

Designing Emissions Trading Systems in Emerging Economies: A Firm-Level Simulation Framework and Application to Thailand

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Firm Level Simulation Framework for Emissions Trading System Design in Emerging Economies with Application to Thailand

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Abstract

Emissions trading systems are increasingly considered in emerging economies, but their design must reconcile environmental credibility, administrative feasibility, industrial competitiveness, and firm-level transition risk. These trade-offs matter directly for sustainable development because industrial decarbonization influences progress toward climate action, responsible production, and resilient industrial transformation. This study develops a firm-level simulation framework for ex ante emissions trading system design and applies it to Thailand's industrial estates. The framework integrates threshold-based coverage, cap setting, free allocation, auctioning, limited domestic offsets, direct-abatement price formation, heterogeneous abatement costs, monitoring and reporting burdens, revenue recycling, and leakage-risk screening. The Thailand application uses industrial-estate coverage evidence together with transparent proxy assumptions for abatement costs, firm finances, offset availability, and administrative costs in order to compare alternative policy designs before mandatory implementation. The results suggest that partial coverage can capture a large share of emissions while limiting administrative burden, and that scenarios with moderate stringency, gradual auctioning, limited offsets, and targeted recycling produce a more balanced transition profile than either a very soft pilot design or an immediately stringent mature design. The paper therefore contributes a policy-calibration tool for regulators and market supervisors that can help align industrial decarbonization with SDG 13 Climate Action, SDG 9 Industry Innovation and Infrastructure, and SDG 12 Responsible Consumption and Production, while emphasizing that

the reported rankings are conditional simulation outputs rather than empirical estimates of realized emissions trading system effects.

Keywords: emissions trading system; carbon pricing; sustainable development; emerging economies.

1 Introduction

Carbon pricing has moved from a theoretical recommendation to a central component of climate-policy design. Direct carbon-pricing instruments now include emissions trading systems (ETSs), carbon taxes, and carbon-crediting mechanisms, and their use has expanded across national, regional, and subnational jurisdictions [14, 15]. Among these instruments, an ETS is distinctive because the regulator fixes an aggregate emissions quantity, issues tradable allowances, and requires regulated entities to surrender allowances equal to verified emissions. Under standard conditions, allowance trading equalizes marginal abatement costs across heterogeneous firms and can achieve a given emissions target at lower aggregate cost than uniform command-and-control regulation. In practice, however, that efficiency result is only a starting point. Environmental and economic outcomes depend on coverage, cap stringency, allowance allocation, offset eligibility, banking, price-stability rules, monitoring, reporting and verification (MRV), enforcement credibility, revenue recycling, and the treatment of competitiveness exposure. For sustainability policy, those design choices sit at the intersection of SDG 13 Climate Action, SDG 9 Industry Innovation and Infrastructure, and SDG 12 Responsible Consumption and Production because they shape how industrial decarbonization is financed, governed, and implemented.

The recent empirical literature has strengthened the case that carbon pricing can reduce emissions, while also showing that effectiveness is heterogeneous across designs and institutional contexts. A systematic review and meta-analysis of ex-post evaluations reports statistically significant emissions reductions for most evaluated carbon-pricing schemes, with corrected effect sizes commonly in the range of several percentage points [16]. Aggregate cross-country evidence similarly finds that higher carbon taxes and higher ETS permit prices are associated with lower carbon emissions [17]. The EU ETS provides the richest body of firm- and plant-level evidence. Studies find that the EU ETS reduced emissions despite initially low prices [18], improved emissions outcomes without clear evidence of large aggregate losses in economic performance [3], and induced regulated firms to reduce emissions intensity without detectable economic contraction [19]. At the same time, the literature on carbon leakage and competitiveness cautions that unilateral carbon pricing must be designed with trade exposure, cost pass-through, and allocation rules in mind [20]. In sustainable development terms, the relevant question is therefore not only whether carbon pricing reduces emissions, but whether it can do so in a way that preserves productive capacity, supports cleaner industrial upgrading, and produces operational guidance for real-world implementation.

These findings do not imply that an ETS is automatically successful once established. Rather, they imply that institutional design is decisive. Coverage rules determine whether the system captures the principal emissions sources or instead overwhelms the regulator with small installations whose reporting burden is disproportionate to their emissions contribution [1]. Cap trajectories determine scarcity and investment incentives. Free allocation can protect emissions-intensive and trade-exposed firms during transition, but poorly designed grandfathering can create windfall gains or weaken perceived fairness. Auctioning improves price discovery and generates public revenue, but it can also raise short-run compliance costs for firms with thin margins. Offsets and banking can moderate compliance-cost volatility, but excessive reliance on low-integrity credits may delay direct abatement. These trade-offs are particularly acute in emerging economies, where facility-level emissions data, verifier capacity, registry infrastructure, and enforcement systems may be less mature than in long-established ETS jurisdictions [9, 15].

The emerging-economy context has become increasingly important in global carbon-market development. Recent ETS expansion is no longer confined to Europe and North America. ICAP reports continuing momentum for emissions trading, especially among emerging economies, with systems under development or consideration in jurisdictions such as Brazil, India, Indonesia, Türkiye, and Vietnam [15]. China also provides a relevant benchmark because its national ETS has moved from a power-sector system toward broader industrial coverage, including cement, steel, and aluminium, with strong emphasis on data quality, phased implementation, and MRV improvement [2, 21]. These examples suggest that the policy question for emerging economies is not simply whether to adopt carbon pricing, but how to sequence coverage, reporting obligations, allocation, trading, offsets, and revenue use so that the system is environmentally credible and administratively feasible.

Thailand is a timely case for this design problem. Thailand’s NDC 3.0 sets an economy-wide absolute target to reduce net greenhouse-gas emissions to 152 million tCO₂e in 2035, corresponding to a 47% reduction from 2019 net emissions [12]. At the same time, Thailand is preparing a more formal carbon-pricing architecture. Recent policy materials describe a pathway involving carbon taxation, an ETS, a regulated carbon-credit market, and a carbon border adjustment mechanism, together with annual MRV obligations and a national greenhouse-gas data infrastructure [8, 13, 22]. This domestic agenda also interacts with external trade pressure. The EU Carbon Border Adjustment Mechanism (CBAM) moved from its transitional phase to its definitive regime in 2026, increasing the importance of reliable embedded-emissions accounting for exporters of carbon-intensive goods [23]. For an export-oriented manufacturing economy, ETS design is therefore not only an environmental-policy issue but also an industrial-competitiveness, disclosure, and transition-finance issue.

Industrial estates are a natural starting point for a Thai ETS because they are administratively identifiable, emissions are concentrated in large manufacturing facilities, and many firms are linked to domestic and international supply chains. The empirical basis for the present study is Raksakulkarn et al. [10], who assessed designated factories in 61 Thai industrial estates and showed that threshold-based partial

coverage can capture a large share of emissions with a relatively small number of regulated installations. That finding is important, but it is not yet a complete ETS-design model. Coverage evidence alone does not determine the cap trajectory, allowance allocation, auction share, offset limit, allowance price, firm-level compliance burden, revenue-recycling potential, or leakage-risk distribution.

This study addresses that gap by developing a firm-level ETS simulation framework and applying it to Thailand’s industrial estates. The aim is to evaluate how alternative ETS design choices can support a more practical industrial sustainability transition before mandatory implementation. Unlike ex-post evaluations of mature schemes, the framework is an ex-ante regulatory-impact and transition-risk tool: it does not claim to estimate observed causal treatment effects from a mandatory Thai ETS that has not yet been implemented. Instead, it evaluates how alternative design choices translate into emissions coverage, allowance scarcity, abatement incentives, offset use, administrative burden, auction revenue, firm affordability, and competitiveness exposure. The framework is designed for regulators, market supervisors, industrial-estate authorities, listed firms, and investors who need to evaluate carbon-policy exposure before full ETS implementation and who need policy evidence that is operational in a broader socio-technical sustainability system.

The study makes four contributions. First, it reframes the Thailand ETS problem as a transferable firm-level design framework for emerging economies with incomplete facility data and limited administrative capacity. Second, it integrates threshold-based coverage, dynamic caps, allowance allocation, auctioning, externally limited domestic offsets, heterogeneous abatement costs, MRV costs, and revenue recycling within a single simulation structure. The framework allows grandfathered or benchmark-based allocation; the Thailand demonstration implements a disclosed benchmark-style proxy rule that combines revenue proxies, sector benchmark intensities, and transitional protection weights because facility-level output and verified product benchmarks are not yet available in the public workspace. Third, it connects ETS design to firm-level financial exposure and leakage risk rather than treating compliance cost solely as allowance-purchase cost. Fourth, it links present policy calibration to future empirical evaluation by identifying the facility–firm data required for regression-discontinuity, difference-in-differences, or event-study designs once a mandatory Thai ETS is implemented.

The remainder of the paper proceeds as follows. Sections 2–5 develop the design problem, simulation structure, and analytical results. Section 6 uses a synthetic sectoral experiment as a numerical consistency check. Section 7 applies the framework to Thailand’s proposed ETS designation problem. Sections 8 and 9 discuss the policy implications and conclude.

2 ETS Design Problem and Core Policy Elements

An ETS is a regulatory market created by law. The regulator sets a cap on covered emissions, issues allowances, requires surrender against verified emissions, and permits trading. Its core design problem is to transform a national or sectoral emissions

objective into firm-level obligations without imposing unnecessary economic or administrative burden. Four objectives must be balanced: environmental integrity, economic efficiency, administrative feasibility, and competitiveness management.

Table 1 Core ETS design trade-offs

Design choice	Main benefit	Main risk if poorly designed
Coverage threshold and Cap stringency	Captures major emissions sources Creates scarcity and abatement incentives	Excessive MRV burden for small emitters High prices if firms lack adjustment time
Free allocation	Protects exposed firms during transition	Windfall gains and weak fairness if grandfathered
Auctioning	Reveals prices and generates revenue	Cost shock for trade-exposed sectors
Offsets and banking	Reduce short-run compliance cost	Weak direct abatement if quality rules are loose
Price stability	Improves planning and political durability	Weak cap credibility if reserves are ad hoc
Revenue recycling	Finances MRV and low-carbon investment	Limited effect if used as broad compensation

The regulator chooses a policy vector that determines coverage, scarcity, flexibility, and cost distribution. The main implemented parameters are the coverage boundary, entry threshold, cap trajectory, allowance-allocation rule, auction share, offset limit, and revenue-recycling rule. Banking and price-stability mechanisms remain relevant policy extensions, but they are not activated in the baseline empirical calibration used in this paper. Each parameter affects multiple policy objectives. A high threshold reduces MRV burden but excludes emissions; a low threshold raises coverage but may regulate many small emitters. Benchmark-based free allocation can protect efficient and exposed firms, but requires reliable output data. Auctioning improves price discovery and generates public revenue, but may create short-run cost shocks.

