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Directing environmental innovation toward radical clean technologies for sustainable transitions: Market-based vs. command-and-control policies

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Key Points

- Market-based environmental policies significantly boost firms' clean technology innovation and raise technological radicalness; command-and-control (C&C) regulation generates no meaningful impact on green patent output.
- Market instruments create sustained price signals and cross-economy market restructuring, shrinking dirty-tech market scale while expanding commercial space for radical clean breakthroughs.
- C&C policies only drive minimal end-of-pipe abatement upgrades instead of transformative innovation, constrained by fixed compliance thresholds and rigid technical mandates.
- Empirical DID evidence from France's carbon tax (market policy) and Germany's tightened TA Luft emission rules (C&C policy) confirms divergent innovation effects of the two regulatory modes.

photo from Gui Yata

Policy Focus

Global net-zero transition hinges on radical clean technology breakthrough rather than incremental end-of-pipe pollution abatement; existing environmental policy research mostly focuses on innovation quantity while ignoring innovation direction. Based on 17 EU manufacturing firms' long-run patent evidence, this paper empirically verifies the directional innovation effects of two core policy types to optimize decarbonization policy portfolios. Governments should prioritize market-based tools (carbon tax, cap-and-trade, ETS) as core decarbonization instruments to foster radical clean innovation,while positioning C&C rules as supplementary measures for mature clean-tech large-scale deployment; coordinated policy mixes are required to complete full socio-technical sustainability transition.

Study Methodology

The research constructs a 1991–2000 firm-level panel dataset combining five data sources: OECD environmental policy stringency index, PATSTAT European patent database, ORB firm financial data, SDC M&A dataset and World Bank macro statistics, covering 6,550 listed manufacturing firms across 17 EU economies (68,029 firm-year observations, 158,839 granted EPO patents).

Patent classification: Split environmental patents into two categories per OECD's environmental patent coding system: clean technologies (solar, EV, fuel cell, circular recycling) and abatement end-of-pipe tech (scrubber, engine efficiency retrofit); radicalness is measured via originality index (knowledge source diversity) and exploration index (new tech domain entry) weighted by seven-year forward patent citations.

Baseline regression: Adopt PPML (Poisson PML with high-dimensional fixed effects), control firm + year fixed effects, one-year lag for independent variables, two-way clustered bootstrap standard errors (country + parent firm, 1000 replications); separate regressions for total environmental, clean, abatement patents and two radicalness indicators.

Causal identification via DID: Two quasi-natural experiments:

1.Market policy shock: France's CCE carbon tax (announced 2012, implemented 2014, treatment=France, post≥2012);

2.C&C policy shock: Germany revised TA Luft stringent emission standard (approved 2001, enforced 2002, treatment=Germany, post≥2001).

Robustness: Alternate 5-year citation weighting, additional country/industry new-firm controls and R&D intensity controls to validate core results.

Findings and Analysis

Market Policies Boost Clean Innovation & Radicalness; C&C Has Zero Significant Patent Effects

Baseline regression shows one standard deviation rise in market-based policy index lifts firms' weighted clean patent count by 32.9% (+0.05 extra clean patents per average firm); market policies positively improve clean tech originality ($p<0.1$) and exploration index ($p<0.1$), meaning firms explore more cross-domain, breakthrough radical clean R&D. All C&C coefficients are small and statistically insignificant across clean/abatement/radicalness outcomes; stricter mandatory emission standards cannot stimulate patentable green innovation.

DID Causal Test Confirms Divergent

1. France CCE Carbon Tax (Market Reform): Post-2012 policy announcement, treated French firms see significant rise in clean patent volume and two radicalness metrics (treat×post all $p<0.01$), abatement innovation remains flat; pre-event parallel trend verified via event-study graph, ruling out pre-existing innovation gaps.

2. Germany TA Luft Strict C&C Upgrade: Post-2001 tighter regulatory reform, all interaction coefficients are negative yet statistically insignificant across all innovation indicators; event study confirms no post-policy surge in clean or abatement patenting.

