Carbon Emissions Trading and Firms' Environmental Performance: Evidence from China's Pilot Carbon Markets

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Abstract. China operates the world's largest carbon emissions trading scheme (ETS), while whether this market-based tool improves firms' environmental performance needs more focuses. We use the staggered difference-in-differences design on 50,776 firm-year observations of A-share listed firms from 2008 to 2024. We find that ETS coverage raises firms' environmental performance scores by 0.536 points, a rising equal to roughly one quarter of the sample mean. The result is robust to PSM-DID matching, placebo testing with 500 random assignments, lagged outcomes, an alternative performance measure, and panel Tobit estimation. The mechanism analysis shows that green technology innovation transmits the effect, and its substantive component, green invention patents, contributes substantially more than its strategic component, green utility models. We further find that executive compensation positively moderates the policy effect, whereas female executive representation moderates it negatively. This effect is more concentrated in high-regulation regions, large firms, and financially constrained firms. Carbon emissions trading scheme thus appears to work through genuine technology change, with benefits that hinge on regulatory complementarity, firm capability, and internal governance.

Keywords: Carbon emissions trading, Firm's environmental performance, Green innovation, Staggered DID, Executive characteristics.

1 Introduction

China emitted roughly 12.6 billion tons of CO_2 in 2024, about one-third of the global total, and operates the world's largest carbon emissions trading scheme (ETS). Starting with 7 regional pilots in 2013–2014 and expanding to a national market in 2021, the scheme caps total emissions and allows regulated firms to trade emission permits. The policy's environmental objective, reducing emissions and improving firms' environmental management, has received less direct empirical scrutiny than its economic consequences.

Most prior work tests financial performance, market valuation, or productivity outcomes [1]. Studies that do address environmental outcomes typically rely on macro-level carbon emissions rather than micro-level firm performance [2]. Yet the Porter

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Hypothesis predicts regulation can improve both environmental and economic outcomes when properly designed [3]. This paper provides direct firm-level evidence on the environmental channel.

This paper makes 3 contributions. First, environmental performance is measured through a granular nine-dimension scoring system, capturing concrete organizational actions rather than aggregate emissions. Second, an integrated mediation framework links ETS exposure → green innovation → environmental performance, decomposing innovation into substantive green invention patents and strategic green utility models [4]. Third, we identify how executive team composition and incentives moderate the translation of regulatory pressure into environmental action.

The staggered rollout of China's ETS pilots provides a natural experiment for identifying causal effects using a staggered DID design with firm and year fixed effects: Shenzhen, Shanghai, Beijing, Guangdong, and Tianjin launched in 2013; Hubei and Chongqing followed in 2014; Fujian in 2016, and a national market in 2021. Recent econometric work highlights the importance of diagnosing treatment effect heterogeneity in staggered adoption designs [5,6]. Event-study estimation of dynamic treatment effects addresses these concerns.

2 Theoretical Framework and Research Hypotheses

The ETS is grounded in Coasean logic [7]: tradable emission permits internalize externalities at minimum social cost. Firms with low abatement costs over-comply and sell surplus permits; high-cost firms buy permits or invest in cleaner technology. Both pathways push toward improved environmental management.

The Porter Hypothesis posits that market-based regulation induces innovation that offsets compliance costs [3]. Carbon pricing creates dual incentives for green innovation: cost-push, whereby rising carbon costs make high-emission production expensive, and demand-pull, whereby selling surplus permits generates revenue. Following Li and Zheng [4], we distinguish substantive innovation, which involves fundamental technology change with large abatement potential, from strategic innovation, which is more compliance-oriented. Substantive innovation is measured by green invention patents (EGI) and strategic innovation by green utility model patents (SGI). If ETS operates through genuine technology change, the substantive channel should dominate.