Firm heterogeneity is the reason for a firm-level approach. Firms differ in emissions intensity, fuel mix, technology, abatement opportunities, profit margins, trade exposure, and cost pass-through ability. The same allowance price can therefore make one firm an allowance seller and another a high-risk allowance buyer. Aggregate emissions data cannot identify these distributional effects. A firm-level model is needed to identify who is covered, who abates, who buys allowances, who sells allowances, which sectors need transitional protection, and where auction revenue should be recycled.

3 ETS Design Structure

Coverage defines which emissions sources face compliance obligations. For firm or installation i with baseline emissions E_{i0} and regulatory threshold τ , a simple rule is

$$D_i(\tau) = \begin{cases} 1, & E_{i0} \geq \tau, \\ 0, & E_{i0} < \tau. \end{cases} \quad (1)$$

The cap for period t is commonly written as

$$C_t = (1 - r_t)E_0^{cov}, \quad (2)$$

where E_0^{cov} is covered baseline emissions and r_t is the reduction rate. Allowance allocation then determines cost distribution but not the aggregate cap. Under benchmark-based allocation,

$$A_{it}^F = \theta_t b_s Y_{it}, \quad (3)$$

where θ_t is the free-allocation share, b_s is a sector benchmark, and Y_{it} is output.

Compliance requires verified emissions to be matched by surrendered allowances and eligible offsets:

$$S_{it} + O_{it} \geq E_{it}, \quad 0 \leq O_{it} \leq \omega E_{it}. \quad (4)$$

Offsets and banking lower compliance cost, but weak offset quality or excessive offset limits can delay direct abatement. In the implemented proxy design, the aggregate offset cap is benchmarked to covered baseline emissions and then assigned across installations in proportion to residual emissions after abatement; Section 4 states that operational rule explicitly. Price-stability rules, such as auction reserve prices or cost-containment reserves, can reduce volatility while preserving scarcity if they are transparent and rule-based. Auction revenue should be treated as part of ETS design because it can finance MRV capacity, energy audits, efficiency upgrades, electrification, renewable electricity, and other low-carbon investments.

Competitiveness protection should focus on emissions-intensive and trade-exposed sectors. If x_i^E is emissions-intensity exposure, x_i^T is trade exposure, and x_i^P is pass-through ability, a leakage-risk indicator can be represented as

$$L_i = f(x_i^E, x_i^T, 1 - x_i^P). \quad (5)$$

High-risk firms may receive temporary benchmark-based free allocation or targeted investment support, but permanent exemption would remove the emitters that the ETS is meant to influence.

4 Firm-Level ETS Simulation Framework

Let $i = 1, \dots, N$ index firms or installations, s sectors, c emissions-coverage definitions, and $t = 1, \dots, T$ compliance years. Each firm has baseline emissions E_{i0}^c , sector

Table 2 Core ETS design elements and policy interpretation

Element	Role in the ETS	Interpretation for an emerging economy
Coverage and scope	Selects regulated entities and emissions boundaries	Start where facility data and MRV capacity are strongest.
Entry threshold	Screens installations by base-line emissions	Balance emissions capture against fixed reporting burden.
Cap trajectory	Defines scarcity over time	Begin modestly, then tighten according to a published path.
Allocation	Distributes allowance value	Use benchmark-based free allocation for exposed sectors and increase auctioning gradually.
MRV and enforcement	Makes allowances credible	Build reporting, verification, registry, and penalties before full trading.
Offsets and optional stability tools	Provide flexibility and, where implemented, price stability	Allow limited high-integrity offsets; treat banking and corridor rules as explicit extensions rather than implicit assumptions.
Recycling and leakage protection	Manages distributional effects	Use auction revenue for abatement investment, not permanent compensation.

$s(i)$, output Y_{it} , revenue R_{it} , operating earnings M_{it} , and abatement options. In the implemented baseline calibration, the regulator chooses

$$\Theta = \{c, \tau, r_t, \alpha_t, b_s, \omega, \mu_t, \kappa_t\}, \quad (6)$$

where τ is the entry threshold, r_t cap stringency, α_t free-allocation share, b_s benchmark, ω the maximum offset-use ratio, μ_t the auction share, and κ_t the revenue-recycling share. Price collars and banking are treated as optional extensions and are not activated in the baseline results reported in this paper.

Baseline emissions are written flexibly as

$$E_{i0}^c = E_{i0}^{dir} + \chi_c E_{i0}^{elec} + E_{i0}^{oth,c}, \quad (7)$$

with $\chi_c = 1$ when electricity-related emissions are included and 0 otherwise. Coverage and covered emissions are

$$D_i^{c,\tau} = \mathbf{1}\{E_{i0}^c \geq \tau\}, \quad E_0^{cov,c,\tau} = \sum_{i=1}^N D_i^{c,\tau} E_{i0}^c. \quad (8)$$

The cap and allowance supply are

$$C_t = E_0^{cov,c,\tau}(1 - r_t), \quad C_t = A_t^F + A_t^Q, \quad A_t^Q = \mu_t C_t. \quad (9)$$

Free allocation may be grandfathered, $A_{it}^G = \alpha_t D_i E_{i0}^c$, or benchmarked, $A_{it}^B = \alpha_t D_i b_{s(i)} Y_{it}$, with a correction factor if the benchmark total exceeds the free-allocation budget. In the empirical implementation used here, the free-allocation rule is a disclosed benchmark-style proxy that maps revenue proxies into sector benchmark intensities and then rescales allocations to the free-allocation budget, because facility-level output and verified product benchmarks are not available in the public workspace.

The implemented simulation treats domestic offsets as an externally limited flexibility channel rather than as a jointly cleared second market. Let S_t^O denote the available annual offset supply and define aggregate eligible offsets as

$$\bar{O}_t = \min\{\omega E_0^{cov,c,\tau}, S_t^O, E_0^{cov,c,\tau} - C_t\}. \quad (10)$$

The remaining direct abatement requirement is therefore

$$Q_t^{ab} = \max\{E_0^{cov,c,\tau} - C_t - \bar{O}_t, 0\}. \quad (11)$$

Firm i chooses an abatement rate $q_{it} \in [0, \bar{q}_{is}]$. Emissions and abatement cost are

$$E_{it} = E_{i0}^c (1 - q_{it}), \quad C_{it}^{ab}(q_{it}) = \frac{1}{2} \lambda_{is} q_{it}^2 E_{i0}^c, \quad (12)$$

so $MC_{it}^{ab} = \lambda_{is} q_{it}$ and a price-taking firm uses

$$q_{it}^* = \min\left\{\frac{P_t}{\lambda_{is}}, \bar{q}_{is}\right\}. \quad (13)$$

The allowance price in the implemented model is the shadow price that equates aggregate direct abatement to the remaining direct-abatement target after exogenous offset use:

$$\sum_i D_i^{c,\tau} E_{i0}^c q_{it}^*(P_t) = Q_t^{ab}. \quad (14)$$

The net allowance position is

$$N_{it} = E_{it} - A_{it}^F - O_{it}, \quad (15)$$

where $N_{it} > 0$ denotes an allowance deficit and $N_{it} < 0$ denotes an allowance surplus. In the no-banking baseline, the net allowance-market cash flow is therefore

$$C_{it}^A = P_t N_{it}, \quad (16)$$

so allowance purchases enter as positive cost and allowance sales enter as negative cost. Total cost, administrative cost, and affordability ratios are

$$C_{it}^{tot} = C_{it}^A + C_{it}^{ab} + C_{it}^{adm} + C_{it}^{off} - S_{it}^g, \quad C_{it}^{adm} = w_{it} h_{it} + C_{it}^{ext} + F_{it}, \quad (17)$$

Table 3 Simulation modules and main outputs

Module	Main role	Key outputs
Coverage and threshold	Determines which firms enter the ETS under a selected emissions boundary and threshold.	Number of covered firms; covered emissions; coverage share.
Cap and allowance supply	Converts the baseline into a declining emissions cap and divides supply between free allocation and auctioning.	Annual cap; free allowances; auction volume.
Allocation	Distributes free allowances through grandfathering or benchmarking.	Firm-level allowance position; surplus or deficit.
Abatement and off-sets	Simulates firm responses to allowance prices and offset limits.	Emissions after abatement; offset use; abatement cost.
Market clearing	Solves for the allowance price consistent with the direct-abatement requirement after exogenous offset use.	Allowance price; direct abatement.
Cost and competitiveness	Computes compliance costs, affordability ratios, and leakage-risk indicators.	Cost-to-revenue; cost-to-profit; leakage-risk ranking.
Revenue and investment	Estimates auction revenue and lump-sum recycling under the selected scenario rule.	Government revenue; recycled support.

$$\xi_{it}^R = \frac{C_{it}^{tot}}{R_{it}}, \quad \xi_{it}^M = \frac{C_{it}^{tot}}{M_{it}}. \quad (18)$$

Auction revenue and recycling are

$$G_t = P_t A_t^Q, \quad G_t^R = \kappa_t G_t. \quad (19)$$

Net cost after pass-through and leakage risk are

$$C_{it}^{net} = C_{it}^{tot}(1 - \rho_s), \quad L_i = w_1 x_i^E + w_2 x_i^T - w_3 x_i^P. \quad (20)$$

A policy score is reported only after normalization:

$$\Omega_j = \sum_{k=1}^K \beta_k S_{jk}, \quad \sum_{k=1}^K \beta_k = 1, \quad S_{jk} \in [0, 1], \quad (21)$$

where j indexes scenarios, S_{jk} are normalized score components, and the β_k parameters encode policy priorities. The specific normalization and weights used in the empirical ranking exercise are reported with the case-study results.

The simulation sequence is: select Θ ; identify covered firms and compute the cap; determine the eligible aggregate offset quantity from the offset limit and external supply; allocate allowances; solve for the allowance price that supports the remaining direct-abatement requirement; compute firm-level and aggregate indicators; and rank designs by environmental, financial, administrative, fiscal, and competitiveness criteria.