Core Mechanisms for Policy Heterogeneity

1. Market-based policy dual incentive: Continuous carbon/pollutant price signals deliver permanent marginal reward for over-compliance; flexible compliance allows firms to delay low-value abatement spending and allocate capital into long-cycle radical clean R&D; economy-wide price shifts shrink incumbent polluting industries' market size while opening large emerging market space for zero-carbon clean tech, pushing incumbents to pursue disruptive innovation to avoid market shrinkage.

2. C&C policy inherent limitation: Fixed uniform emission ceiling only incentivizes firms to meet legal minimum standard with cheapest existing end-of-pipe equipment; no extra economic gain for beyond-standard innovation; rigid mandated tech paths narrow firms' R&D option set and discourage exploratory radical clean investment.

Table 1 Descriptive Statistics

	(1) environmental	(2) clean	(3) abate	(4) clean x originality	(5) clean x exploration
market	0.448**	0.350**	0.332	0.314*	0.231*
	(0.178)	(0.167)	(0.325)	(0.178)	(0.133)
C&C	-0.042	-0.018	-0.137	-0.026	-0.083
	(0.118)	(0.164)	(0.143)	(0.171)	0.030
Firm-level controls	Yes	Yes	Yes	Yes	Yes
Country-level controls	Yes	Yes	Yes	Yes	Yes
Firm fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Number of firms	691	594	308	587	517
Number of Observations	10,373	9,169	5,080	9,092	8,574
Chi-squared	18.079	22.927	18.913	22.375	11.328

Notes: All regressions are estimated by poisson pseudo-likelihood with firm and year fixed effects controlled, using Stata command *ppmlhdfe* (Correia et al., 2020). All right hand side variables are lagged by one year. On a country level, we control for environmental R&D support, GDP per capita , GDP growth rate, population size, urbanization rate, net foreign direct investment (FDI) as share of GDP and industrial value added as share of GDP. On a firm level, we control for total assets (ln), return on total assets and firm age (dummy indicating 1 when a firm is in the youngest 25th percentile of its respective industry). Standard errors are clustered by firm-headquarter and country and bootstrapped 1000 times, reported in parentheses. * $p<0.1$; ** $p<0.05$; *** $p<0.01$.