The Upper Echelons Theory has predicted executive characteristics condition responses to external pressure [8]. Female executives generally exhibit stronger environmental sensitivity [9]. This predicts a positive moderation, but only if female executives possess sufficient authority to direct capital toward large and long-payback green investments. At roughly 17% average representation in China's executive teams, their influence over such investments may be structurally limited [10]. Green investments incur immediate costs while returns accrue over years. Higher executive compensation, particularly equity-based components with longer vesting, can buffer the associated career risk and align incentives with long-term environmental performance [11]. Accordingly, we propose following hypotheses.

H1: ETS improves firms' environmental performance.

H2: Green innovation mediates the ETS–performance link; substantive innovation is the dominant channel.

H3a: Female executive representation negatively moderates the ETS effect.

H3b: Executive compensation positively moderates the ETS effect.

3 Research Design

3.1 Sample and Variables

Following Liu and Zhang [12], treated firms are those in 8 high-emission industries within ETS pilot regions: petrochemicals, chemicals, construction materials, iron and steel, non-ferrous metals, papermaking, power, and aviation. The sample covers Shanghai and Shenzhen A-share listed firms, 2008–2024, excluding financial firms and ST/*ST firms. All continuous variables are winsorized at 1% and 99%, yielding 50,776 firm-year observations. Financial, governance, and environmental data comes from CSMAR database, and green patent data is from CNRDS database.

Environmental performance (EP) is a cumulative 0–9 score covering 9 dimensions: environmental philosophy, objectives, management systems, training, protection actions, emergency response, the "three simultaneities" rule, environmental honors, and ISO 14001 certification [13]. The sample mean is 2.03 3(SD= 2.29), indicating substantial cross-firm variation in environmental management practices. EP2, an alternative measure used in robustness, captures actual pollution-control outcomes across 6 dimensions (waste gas reduction, wastewater reduction, dust treatment, solid waste utilization and disposal, noise and light pollution control, and cleaner production), each scored 0 (undisclosed), 1 (qualitative disclosure), or 2 (quantitative disclosure).

The key regressor is $DID_{it}=Treat_{it}\times Post_{it}$, where Treat equals 1 for firms in covered industries within pilot regions and Post equals 1 from the year the firm's region launched its carbon market. Green innovation is ln (green patent applications+1), decomposed into total (GI), substantive (EGI, mean=0.52), and strategic (SGI, mean =0.49). Moderators are female executive ratio (FemaleM) and log total executive compensation (Salary, mean=14.98). Control variables include firm size, leverage, cash flow, fixed asset intensity, board size, independent director ratio, ownership concentration, and listing age.

3.2 Model

The baseline staggered DID specification is as follows:

$$EP_{it} = \alpha + \beta DID_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where μ_i and $\lambda_t$are firm and year fixed effects; standard errors are clustered at the firm level. Mediation follows the three-step method [14] with Bootstrap inference (500 replications):

$$M_{it} = \alpha_1 + \beta_1 DID_{it} + \gamma_1 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

$$EP_{it} = \alpha_2 + \beta_2 DID_{it} + \theta M_{it} + \gamma_2 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

Moderation uses DID×Moderator interaction terms. Heterogeneity splits the sample at the median of each dimension; between-group differences are tested via Fisher's permutation test (500 replications).

4 Empirical Results

4.1 Baseline and Robustness

Table 1 reports stepwise estimation of the baseline specification. Column (1) presents the raw association between ETS exposure and environmental performance without controls or fixed effects; its coefficient of 1.414 is likely confounded by time-invariant firm heterogeneity and common time shocks. Column (2) introduces firm and year fixed effects, absorbing unobserved firm characteristics and aggregate trends, and the estimate falls to 0.562. Column (3) instead adds the full set of controls without fixed effects, yielding 0.730. Column (4) is the preferred specification, combining full controls with two-way fixed effects, and yields DID=0.536. H1 is supported.