5 Theoretical Analysis

The implemented framework has four basic theoretical properties. First, a common allowance price coordinates heterogeneous abatement. Second, conditional on an exogenously specified aggregate offset quantity, an allowance price exists when aggregate abatement supply is continuous and increasing in price. Third, free allocation changes private burden but not the marginal abatement rule under trading. Fourth, a competitive ETS is cost effective because interior firms equalize marginal abatement costs. The formal results below are therefore used as policy diagnostics for the implemented simulation rather than as a general theory of all possible ETS microstructures.

Let $\mathcal{S}$ be all sectors and $\mathcal{S}^H \subseteq \mathcal{S}$ the high-impact subset selected for early implementation. The covered set is

$$\mathcal{I}^E(\tau, \mathcal{S}^H) = \{i : E_{i0} \geq \tau, s(i) \in \mathcal{S}^H\}. \quad (22)$$

For a covered firm, verified emissions and convex abatement cost are

$$E_{it} = E_{i0}(1 - q_{it}), \quad C_{it}^{ab}(q_{it}) = \frac{1}{2}\lambda_i q_{it}^2 E_{i0}, \quad \lambda_i > 0. \quad (23)$$

Let $\bar{O}_{it}$ denote the firm's eligible offsets under an externally specified aggregate offset allocation rule. Conditional on $\bar{O}_{it}$, the firm solves

$$\min_{q_{it} \in [0, \bar{q}_i]} C_{it}^{ab}(q_{it}) + P_t [E_{i0}(1 - q_{it}) - A_{it}^F - \bar{O}_{it}]. \quad (24)$$

The first formal result translates the allowance price into a firm-level behavioral rule. It shows how a covered firm converts the carbon price signal into an optimal abatement rate when abatement costs are convex and technological limits are present.

Proposition 1 (Firm-level abatement rule) *The cost-minimizing abatement rate is*

$$q_{it}^* = \min \left\{ \max \left\{ \frac{P_t}{\lambda_i}, 0 \right\}, \bar{q}_i \right\}. \quad (25)$$

For an interior solution, $MC_{it}^{ab} = P_t$.

Proof The derivative of Eq. (24) with respect to q_{it} is $\lambda_i q_{it} E_{i0} - P_t E_{i0}$. Setting it to zero gives $q_{it} = P_t / \lambda_i$, and projection onto $[0, \bar{q}_i]$ gives Eq. (25). $\square$

Proposition 1 provides the microeconomic foundation of the simulation. Once the allowance price is known, the model can compute firm-level abatement, residual emissions, and compliance cost transparently. In the implemented empirical calibration, domestic offsets are not jointly chosen with abatement inside the firm problem; instead, the aggregate offset quantity is fixed ex ante by the offset limit and available credit supply. This means the allowance price is solved conditional on the remaining direct-abatement requirement.

Let aggregate direct abatement be

$$A_t(P_t) = \sum_i D_i E_{i0} q_{it}^*(P_t), \quad (26)$$

and let $Q_t^{ab} \geq 0$ be the direct-abatement target after exogenous offset use has been deducted from the required total emissions reduction. Equilibrium requires

$$A_t(P_t^*) = Q_t^{ab}. \quad (27)$$

After firm-level abatement supply is defined, the simulation must ensure that an allowance price can be found. The next proposition establishes the price existence result for the implemented direct-abatement clearing problem and explains why a numerical root-finding procedure such as bisection is economically meaningful.

Proposition 2 (Existence and uniqueness of the allowance price) *If $A_t(P)$ is continuous and weakly increasing, and there exist P^L, P^U with $A_t(P^L) \leq Q_t^{ab}$ and $A_t(P^U) \geq Q_t^{ab}$, then an equilibrium price $P_t^* \in [P^L, P^U]$ exists. It is unique if $A_t(P)$ is strictly increasing over the relevant interval.*

Proof Apply the intermediate value theorem to $Z_t(P) = A_t(P) - Q_t^{ab}$; strict monotonicity gives uniqueness. $\square$

Proposition 2 is important because the allowance price is the central endogenous object of the ETS simulation. In the implemented model it connects cap stringency, exogenous offset availability, and heterogeneous abatement opportunities to a single shadow price of direct abatement that can be compared across policy scenarios.

Cost effectiveness follows by comparing the ETS equilibrium with the planner's problem

$$\min_{a_{it}} \sum_i D_i C_{it}^{ab}(a_{it}) \quad \text{s.t.} \quad \sum_i D_i a_{it} \geq Q_t^{ab}, \quad Q_t^{ab} = \sum_i D_i E_{i0} - C_t - \bar{O}_t. \quad (28)$$

The market-clearing price alone does not prove that the ETS is economically attractive. The following proposition explains why trading is valuable: it shows that, under the standard competitive assumptions, decentralized allowance trading reproduces the least-cost allocation of abatement across heterogeneous firms.

Proposition 3 (Cost effectiveness) *If firms are price takers, allowances are tradable, and abatement costs are convex, the competitive ETS equilibrium is cost effective: all interior firms have equal marginal abatement costs equal to the allowance price, while boundary firms satisfy the corresponding Kuhn–Tucker inequalities at zero abatement or at $\bar{q}_i$.*

Proof Proposition 1 gives $MC_{it}^{ab} = P_t$ for each interior firm, with the projection onto $[0, \bar{q}_i]$ supplying the complementary slackness conditions at the boundaries. The planner’s first-order condition requires common marginal cost equal to the shadow value of the aggregate abatement constraint. Hence the ETS allocation satisfies the planner’s KKT conditions, with P_t as the shadow price on Q_t^{ab} . $\square$

Proposition 3 is the main welfare argument for using an ETS instead of a uniform abatement mandate. It explains why firm heterogeneity is not only a modelling complication but also the source of the gains from trading, because firms with lower marginal abatement costs undertake more abatement while high-cost firms can purchase allowances.

The two corollaries below translate the cost-effectiveness result into policy-relevant comparative statics. They identify which design levers change the scarcity signal and which levers mainly redistribute compliance burden across firms.

Corollary 1 (Cap stringency) *If aggregate allowance demand is decreasing in price, a lower cap weakly increases the equilibrium allowance price and aggregate abatement.*

Proof A lower cap reduces allowance supply; market clearing then requires a weakly higher price except on flat demand segments. $\square$

Corollary 1 is important because it identifies the cap trajectory as the primary scarcity instrument of the ETS. In the scenario analysis, tighter caps should therefore raise the allowance price and increase aggregate abatement unless price controls or flat demand segments bind.

Corollary 2 (Allocation neutrality under trading) *Under price-taking behavior, convex abatement costs, and tradable allowances, lump-sum free allocation changes net cost but not the firm’s marginal abatement rule.*

Proof In Eq. (24), A_{it}^F enters as $-P_t A_{it}^F$, which is independent of q_{it} . $\square$

Corollary 2 is important because it prevents a common policy misunderstanding. Free allocation can reduce private compliance cost and protect exposed firms, but under competitive trading it does not by itself determine the marginal incentive to abate; that incentive is governed by the allowance price.

For policy design, the regulator also needs comparative statics linking ETS parameters to administrative efficiency and firm risk. Let the fixed annual MRV and reporting cost per covered firm be $F > 0$, the number of covered firms be

$$N(\tau) = \sum_i \mathbf{1}\{E_{i0} \geq \tau, s(i) \in \mathcal{S}^H\}, \quad (29)$$

and total covered baseline emissions be

$$E^{cov}(\tau) = \sum_i \mathbf{1}\{E_{i0} \geq \tau, s(i) \in \mathcal{S}^H\} E_{i0}. \quad (30)$$

Define administrative targeting efficiency as emissions covered per regulated firm,

$$\eta(\tau) = \frac{E^{cov}(\tau)}{N(\tau)}. \quad (31)$$

The previous results focus on market behavior, but emerging-economy ETS design also requires administrative feasibility. The next proposition explains why threshold selection is a central design issue when MRV capacity is scarce and small emitters impose fixed reporting and verification costs.

Proposition 4 (Threshold targeting and administrative efficiency) *Suppose covered firms are ranked by baseline emissions and a higher threshold removes only the lowest-emitting currently covered firms. Then $\eta(\tau)$ is weakly increasing in τ . Hence, with a fixed per-firm MRV cost, administrative cost per covered ton is weakly decreasing as the threshold is raised.*

Proof Raising τ removes firms from the lower tail of the currently covered emissions distribution. Removing observations below the current average weakly raises the average of the remaining observations, so Eq. (31) weakly increases. Since total fixed administrative cost is $FN(\tau)$, cost per covered ton is $FN(\tau)/E^{cov}(\tau) = F/\eta(\tau)$, which therefore weakly decreases. $\square$

Proposition 4 is useful for policymakers because it formalizes the standard implementation trade-off: a higher threshold improves administrative efficiency but can reduce total emissions coverage, so the economically relevant choice is not “maximum coverage” alone, but the coverage gained per regulated installation and per unit of state enforcement capacity. This result motivates the threshold analysis in the empirical section because it gives a principled reason to compare emissions captured against reporting hours and administrative cost.

For firm-risk analysis, let total compliance cost after pass-through be

$$\tilde{C}_{it}^{net} = (1 - \rho_i) [P_t \max\{E_{it} - A_{it}^F - O_{it}, 0\} + C_{it}^{ab} + C_{it}^{adm}], \quad (32)$$

where $\rho_i \in [0, 1]$ is the firm's pass-through ability. Define exposure ratios

$$\xi_{it}^R = \frac{\tilde{C}_{it}^{net}}{R_{it}}, \quad \xi_{it}^M = \frac{\tilde{C}_{it}^{net}}{M_{it}}, \quad (33)$$

for revenue $R_{it} > 0$ and operating surplus $M_{it} > 0$.

The final proposition links ETS design to firm-level financial vulnerability. It explains how free allocation, pass-through ability, administrative cost, and uncovered emissions enter affordability indicators that are relevant for supervisors, investors, and listed-company transition-risk disclosure.