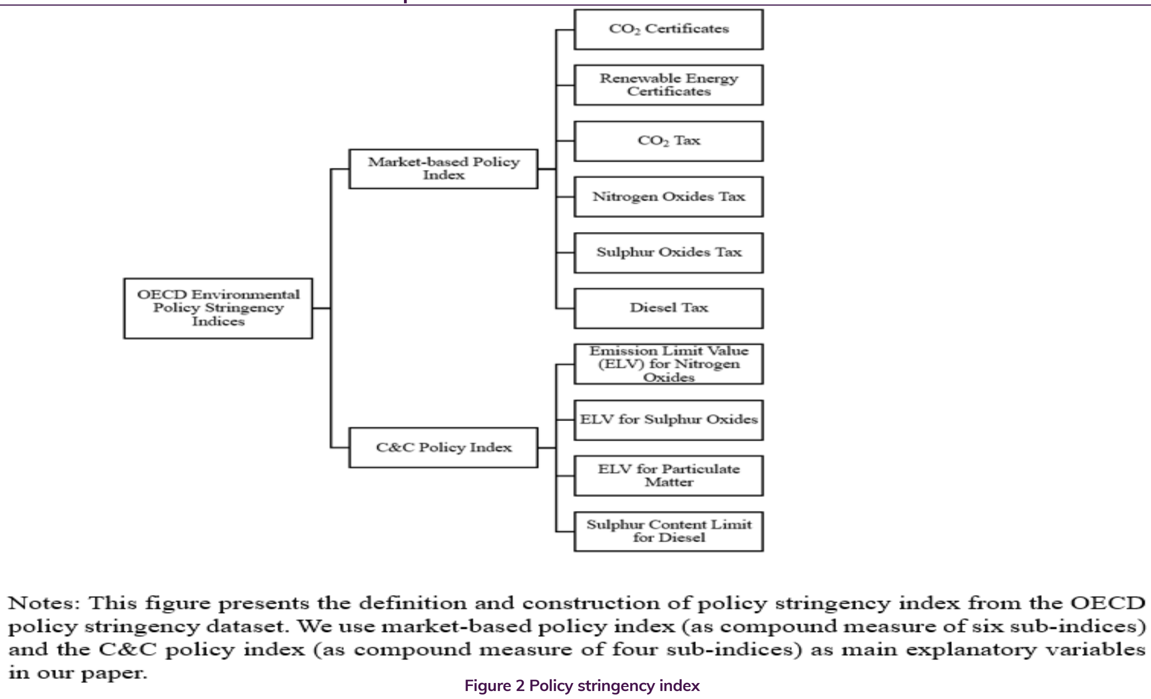

Figure 2 Policy stringency index

Policy OutcomesSupplementary Heterogeneity & Boundary

EU countries gradually converged to near-max C&C stringency by 2010, while market policy stringency stays universally low with large upgrade space; C&C may boost existing mature clean-tech deployment but fails to generate new patentable radical innovation; study sample only covers listed manufacturing firms, excluding small private enterprises and utility industries.

Recommendations

Prioritize Market Instruments as Core Decarbonization Policy

Design stepwise, predictable carbon tax or cap-and-trade systems to generate stable long-run price signals; gradually raise market policy stringency to reshape industrial market structure and drive radical clean R&D; reference France's progressive carbon pricing path to lock in future cost expectations for corporate long-term green investment planning.

Deploy C&C Rules as Complementary Supplementary Tools

Retain appropriate command-control emission standards to ensure mature clean technologies' large-scale market penetration after radical tech is invented; avoid over-reliance on rigid uniform regulatory mandates which lock firms into incremental end-of-pipe abatement rather than transformative clean innovation.

Build Multi-layer Complementary Policy Mix for Full Sustainability Transition

Pair market pricing mechanism with targeted public environmental R&D subsidies, green infrastructure investment and emerging clean-tech niche protection policies; market policy alone can spur radical clean invention but cannot complete full industrial transition; auxiliary policies help scale niche clean technologies to replace incumbent polluting socio-technical regimes.

Dynamic Policy Adjustment across Regions & Industries

For high-emission traditional manufacturing sectors, combine moderate carbon pricing with phased emission standards; for emerging clean sectors, lower regulatory threshold and leverage market demand to accelerate radical clean technology commercialization; tailor market policy tightening pace based on regional industrial foundation and cost-bearing capacity.

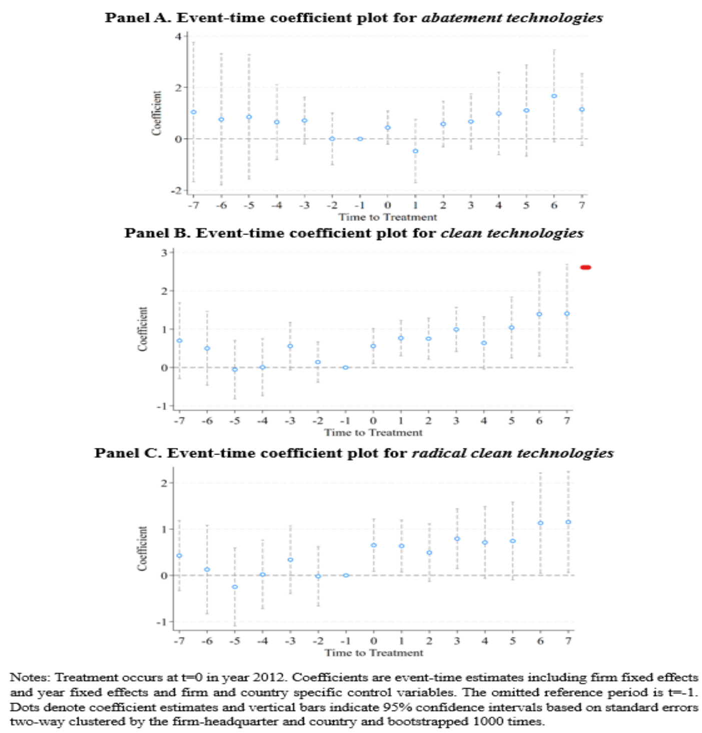

Figure 3 Additional Event-time coefficient plots for TA LUFT in Germany

Main Reference

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