Table 1. Baseline DID estimates

	(1)	(2)	(3)	(4)
DID	1.414***	0.562***	0.730***	0.536***
	(9.956)	(4.385)	(5.636)	(4.192)
Control variables	No	No	Yes	Yes
Firm FE	No	Yes	No	Yes
Year FE	No	Yes	No	Yes
N	50,776	50,686	50,776	50,686
Adj. R^2	0.014	0.635	0.202	0.644

Note: t-statistics (firm-clustered) are in parentheses. ***p < 0.01.

6 robustness checks confirm this result. First, Fig.1 displays event-study estimates: pre-treatment coefficients are individually and jointly insignificant across 5 pre-periods, supporting the parallel trends assumption. Second, PSM-DID with nearest-neighbor matching on all controls yields DID=0.469 (t=3.09, p<0.01, N=5,580); post-matching, all covariates achieve standardized bias below 10%. Third, Figure 2 shows 500 random-treatment placebo estimates center near zero with the actual estimate lying far in the right tail of the null distribution. Fourth, lagging EP by 1 period yields DID=0.511 (t=3.69, p<0.01). Fifth, an alternative EP measure (EP2, 6 pollution-reduction dimensions) gives DID=0.321 (t=2.16, p<0.05). Sixth, panel Tobit estimation yields DID = 0.513 (t=6.26, p<0.01).

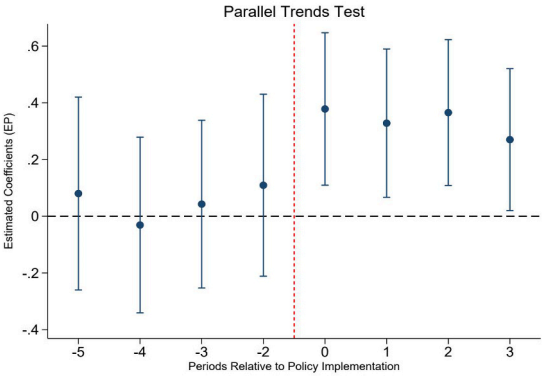


Fig. 1. Event-study estimates of the ETS effect on environmental performance

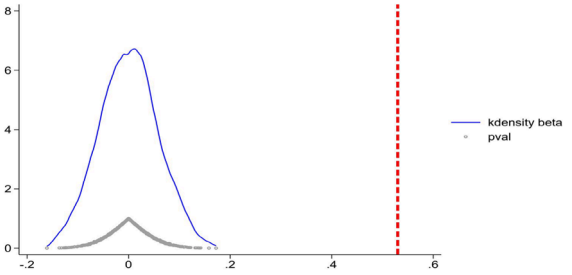


Fig. 2. Distribution of DID coefficients from 500 random-treatment placebo regressions

4.2 Mediation: The Green Innovation Channel

Table 2. Mediation analysis: green technology innovation

Dep. var.	(1) EP	(2) EGI	(3) EP	(4) SGI	(5) EP
DID	0.536***	0.222***	0.510***	0.230***	0.521***
	(4.19)	(3.31)	(3.99)	(3.57)	(4.06)
EGI			0.117***		
			(6.64)		
SGI					0.066***
					(3.94)
Bootstrap 95% CI			[0.016, 0.036]		[0.007, 0.023]

Note: All columns include full controls, firm FE, and year FE. t-statistics (firm-clustered) in parentheses. ***p < 0.01. Bootstrap: 500 replications, bias-corrected.

Table 2 reports the three-step mediation results. The ETS significantly increases both EGI and SGI. In step 3, EGI shows a substantially larger coefficient on EP (0.117, t= 6.64) than SGI (0.066, t=3.94). Including EGI as mediator reduces the direct DID coefficient from 0.536 to 0.510; the corresponding reduction through SGI is only to

0.521. Bootstrap 95% confidence intervals confirm both indirect effects exclude 0. The substantive innovation channel is considerably larger, indicating ETS improves environmental performance primarily by inducing genuine technology breakthroughs rather than compliance-motivated patent filings. H2 is supported.