Proposition 5 (Firm-risk monotonicity) *Holding P_t , abatement technology, and output fixed, ξ_{it}^R and ξ_{it}^M are weakly decreasing in free allocation A_{it}^F and pass-through ability ρ_i , and weakly increasing in administrative cost C_{it}^{adm} and uncovered emissions $E_{it} - A_{it}^F - O_{it}$. For two firms with the same compliance bill, the lower-margin firm has the higher cost-to-profit exposure.*

Proof The bracketed term in Eq. (32) is affine in A_{it}^F , O_{it} , and C_{it}^{adm} over the relevant region and is multiplied by $(1 - \rho_i)$. Therefore higher free allocation or higher pass-through weakly lowers $\tilde{C}_{it}^{net}$, while higher administrative cost or larger uncovered emissions weakly raises it. Dividing by R_{it} or M_{it} preserves these monotonicities for positive denominators. If two firms have the same $\tilde{C}_{it}^{net}$, the one with smaller M_{it} has larger ξ_{it}^M . $\square$

Proposition 5 is directly relevant to economic supervision and listed-firm risk assessment. It implies that carbon-transition vulnerability should be screened using not only emissions intensity, but also free-allocation dependence, cost pass-through ability, and earnings capacity. In policy terms, emissions-intensive and trade-exposed sectors with thin margins are the most likely candidates for temporary benchmark-based protection, phased auctioning, or targeted recycling of auction revenue into abatement investment. The proposition therefore turns the ETS model from an emissions-only simulator into a transition-risk screening tool.

Propositions 1–5 and Corollaries 1–2 provide the analytical basis for the empirical policy dashboard used later in the paper. They show that cap stringency drives scarcity and the allowance price; allocation affects distribution; offsets require explicit credit-supply assumptions; coverage thresholds determine administrative feasibility; and firm heterogeneity determines buyers, sellers, abatement, offset use, and leakage risk.

6 Synthetic GICS Consistency Check

The synthetic experiment is used as a numerical consistency check before the empirical application. It uses the 11-sector Global Industry Classification Standard (GICS): energy, materials, industrials, consumer discretionary, consumer staples, health care, financials, information technology, communication services, utilities, and real estate [4]. The normalized carbon-intensity ranking is motivated by the sectoral carbon-footprint discussion in Marupanthorn et al. [5] and is used only as a transparent calibration, not as an empirical estimate. Because this section is synthetic rather than

country-calibrated, monetary values are reported in synthetic currency units rather than Thai baht or US dollars.

Table 4 GICS sector carbon-intensity calibration used in the synthetic simulation

Sector	Intensity index	High impact	Sampling share
Utilities	5.60	Yes	0.08
Energy	5.00	Yes	0.07
Materials	4.10	Yes	0.12
Industrials	2.45	Yes	0.18
Real Estate	1.15	No	0.06
Consumer Staples	0.95	No	0.11
Consumer Discretionary	0.70	No	0.10
Communication Services	0.48	No	0.06
Health Care	0.42	No	0.07
Information Technology	0.34	No	0.08
Financials	0.16	No	0.07

The simulation generates 330 firms. Baseline emissions are lognormal with sector means increasing in carbon intensity. The ETS covers only high-impact sectors, $\mathcal{S}^H = \{\text{utilities, energy, materials, industrials}\}$, and firms above 20,000 tCO₂e:

$$\mathcal{I}^E = \{i : E_i^0 \geq 20,000, s(i) \in \mathcal{S}^H\}. \quad (34)$$

This gives 117 covered firms and 11.00 MtCO₂e of baseline covered emissions.

Table 5 Synthetic GICS sector summary and ETS coverage

Sector	CI index	High impact	Firms	Covered	All emissions (Mt)	Covered emissions (Mt)
Utilities	5.60	Yes	34	31	3.78	3.75
Energy	5.00	Yes	15	12	1.20	1.17
Materials	4.10	Yes	39	36	3.36	3.33
Industrials	2.45	Yes	49	38	2.88	2.75
Real Estate	1.15	No	17	0	0.50	0.00
Consumer Staples	0.95	No	35	0	0.76	0.00
Consumer Discretionary	0.70	No	37	0	1.07	0.00
Communication Services	0.48	No	23	0	0.25	0.00
Health Care	0.42	No	18	0	0.16	0.00
Information Technology	0.34	No	32	0	0.23	0.00
Financials	0.16	No	31	0	0.13	0.00

For firm i , abatement a_i has convex cost

$$C_i^a(a_i) = \frac{1}{2} \theta_i \left(\frac{a_i}{E_i^0} \right)^2 E_i^0, \quad 0 \leq a_i \leq x_i^{\max} E_i^0, \quad (35)$$

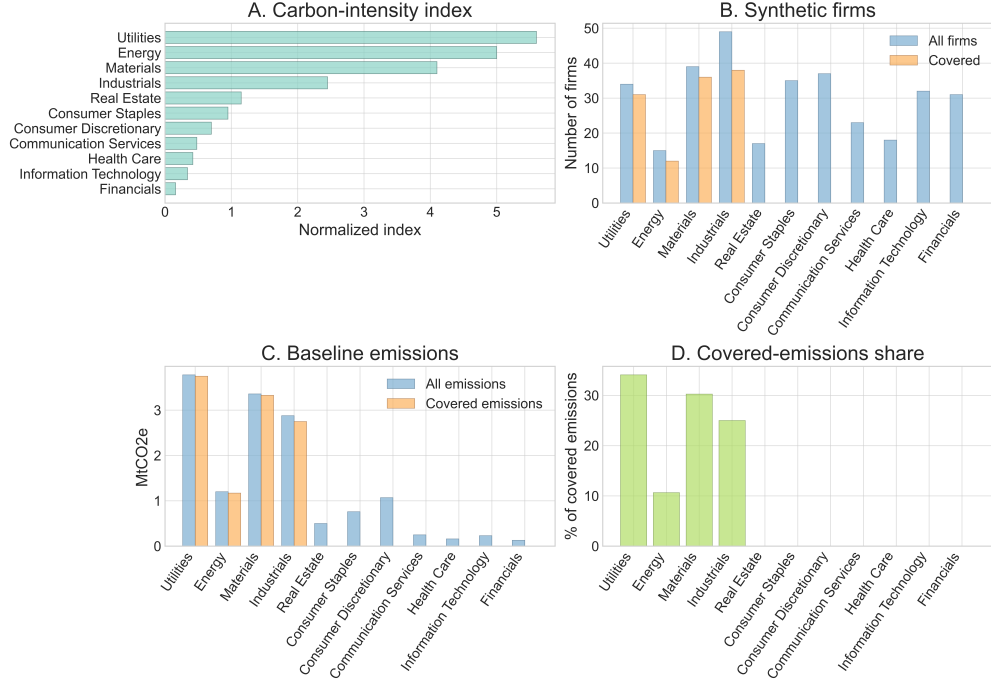


Fig. 1 GICS sector calibration and synthetic ETS coverage. Notes: the covered set requires both high-impact sector membership and baseline emissions above 20,000 tCO₂e.

so

$$MC_i(a_i) = \theta_i \frac{a_i}{E_i^0}, \quad a_i(P^A) = E_i^0 \min \left\{ x_i^{\max}, \frac{P^A}{\theta_i} \right\}. \quad (36)$$

The scenario grid varies cap reduction $\rho \in \{5\%, 10\%, 15\%, 20\%, 25\%, 30\%, 35\%, 40\%, 45\%, 50\%\}$, offset limit $\omega^S \in \{0\%, 5\%, 10\%, 15\%\}$, and free allocation $\phi \in \{30\%, 60\%, 90\%\}$. Offsets follow

$$S^O(P^O) = \min \left\{ \omega^S E^0, 0.30 E^0 \frac{P^O}{P^O + 850} \right\}, \quad P^O = \max\{0, P^A - 50\}. \quad (37)$$

For each scenario, P^A is found by bisection from

$$\sum_{i \in \mathcal{I}^E} a_i(P^A) + S^O(P^O) = \rho E^0. \quad (38)$$

Free allowances are $A_i^F = \phi C E_i^0 / E^0$ and net private cost is

$$C_i^{\text{net}} = C_i^a(a_i) + P^A(E_i^0 - a_i - o_i - A_i^F) + P^O o_i + C_i^{\text{adm}}. \quad (39)$$

Table 6 Selected GICS-based synthetic ETS scenarios, 60% free allocation

Cap cut	Offset limit	P^A	P^O	Abate (Mt)	Offsets (Mt)	Cost (m SCU)	Revenue (m SCU)
10%	0%	249	0	1.10	0.00	1130	984
10%	10%	162	112	0.72	0.38	750	641
10%	15%	162	112	0.72	0.38	750	641
20%	0%	497	0	2.20	0.00	2306	1750
20%	10%	318	268	1.41	0.79	1565	1120
20%	15%	318	268	1.41	0.79	1565	1120
30%	0%	778	0	3.30	0.00	3646	2397
30%	10%	497	447	2.20	1.10	2579	1531
30%	15%	491	441	2.17	1.13	2551	1512

The synthetic results illustrate three mechanisms. Tighter caps raise allowance prices: without offsets, P^A rises from 249 SCU/tCO₂e at a 10% cap cut to 778 SCU/tCO₂e at a 30% cut. Offsets lower the price: at a 20% cut, a 10% offset limit reduces P^A from 497 to 318 SCU/tCO₂e. Offset-credit prices stay below allowance prices because of the assumed spread.

The synthetic setup also illustrates why the model is useful for economic policy design. First, the coverage rule in Figure 1 shows how a regulator can concentrate limited MRV capacity on the highest-impact firms. The model excludes low-impact sectors and firms below the 20,000 tCO₂e threshold, yet still captures 11.00 MtCO₂e from 117 firms. This illustrates the screening logic available when administrative capacity is limited: the objective is not merely to maximize the number of regulated entities, but to concentrate regulation where emissions per regulated firm are highest, with Section 5 formalizing that administrative-efficiency trade-off.

Second, Figure 2 shows how the main ETS design levers work together in economic terms. Panel A shows that tighter caps create more scarcity and therefore higher allowance prices. Panel B shows that offsets soften the carbon-price path by giving firms a limited lower-cost compliance channel. Panel D shows that free allocation mainly reallocates private burden rather than changing the common market price. For policymakers, this means cap stringency and offset rules are the main levers for environmental ambition and price management, while free allocation is the main lever for transition-risk distribution across firms and sectors. Section 5 gives the formal comparative-statics interpretation of those patterns.

