*}$, if $t < \tilde{t}_7$;
iv) $\frac{\partial \tilde{t}_7}{\partial \delta} > 0$.

Proposition 5 provides insights when considering consumer preferences for renewable energy. i) indicates that the equilibrium investment in renewable energy, denoted as $k_1^{\delta*}$ and $k_2^{\delta*}$, is highest under MIX and lowest under NOP. ii) and iii) shows that when the carbon tax exceeds the threshold $\widetilde{t}_7$, the investment in renewable energy under TAX is higher than RPS. iv) indicates that the threshold $\widetilde{t}_7$ is positively related to consumers' preference for renewable energy.

Please refer to Appendix A3 for the proof of Proposition 5.

8 Conclusion and policy implications

The principal objective of the implementation of carbon tax and RPS is to facilitate the transition towards a low-carbon society. This study proposes an electricity supplier model that incorporates four distinct policy scenarios to evaluate the impact on hybrid renewable energy capacity investments, carbon emissions, consumer surplus, and social welfare. By comparing the equilibrium decisions of electricity supplier under each scenario, this study provides valuable insights for policymakers. The key findings can be summarized as follows:

(1) Both TAX and RPS are effective in promoting hybrid renewable energy investments. The amount of investment increases under TAX as the carbon tax rises, while the investment decreases under RPS with higher quota obligations. Nonetheless, both TAX and RPS lead to higher investments compared to NOP. Notably, MIX is found to be the most effective in promoting renewable energy investments.
(2) Both TAX and RPS effectively reduce carbon emissions. Specifically, as carbon tax or the quota obligation increases, carbon emissions decrease under both policies, although the investment is higher under both than under NOP. Additionally, when the carbon tax is high or the renewable energy quota is low, TAX is more effective than RPS in reducing emissions. Conversely, when the carbon tax is low, RPS is more effective than TAX. Furthermore, among the four scenarios considered, MIX is the most effective in promoting carbon emission reduction.
(3) The trends for consumer surplus and social welfare align closely. The social welfare of the MIX consistently has lower social welfare than RPS due to the environmental costs imposed on electricity supplier, leading to reduced profits and consumer surplus. Under low quota obligations, MIX has higher social welfare than TAX, but under high quota obligations, it exhibits lower social welfare than TAX. This is because higher quota obligations require more renewable energy investments, leading to lower profits and consumer surplus, ultimately impacting social welfare. To achieve higher social

welfare, electricity supplier needs to innovate in renewable energy production to reduce generation costs.

(4) The intermittency of renewable energy affects electricity supplier's investment decisions but does not alter the relative effectiveness of renewable energy policies. Additionally, consumer preference for renewable energy is directly proportional to the threshold value $\tilde{t}_7$.

Furthermore, this study provides meaningful policy implications for renewable energy investment and carbon mitigation strategies, while also acknowledging the practical feasibility of joint implementation. Although the analysis is rooted in the Chinese context, the insights derived hold broader applicability across different regulatory and market environments.

First, governments should efficiently coordinate and integrate carbon tax and RPS policies to promote renewable energy development and increase its consumption share. Flexibly adjusting carbon tax rates based on actual market conditions and setting renewable energy quota obligations can enhance policy effectiveness. Simultaneously, regulators should consider transaction and enforcement costs, such as compliance monitoring and renewable energy certificate management. Streamlining administrative procedures and reducing regulatory costs are crucial to ensuring the dual carbon policy framework remains effective. Similarly, the U.S. federal and state-level policy mix, the European Union, and India's renewable energy certificate schemes, can adopt flexible combinations of market-based instruments and command-and-control measures to enhance renewable energy penetration and reduce carbon intensity.

Second, incremental implementation of emission reduction policies is recommended to achieve carbon peaking and carbon neutrality targets. Policymakers can gradually increase quota obligations in the early stage of regulation to avoid sudden shocks to electricity demand, while progressively raising carbon taxes in later stages as the Tradable Green Certificate (TGC) market matures and renewable energy technologies become more cost-competitive. This staged approach distributes compliance and enforcement costs over time, minimizes market disruptions, and improves the long-term sustainability of policy measures. Such a gradual pathway ensures that a mixed policy approach is both theoretically sound and practically attainable within evolving regulatory contexts.

Finally, considering the intermittency of renewable energy and the evolving low-carbon preferences of consumers, the government should incentivize electricity suppliers by promoting green electricity and raising consumer environmental awareness through targeted campaigns. To mitigate output fluctuations, regulators are also encouraged to support the deployment of energy storage systems, demand response programs, and smart-grid technologies that smooth renewable variability and enhance grid stability. When consumers demonstrate stronger demand for low-carbon electricity, suppliers are more likely to invest in renewable energy. To maximize the efficiency of these initiatives, policy designs should integrate both behavioral incentives and administrative efficiency, ensuring that enforcement costs remain proportionate to the expected environmental and social benefits.

While this study offers important insights, several limitations point to avenues for further work. Incorporating learning-by-doing, which reduces renewable costs over time (Elia et al., 2021), and differentiating among energy sources, such as natural gas versus coal, would improve realism. Relaxing the assumption of uniform pricing between renewable and con-

ventional power could also yield richer equilibrium dynamics. Endogenizing carbon policy through a Stackelberg game framework may also allow the optimal design of carbon taxes and quotas under social welfare objectives. Beyond model refinements, future research should assess the robustness of equilibrium outcomes under stochastic demand and renewable intermittency, explicitly accounting for random shocks and heterogeneous consumer preferences. In particular, the intermittency parameter could be further developed to incorporate storage technologies, grid integration constraints, and forecast uncertainty, which jointly determine the reliability and cost-effectiveness of renewable deployment. Finally, embedding these technical, behavioral, and policy complexities into a unified analytical framework would offer a more comprehensive assessment of how carbon regulation adapts to real-world system constraints, providing deeper insights into the long-term effectiveness and resilience of climate policies.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10668-025-07203-2.

Funding Open access funding provided by Aalborg University

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