4.3 Moderation Effects

Table 3 reports the moderation analysis. DID×FemaleM=−0.816: higher female executive representation attenuates the ETS effect. This does not imply weaker environmental preferences; the literature documents the opposite [9]. Rather, at minority representation levels, female executives face structural constraints on their authority to direct capital toward large, long-payback green investments [10]. DID×Salary= 0.237: higher compensation strengthens the ETS effect, consistent with compensation buffering executives' career risk and aligning incentives with long-term environmental performance [11]. H3a and H3b are supported.

Table 3. Moderation effects of executive team characteristics

	(1) Baseline	(2) Female Exec.	(3) Exec. Pay
DID	0.536***	0.645***	0.491***
	(4.19)	(4.63)	(4.01)
FemaleM		−0.181**	
		(−1.99)	
DID × FemaleM		−0.816**	
		(−2.00)	
Salary			0.067***
			(2.78)
DID × Salary			0.237**
			(2.37)
Controls, Firm FE, Year FE	Yes	Yes	Yes
N	50,686	50,686	50,686
Adj. R^2	0.644	0.645	0.645

Note: t-statistics (firm-clustered) are in parentheses. ***p < 0.01, **p < 0.05.

4.4 Heterogeneity Analysis

Table 4 reports heterogeneity across 3 dimensions, with between-group differences tested via Fisher's permutation test (500 replications). The ETS effect is larger in high-regulation regions, suggesting carbon markets and conventional regulation are complements. The effect concentrates in large firms and is absent in small firms, a "green divide" requiring targeted SME policy. Financially constrained firms respond more (0.806 vs. 0.369), likely because ETS coverage, by mandating verified emissions disclosure through the MRV system, improves access to green credit by making carbon compliance a credible signal of environmental commitment [15].

Table 4. Heterogeneity analysis

	Regulation intensity		Firm size		Financing constraints	
	High	Low	Large	Small	High	Low
DID	0.618***	0.459***	0.589***	0.184	0.806***	0.369*
	(3.31)	(2.89)	(3.71)	(0.70)	(4.64)	(1.83)
N	22,157	27,103	25,171	25,103	24,938	25,452
Adj. R^2	0.646	0.654	0.661	0.618	0.634	0.683
Fisher p	<0.05		<0.01		<0.05	

Note: All specifications include controls, firm FE, and year FE. t-statistics (firm-clustered) are in parentheses. ***p<0.01, *p<0.10. Fisher permutation tests: 500 replications. All splits at industry-year medians.

5 Conclusion

China's carbon ETS significantly improves firms' environmental performance. This result is robust across 6 validation strategies. Substantive green innovation, captured by invention patents representing genuine technology change, is the primary transmission channel. Executive compensation amplifies the policy effect; female representation attenuates it for structural rather than preference-based reasons. The effect is concentrated in high-regulation regions, large firms, and financially constrained firms.

4 policy implications emerge. First, the robust baseline result supports expanding the national ETS beyond the power generation sector. Second, green innovation subsidies should distinguish invention patents from utility models, targeting resources toward substantive technology breakthroughs rather than compliance-motivated patent filings. Third, integrating environmental metrics into executive compensation can strengthen firms' responsiveness; board diversity initiatives should prioritize ensuring female executives have genuine decision-making authority over green investment, not merely achieving headcount targets. Fourth, complementary measures such as public R&D platforms, green credit access, and regulatory capacity building are needed to close the compliance gap for small firms and those in low-regulation regions.

The following research limitations warrant mention. The EP measure captures disclosed practices rather than independently monitored emissions, future work should validate findings against direct measurements as China's MRV system matures. The moderation analysis identifies associations rather than causal effects; exogenous shocks to team composition or compensation structure could strengthen identification.

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Disclosure of Interests. The authors have no competing interests to declare.

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