Table 7 Diagnostics for theoretical implications in the GICS-based synthetic simulation

Diagnostic	Value
Maximum market-clearing residual (Mt)	4.66×10^{-16}
Maximum price range across free-allocation shares	0.00
Cap-price correlation, $\omega^S = 10\%$	0.999
Monotonicity violations in cap-price relation	0
Mean interior marginal-cost error (SCU/t)	6.65×10^{-15}
Low-impact covered firms under GICS rule	0

The numerical diagnostics are internal consistency checks for the implemented solver rather than external validation. The maximum market-clearing residual is

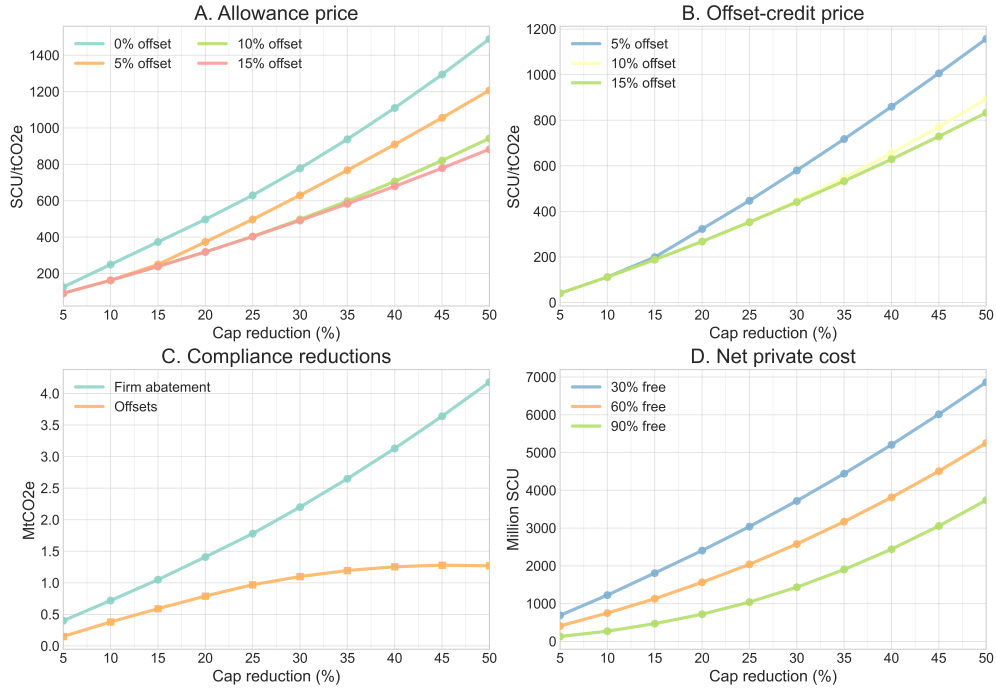


Fig. 2 GICS-based synthetic ETS scenario outcomes. Notes: all panels use the synthetic dataset with the high-impact GICS coverage rule and a 20,000 tCO₂e threshold. Panels A–C use 60% free allocation unless otherwise indicated.

4.66×10^{-16} MtCO₂e; the cap-price correlation is 0.999 under the 10% offset case; free allocation has zero effect on the allowance price when cap and offset rules are fixed; the mean interior marginal-cost error is 6.65×10^{-15} SCU/tCO₂e; and no low-impact-sector firms enter the ETS obligation set.

These checks matter because they confirm that the synthetic simulation solves the equations it reports. Near-zero residuals indicate that the reported prices come from the implemented market-clearing condition rather than from a plotting shortcut. The zero price range across free-allocation shares clarifies that free allocation is a burden-allocation instrument, not a scarcity instrument, when the cap and offset assumptions are held fixed. The widening private-cost gap in Panel D of Figure 2 shows the same distributional point from the firm side: once the common allowance price is determined, moving from 30% to 90% free allocation materially lowers private compliance cost even though the market price is unchanged. These are numerical checks of internal consistency, not empirical validation against observed ETS outcomes.

For firms, the synthetic section therefore gives a simple risk interpretation before the empirical application is introduced. A firm benefits from the ETS design when it can abate cheaply, pass through part of the carbon cost, or receive temporary free allocation while it adjusts. A firm is more exposed when it faces the common allowance price with limited pass-through and little free allocation. That is the main reason

the empirical case study focuses on cost-to-revenue, cost-to-EBITDA, and leakage-risk indicators rather than on emissions volume alone.

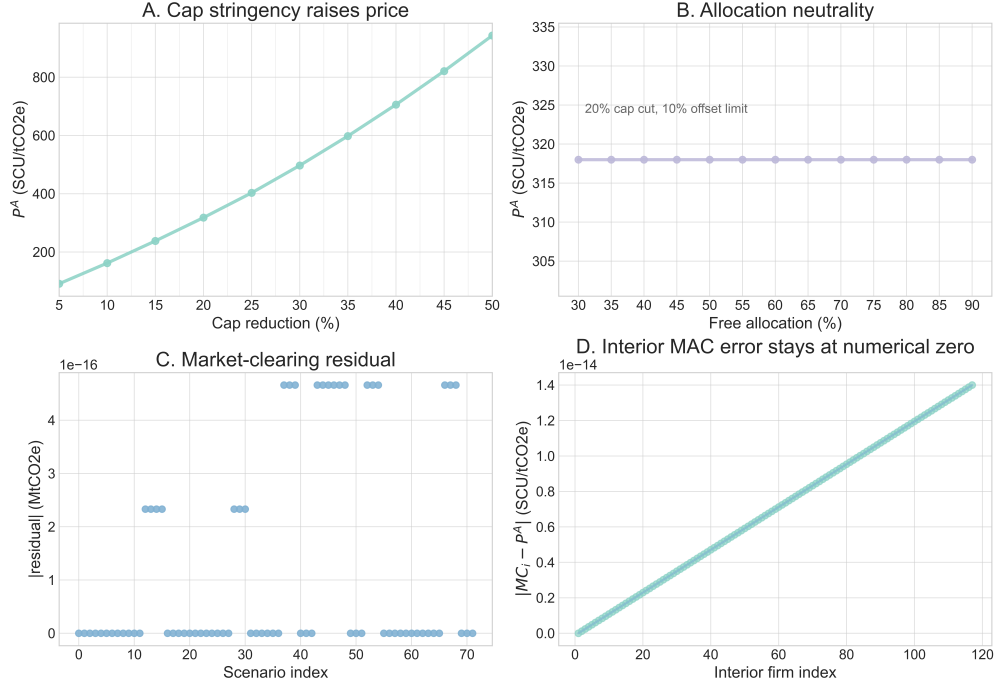


Fig. 3 Numerical diagnostics supporting the theoretical propositions. Notes: Panel D uses the scenario with a 20% cap cut, 10% offset limit, and 60% free allocation.

7 Application to the Thailand ETS Designation

Thailand's industrial estates are a natural starting point because they are concentrated, administratively identifiable, and important to manufacturing. They include sectors such as chemicals, petrochemicals, non-metallic minerals, metals, machinery, food processing, and energy-related activities. The ETS design must account for Thailand's electricity-market structure, power purchase agreements, firm-level data constraints, and export exposure. A design that begins too broadly may overload MRV capacity; a design that begins too narrowly may fail to create a meaningful price signal.

7.1 Prior coverage evidence

The Thailand calibration builds on Raksakulkarn et al. [10], who assessed 1,295 designated factories in 61 industrial estates over 2018–2020. The previous study considered three coverage boundaries: S1, Scope 1 including electricity generation; S2, Scope 1

excluding electricity generation; and S3, Scope 1 plus Scope 2 excluding electricity generation. It then applied thresholds of 15,000, 20,000, and 25,000 tCO₂e.

Table 8 Coverage results from the previous industrial-estate assessment

Scenario	Threshold rule	Installations (places)	Share of total (%)	Emissions (ktCO ₂ e/y)	Emissions share (%)
S1	All considered	740	100.00	44,534.05	100.00
S1-1	≥15,000 tCO ₂ e	101	13.65	43,337.18	97.31
S1-2	≥20,000 tCO ₂ e	90	12.16	43,146.59	96.88
S1-3	≥25,000 tCO ₂ e	79	10.68	42,901.22	96.33
S2	All considered	704	100.00	10,800.05	100.00
S2-1	≥15,000 tCO ₂ e	65	9.23	9,603.17	88.92
S2-2	≥20,000 tCO ₂ e	55	7.81	9,429.98	87.31
S2-3	≥25,000 tCO ₂ e	45	6.39	9,205.23	85.23
S3	All considered	1,259	100.00	23,124.88	100.00
S3-1	≥15,000 tCO ₂ e	200	15.89	18,613.10	80.49
S3-2	≥20,000 tCO ₂ e	160	12.71	17,909.65	77.45
S3-3	≥25,000 tCO ₂ e	129	10.25	17,210.76	74.43

Source: adapted from Raksakulkarn et al. [10].

The main implication is that partial coverage captures most emissions in each scenario. Under S2, only 45–65 factories are covered, yet they account for 85.23–88.92% of emissions within the S2 universe. S2 is therefore treated as the baseline because it focuses on direct industrial emissions and avoids power-sector complications. S1 and S3 remain useful sensitivity cases.

Table 9 Administrative burden implied by coverage thresholds

Scenario	Threshold rule	Installations (places)	Time burden (hours/y)	Financial burden (million baht/y)
S1-1	≥15,000 tCO ₂ e	101	9,797	18.18
S1-2	≥20,000 tCO ₂ e	90	8,730	16.20
S1-3	≥25,000 tCO ₂ e	79	7,663	14.22
S2-1	≥15,000 tCO ₂ e	65	6,305	11.70
S2-2	≥20,000 tCO ₂ e	55	5,335	9.90
S2-3	≥25,000 tCO ₂ e	45	4,365	8.10
S3-1	≥15,000 tCO ₂ e	200	19,400	36.00
S3-2	≥20,000 tCO ₂ e	160	15,520	28.80
S3-3	≥25,000 tCO ₂ e	129	12,513	23.22

Source: calculated from Raksakulkarn et al. [10]; assumptions are 97 hours and 180,000 baht per covered installation.

Administrative costs are based on the Standard Cost Model assumptions of 97 hours and 180,000 baht per covered installation. These should be read as simplifying scenario inputs rather than as precise estimates of regulator, verifier, or internal firm cost for every facility type. Under S2, moving from the 15,000 to 25,000 tCO₂e threshold reduces covered installations from 65 to 45 and administrative burden from 6,305 to 4,365 hours, while covered emissions fall only from 9.60 to 9.21 MtCO₂e. This pattern motivates a moderate threshold for early implementation, but it remains conditional on the fixed per-installation burden assumption.

7.2 Policy scenario design

The baseline coverage scenario is S2: Scope 1 emissions excluding electricity generation. S1 is retained for sensitivity because it has high emissions coverage but raises power-sector issues. S3 is retained because it broadens emissions accounting but may double-count electricity emissions if power-sector regulation is later introduced. Under S2, the 20,000 tCO₂e threshold covers 55 factories and 9.43 MtCO₂e per year, making it a practical compromise between coverage and administrative burden.

Table 10 Proposed ETS-design scenarios for Thailand’s industrial sector

Scenario	Cap reduction	Free allocation	Auctioning	Offset limit	Policy logic
P1 Soft transition	5%	90%	10%	15%	Minimize short-run burden and build MRV readiness.
P2 Balanced ETS	10%	70%	30%	10%	Balance emissions reduction and competitiveness protection.
P3 Strict ETS	20%	50%	50%	5%	Strengthen the carbon-price signal and direct abatement.
P4 Auction with recycling	15%	50%	50%	10%	Use auction revenue to support energy efficiency and technology investment.
P5 Mature ETS	25%	20%	80%	5%	Represent a long-run design after firms and regulators gain experience.

P1 represents a soft transition or pilot phase; P2 provides a moderate benchmark scenario; P3 tests stricter environmental ambition; P4 tests auctioning with revenue recycling; and P5 represents a mature design after MRV and firm adjustment capacity improve.

Table 11 Illustrative dynamic transition path

Phase	Year	Cap reduction	Free allocation	Auctioning
Preparation and MRV strengthening	2027	0%	–	–
Pilot compliance	2028	5%	90%	10%
Early market phase	2030	10%	70%	30%
Tightening phase	2032	15%	60%	40%
Pre-2035 alignment	2035	25%	40%	60%

A credible transition should begin with MRV strengthening, then move from a 5% cap cut and 90% free allocation toward a 25% cap cut and higher auctioning by 2035. Publishing the trajectory in advance reduces regulatory uncertainty and discourages firms from delaying investment.

7.3 Implementation and uncertainty

The model requires emissions, output, financial, abatement, trade-exposure, ETS-compliance, and administrative-cost data. In the current Thailand application, some of these inputs come from direct downloaded sources in this workspace, while others are transparent proxy constructions because verified installation-level microdata are not publicly available.

The T-VER price input also requires interpretation. Public TGO statistics report both an aggregate weighted-average transaction price and a latest-month weighted-average transaction price. These are not conflicting observations. The aggregate price summarizes a broader transaction history, whereas the latest-month price reflects more recent market conditions. In an illiquid and heterogeneous offset market, those values can differ materially because transaction timing, project mix, negotiated contract terms, and traded volume vary across periods. The paper therefore treats the T-VER price as an offset-reference parameter rather than as a unique market-clearing spot price.

If confidential facility data are available, the model can be implemented directly at installation level. Otherwise, an initial version can use listed-company data, sector-average emissions intensity, public sustainability reports, and scenario assumptions for abatement cost and pass-through.

The Thailand simulation follows Algorithm 1.

The Thailand application reports deterministic baseline scenarios together with Monte Carlo sensitivity analysis over key proxy inputs. Table 13 summarizes the main uncertainty dimensions considered in that robustness framework.

Table 12 Actual data sources used in the Thailand implementation

Data category	Variables used	Actual source or construction in this project
Industrial-estate emissions base	Covered installations, covered Scope 1 emissions, threshold scenarios	Raksakulkarn et al. [10], used as the S2 coverage baseline and threshold-sensitivity anchor
Thai listed-firm universe	Sector membership and market-cap weights for the proxy installation panel	Refinitiv Workspace downloads; used to construct the SEC-facing sector universe and firm-weight proxy
Refinitiv ESG and financial context	Emissions, financial, and trade-competitiveness fields reviewed for availability	Refinitiv Workspace downloads; reviewed for data availability, but not directly imposed in the Thailand core equations because there is no verified installation-to-listed-firm crosswalk
Trade exposure	Sector trade-exposure proxy for leakage screening	Ministry of Commerce HS2 trade proxy mapped to the sector classification used in the simulation
Offsets	Domestic offset reference price and available supply cap	TGO/T-VER public registry and visible aggregate market metric; used as the offset-credit reference and the 0.10 MtCO ₂ e/y supply cap
Administrative cost	Reporting hours and fixed compliance cost per covered installation	Standard Cost Model values from Raksakulkarn et al. [10]: 97 hours and 180,000 baht per covered installation-year
Abatement and firm-finance inputs	Marginal abatement parameters, maximum abatement rates, revenue, EBITDA, pass-through	Transparent proxy calibration implemented in the simulation engine, based on sector intensity classes and reproducible random draws rather than confidential observed installation microdata
ETS compliance positions	Allowances, net purchases, offset use, and auction revenue	Simulated within the scenario engine because Thailand does not yet have an observed mandatory ETS registry for these installations

Algorithm 1 Firm-level ETS simulation for the Thailand case study

Require: Coverage scenario c , threshold τ , baseline emissions E_{i0}^c , sector $s(i)$, abatement parameters λ_i and $\bar{q}_i$, financial variables, offset supply parameter, and policy scenario Θ

Ensure: Allowance price, abatement, offset use, firm-level cost exposure, auction revenue, and leakage-risk indicators

- 1: Identify covered installations: $D_i^{c,\tau} \leftarrow \mathbf{1}\{E_{i0}^c \geq \tau\}$
 - 2: Compute covered baseline emissions: $E_0^{cov,c,\tau} \leftarrow \sum_i D_i^{c,\tau} E_{i0}^c$
 - 3: Set cap: $C_t \leftarrow (1 - r_t)E_0^{cov,c,\tau}$
 - 4: Assign free allowances according to the selected allocation rule
 - 5: Set auctioned allowances and determine the eligible aggregate offset quantity from ω and available offset supply
 - 6: **for** each policy scenario **do**
 - 7: Initialize trial allowance price P_t
 - 8: **repeat**
 - 9: **for** each covered installation i **do**
 - 10: Compute abatement: $q_{it}^* \leftarrow \min\{\max(P_t/\lambda_i, 0), \bar{q}_i\}$
 - 11: Compute post-abatement emissions: $E_{it} \leftarrow E_{i0}^c(1 - q_{it}^*)$
 - 12: Assign the installation's share of exogenously available eligible offsets
 - 13: **end for**
 - 14: Aggregate direct abatement $A_t(P_t) \leftarrow \sum_i D_i^{c,\tau} E_{i0}^c q_{it}^*$
 - 15: Update P_t by bisection until aggregate direct abatement matches the required direct-abatement target
 - 16: **until** $|A_t(P_t) - Q_t^{ab}|$ is below the numerical tolerance
 - 17: Compute allowance cost, abatement cost, offset cost, administrative cost, and net private cost
 - 18: Compute auction revenue and revenue recycled to firms or transition investment
 - 19: Compute cost-to-revenue, cost-to-EBITDA, sector exposure, and leakage-risk indicators
 - 20: **end for**
 - 21: Rank policy scenarios using the SEC-oriented multi-criteria objective
-

Table 13 Illustrative uncertainty dimensions for the Thailand calibration

Parameter	Low	Medium	High
Carbon price floor (baht/tCO ₂ e)	100	200	500
Carbon price ceiling (baht/tCO ₂ e)	500	1,000	2,000
Free allocation rate	50%	70%	90%
Offset limit	5%	10%	15%
Abatement-cost parameter	Low	Medium	High
Cost pass-through	20%	50%	80%
Discount rate	3%	5%	8%

7.4 Calibrated Thailand simulation results

The calibrated case uses the S2-2 baseline: 55 covered installations, 9.43 MtCO₂e/y of covered Scope 1 emissions, and 9.90 million baht/y of administrative cost. The current Thailand evidence should be read as a policy-calibration and exploratory risk-mapping exercise rather than an observed ETS treatment effect, because Thailand does not yet operate a mandatory ETS for these installations and T-VER credits are not exchange-traded allowance substitutes. T-VER enters as an offset-availability and shadow-price parameter, while trade exposure is proxied using sector/product data where available. Public TGO statistics report both an aggregate weighted-average T-VER transaction price and a latest-month weighted-average price. The latest-month value is used here as the baseline reference because it is closer to current visible market conditions, while the aggregate value is retained as a broader historical reference for interpretation and sensitivity analysis. The difference should therefore be read as a difference in aggregation window and market activity, not as a contradiction in the underlying data.

Table 14 Threshold sensitivity under the balanced ETS scenario

Threshold	Installations	Emissions (Mt)	Emissions/inst. (kt)	Shadow price	Offsets (Mt)	Admin cost (m THB)	Admin/covered t (THB)	Net cost (m THB)
S2-1	65	9.60	147.7	302	0.10	11.7	1.22	930
S2-2	55	9.43	171.5	294	0.10	9.9	1.05	887
S2-3	45	9.21	204.6	308	0.10	8.1	0.88	904

Notes: all rows use P2, with a 10% cap cut, 70% free allocation, 30% auctioning, and a 10% offset-use limit. Emissions per installation and administrative cost per covered ton are reported to clarify the threshold trade-off. Values are deterministic outputs from one proxy draw.

Under the present calibration, the 20,000 tCO₂e threshold is a reasonable early benchmark rather than a universally optimal cutoff. The three S2 thresholds have similar covered emissions, but different administrative costs. Economically, raising the threshold removes smaller emitters first, so emissions covered per regulated installation rises and fixed MRV cost per covered ton falls. In the Thailand data, moving from 15,000 to 20,000 tCO₂e removes 10 installations and 970 reporting hours while reducing covered emissions by only 0.17 MtCO₂e; moving from 20,000 to 25,000 tCO₂e removes another 10 installations but excludes 0.22 MtCO₂e. This is why S2-2 is used as the baseline scenario. It is a practical compromise under the stated burden assumptions and a useful cutoff for a future threshold-based identification design, not a proof that 20,000 tCO₂e is the unique correct threshold.

The simulated shadow price rises from 131 THB/tCO₂e in P1 to 895 THB/tCO₂e in P5. In the implemented Thailand model, this is a shadow price from direct-abatement clearing after exogenous offset supply is deducted, not a full observed allowance-market price with banking, liquidity, and intertemporal trading. Within that narrower interpretation, tighter caps push the system toward more abatement and a higher common carbon shadow price, while the T-VER reference affects compliance flexibility rather than determining the price. Offset use remains at 0.10 MtCO₂e in every baseline policy scenario because the current calibration imposes an exogenous annual T-VER supply cap at that level, so the supply constraint binds before the

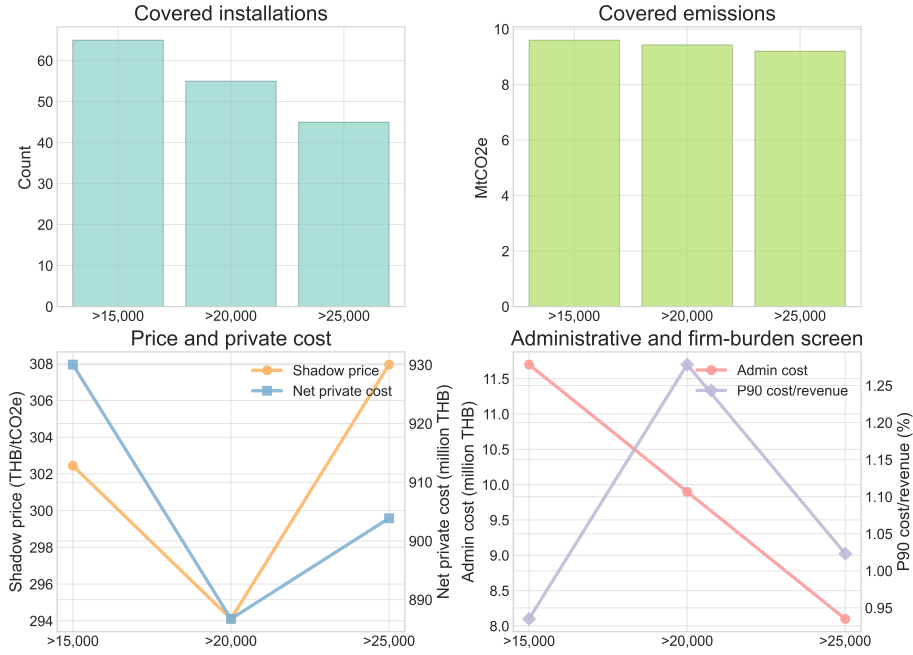


Fig. 4 Threshold sensitivity under the balanced Thailand ETS scenario. Notes: the four panels report covered installations, covered emissions, simulated shadow price with net private cost, and administrative cost with the 90th-percentile cost-to-revenue burden. Values are deterministic outputs from one proxy calibration draw.

Table 15 Deterministic proxy-calibrated Thailand ETS policy-scenario results, S2-2 baseline

Scenario	Cap cut	Offset limit	Shadow price	P^O param.	Abate (Mt)	Offsets (Mt)	Revenue (m THB)	Net cost (m THB)
P1 Soft transition	5%	15%	131	40	0.37	0.10	117	156
P2 Balanced ETS	10%	10%	297	40	0.84	0.10	756	895
P3 Strict ETS	20%	5%	630	40	1.79	0.10	2,376	2,952
P4 Auction with recycling	15%	10%	463	40	1.31	0.10	1,856	1,061
P5 Mature ETS	25%	5%	895	40	2.26	0.10	5,063	4,975

Notes: S2-2 uses 55 installations and 9.43 MtCO₂e/y covered emissions. All values are deterministic outputs of the proxy calibration rather than observed Thai ETS outcomes. The reported shadow price comes from direct-abatement clearing under fixed offset supply. The T-VER price is a current-month reference parameter based on visible TGO market information, not an exchange-traded firm-level price; the broader aggregate weighted-average price is used only in sensitivity interpretation.

percentage offset limit does. P2 gives a moderate shadow price of 297 THB/tCO₂e and direct abatement of 0.84 MtCO₂e. P4 produces a higher shadow price at 463 THB/tCO₂e, but its net private cost remains much closer to P2 than to P3 because the current recycling rule returns a lump-sum share of auction revenue to covered firms in proportion to baseline emissions. These values are deterministic outputs of proxy abatement-cost and financial assumptions rather than observed Thai market outcomes.

Under the selected score weights and feasibility screen, P4 receives the highest score and P2 the second-highest. P4 combines a 15% cap cut, 50% free allocation,



Fig. 5 Proxy-calibrated Thailand ETS scenario outcomes. Notes: the S2-2 baseline is used in all panels. T-VER offset prices are treated as scenario parameters rather than observed exchange-traded prices, and the shadow-price panel is a deterministic output of the direct-abatement clearing model under fixed offset supply.

Table 16 Conditional policy-preference ranking of Thailand ETS scenarios

Rank	Scenario	Score	Feasible	Cap cut	Shadow price	P90 cost/revenue	Revenue (m THB)
1	P4 Auction with recycling	0.725	Yes	15%	463	1.27%	1,856
2	P2 Balanced ETS	0.606	Yes	10%	297	1.12%	756
3	P3 Strict ETS	0.476	No	20%	630	2.81%	2,376
4	P1 Soft transition	0.448	No	5%	131	0.39%	117
5	P5 Mature ETS	0.432	No	25%	895	4.06%	5,063

Notes: the score weights environmental effectiveness, firm affordability, price manageability, transition-finance capacity, competitiveness protection, and feasibility. Feasibility requires at least a 10% cap cut, a shadow price between 200 and 500 THB/tCO₂e, p90 cost-to-revenue not above 1.5%, and an offset limit not above 10%. The ranking is a policy-preference exercise, not a welfare optimum.

50% auctioning, a 10% offset limit, a 463 THB/tCO₂e shadow price, 1.86 billion baht/y auction revenue, and a 90th-percentile cost-to-revenue ratio of 1.27%, which remains inside the paper's 1.5% affordability screen. In economic terms, it preserves a meaningful scarcity signal while converting more allowance value into transition finance instead of leaving all burden adjustment at the firm level. P2 remains attractive

as a lower-burden benchmark because the same design logic operates with a lower carbon price and smaller private-cost shift. But Table 16 is only a policy-preference exercise, not a welfare optimum.

Table 17 Allowance-position accounting under the Thailand policy scenarios

Scenario	Buyers	Sellers	Purchase (Mt)	Sales (Mt)	Net position (Mt)
P1 Soft transition	33	22	1.40	0.51	0.90
P2 Balanced ETS	51	4	2.59	0.04	2.55
P3 Strict ETS	55	0	3.77	0.00	3.77
P4 Auction with recycling	55	0	4.01	0.00	4.01
P5 Mature ETS	55	0	5.66	0.00	5.66

Notes: purchases and sales are computed from installation net allowance positions after benchmark-style free allocation and exogenous offset assignment. Net position equals aggregate auction demand in the no-banking baseline.

Because the Thailand demonstration now records net allowance positions explicitly, the burden screen no longer treats all covered installations as pure buyers by construction. Under the benchmark-style proxy free-allocation rule, softer scenarios generate a limited seller side, while stricter scenarios still leave all installations net short. The table should therefore be read as an accounting disclosure of how the current calibration distributes scarcity, not as evidence of an empirically observed Thai market structure.

Table 18 Ranking sensitivity to score weights, gates, and recycling assumptions

Case	Top scenario	Top score	P4 rank	P2 rank
Baseline	P4 Auction with recycling	0.725	1	2
Equal weights	P4 Auction with recycling	0.751	1	2
No transition-finance score	P4 Auction with recycling	0.745	1	2
Stronger environmental weight	P4 Auction with recycling	0.704	1	2
Stronger affordability weight	P4 Auction with recycling	0.747	1	2
No feasibility gate	P4 Auction with recycling	0.725	1	2
Wider price corridor	P4 Auction with recycling	0.725	1	2
Tighter p90 burden gate	P4 Auction with recycling	0.625	1	2
No recycling	P4 Auction with recycling	0.664	1	2

Notes: each row recomputes the policy ranking under an alternative scoring or feasibility design. The table is intended to show whether the headline ordering is stable.

These robustness outputs materially narrow the interpretation of the Thailand ranking. Table 18 shows that P4 remains first under several alternative score configurations, but that result still depends on the same proxy calibration and the same scenario menu. Table 19 together with Panel A of Figure 6 show that even under one scoring rule, the shadow-price and cost outputs vary materially across plausible proxy

Table 19 Monte Carlo uncertainty summary for Thailand policy scenarios

Scenario	Median shadow price	P05-P95 shadow	Median net cost	Infeasible share	Rank-1 share
P1 Soft transition	55	0-142	86	0.0%	0.0%
P2 Balanced ETS	229	135-322	691	0.0%	0.0%
P3 Strict ETS	573	481-701	2,643	0.0%	0.0%
P4 Auction with recycling	397	297-511	889	0.0%	100.0%
P5 Mature ETS	770	646-993	4,261	6.8%	0.0%

Notes: the Monte Carlo varies proxy abatement costs, maximum abatement rates, revenue and EBITDA proxies, offset supply, offset price, and administrative cost. Rank-1 share reports how often each scenario ranks first under the baseline score. Infeasible share reports the fraction of draws in which the imposed direct-abatement requirement exceeds the modeled technical abatement potential.

Table 20 Offset-use sensitivity to external T-VER supply

Offset supply (Mt)	P1 Soft transition	P2 Balanced ETS	P4 Auction with recycling	P5 Mature ETS
0.05	0.05	0.05	0.05	0.05
0.10	0.10	0.10	0.10	0.10
0.30	0.30	0.30	0.30	0.30
0.60	0.47	0.60	0.60	0.47
1.00	0.47	0.94	0.94	0.47

Notes: values report actual offset use under alternative exogenous T-VER supply assumptions. This table shows when the percentage offset limit becomes active and when external supply is the binding constraint.

draws, and that the most stringent scenario can become technically infeasible in a minority of draws once the direct-abatement requirement exceeds modeled technical potential. Table 20 further shows that the percentage offset limits in P1–P5 become informative only when external T-VER supply rises above the current 0.10 MtCO₂e cap.

Table 21 Pareto-frontier screening across Thai ETS scenarios

Scenario	Reduction (Mt)	Net cost (m THB)	Revenue (m THB)	Pareto efficient
P1 Soft transition	0.47	156	117	Yes
P2 Balanced ETS	0.94	895	756	Yes
P3 Strict ETS	1.89	2,952	2,376	Yes
P4 Auction with recycling	1.41	1,061	1,856	Yes
P5 Mature ETS	2.36	4,975	5,063	Yes

Notes: scenarios are screened on emissions reduction, net private cost, auction revenue, and administrative burden. Administrative burden is constant within the S2-2 policy comparison, so the frontier is mainly driven by reduction, cost, and revenue.

The Thailand diagnostics should be read as solver diagnostics for the implemented calibration rather than as empirical validation. The reported carbon price is a shadow price from direct-abatement clearing, whereas the TGO/T-VER value is only an offset-credit reference. Tighter caps increase scarcity and raise the shadow price, while

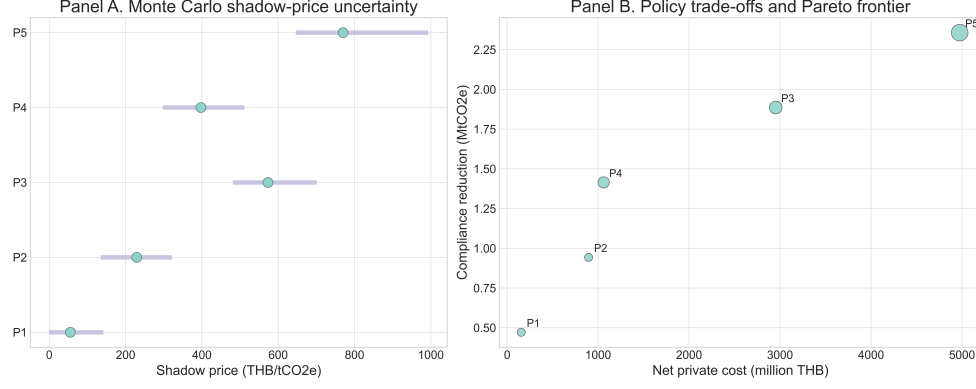


Fig. 6 Uncertainty and trade-off views of the Thai ETS scenario menu. Notes: Panel A reports Monte Carlo shadow-price intervals generated by varying proxy abatement costs, maximum abatement rates, revenue and EBITDA proxies, offset supply, offset price, and administrative cost. Panel B reports the deterministic policy trade-off frontier in the S2-2 calibration, where point size reflects auction revenue. The figure reports simulation dispersion and scenario trade-offs, not observed Thai market outcomes.

Table 22 Solver diagnostics for price formation and market clearing in the Thailand calibration

Diagnostic	Value
P2 endogenous allowance price	297 THB/tCO2e
TGO/T-VER latest-month price	40.41 THB/tCO2e
TGO/T-VER aggregate price	85.48 THB/tCO2e
Market-clearing residual	0.00e+00 MtCO2e
Interior marginal-cost error	4.13e-15 THB/tCO2e
Cap-price monotonicity violations	0
Allowance-price range across free allocation	0.00 THB/tCO2e
Interior installations in P2	55

Notes: the reported shadow price is solved by direct-abatement clearing under fixed offset supply. The TGO/T-VER values are used only as offset-credit reference prices.

changes in free allocation redistribute net private cost and auction revenue without changing the equilibrium price under the no-banking baseline. The zero market-clearing residuals and interior conditions of $MC_{it}^{ab} = P_t$ up to numerical roundoff indicate that the reported scenario outputs satisfy the implemented solver conditions. In that sense, Table 22 and Figure 7 document numerical alignment between the code and the stated economics of scarcity, burden redistribution, market clearing, and least-cost abatement.

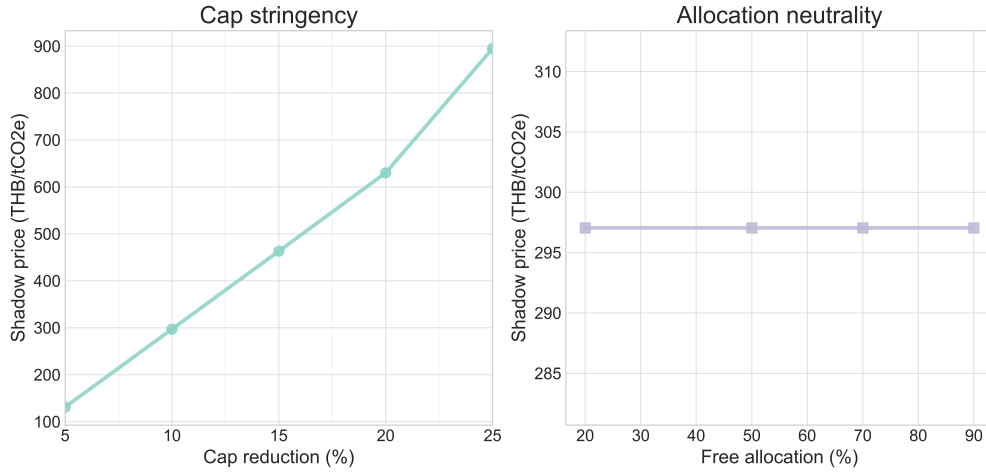


Fig. 7 Economic interpretation of price formation and allocation effects in the Thailand calibration. Notes: Panel A shows that tighter caps increase scarcity and raise shadow prices. Panel B shows that free allocation redistributes private burden without changing the shadow price when the cap and offset assumptions are held fixed. Numerical solver diagnostics are reported in Table 22.

7.5 Firm exposure, disclosure, and leakage risk

The installation-level results are proxy estimates because public data do not provide a verified factory-to-listed-company crosswalk or confidential DEDE energy-management microdata. They are therefore best interpreted as exploratory designation and burden screens rather than as identified causal firm-treatment effects. The mean cost-to-revenue exposure is below one percent in the balanced scenario, but sector heterogeneity remains important. The economic point is that emissions volume alone is not enough to identify vulnerability: exposure rises when a firm has high uncovered emissions, weak pass-through ability, and thin margins, while temporary free allocation and recycled auction support can lower private burden during transition. For SEC Thailand, useful transition-risk indicators therefore include covered Scope 1 emissions, expected allowance purchases or surplus allowances, total compliance cost as a share of revenue and EBITDA, auction exposure, expected offset use, environmental capex, and whether the firm is emissions-intensive and trade-exposed.

The implemented Thailand leakage screen uses normalized sector components rather than a causal leakage estimate. Specifically, the code assigns weight 0.40 to sector carbon intensity, 0.35 to the trade-exposure proxy, 0.20 to low pass-through ability, and 0.05 to sector emissions share, then rescales the result to the unit interval. The ranking should therefore be read as a transparent screening rule for transitional protection, not as measured future relocation behavior.

Basic Materials has the highest leakage index because it combines high emissions intensity, a large emissions share, and strong trade exposure. Industrials is second. Utilities and Energy remain important because their emissions intensity is high, although pass-through differs from manufacturing sectors. Because the index uses sector-level trade and pass-through proxies rather than firm-specific foreign-sales data, it should

Table 23 Sector exposure in the balanced Thailand ETS scenario

Sector	Emissions (Mt)	Trade index	Leakage index	Mean cost/revenue
Basic Materials	3.05	0.76	1.00	0.39%
Industrials	2.71	0.79	0.86	0.39%
Utilities	1.20	0.34	0.77	0.50%
Consumer Cyclicals	0.29	1.00	0.71	0.51%
Energy	0.88	0.09	0.71	0.57%
Technology	0.09	0.72	0.48	0.40%
Consumer Non-Cyclicals	0.47	0.34	0.43	0.56%
Real Estate	0.14	0.34	0.36	0.43%
Healthcare	0.14	0.34	0.33	0.38%
Academic & Educational Services	0.16	0.34	0.27	0.32%
Financials	0.29	0.34	0.23	0.54%

Notes: trade exposure is a sector/product proxy from MOC HS2 data where available. It is not firm-specific foreign sales.

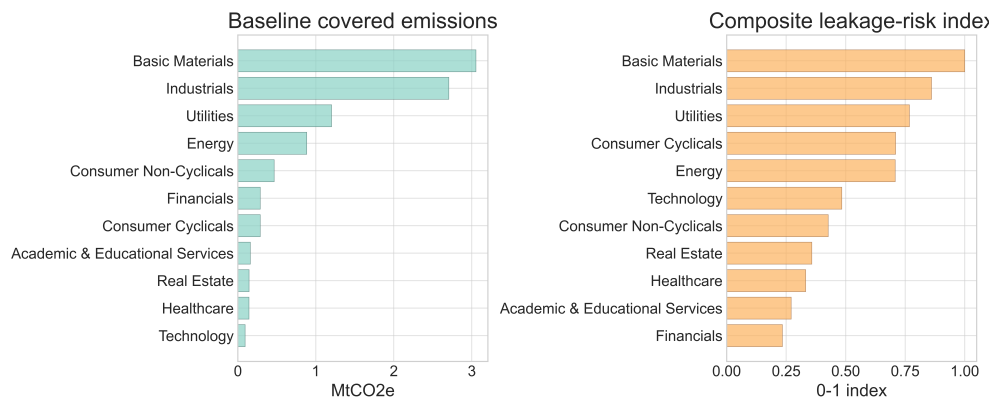


Fig. 8 Proxy-calibrated sector emissions and leakage-risk exposure in the balanced Thailand ETS scenario. Notes: the leakage index combines emissions share, sector trade-exposure proxy, and assumed pass-through ability.

be interpreted as a sector exposure screen, not as a measured firm-level leakage probability. Within that limitation, the ranking suggests that transitional protection is more relevant where carbon costs cannot be easily passed through and where margins are thinner, not simply where emissions are large. That is the economic reason to prefer temporary benchmark-based protection for exposed sectors over broad exemption.

7.6 Exploratory listed-firm disclosure screen

The listed-firm regression extension is retained only as an illustrative disclosure screen. Because the panel uses a current market-cap snapshot, lacks firm fixed effects, and is not linked to verified facility-level ETS exposure, its coefficients should not be interpreted causally or used to forecast realized ROA under an ETS. The main Thailand

contribution remains the proxy-calibrated installation and sector dashboard, while the listed-firm material provides a supplementary view of how transition-risk reporting could be organized at the issuer level.

Table 24 Exploratory Thai listed-firm ROA screening regression

Variable	Coef.	Cluster SE	t-stat
Centered log market cap	0.0130	0.0023	5.58
Centered log total GHG	-0.0083	0.0015	-5.64
PF = revenue/assets	0.0200	0.0052	3.82
IF = capex/assets	-0.4691	0.1388	-3.38
Size x emissions interaction	-0.0014	0.0004	-3.46

Notes: dependent variable is ROA. The sample contains 300 firm-years, 189 firms, and 11 TRBC sectors over 2022–2024. Year and sector fixed effects are included and standard errors are clustered by firm. Because annual market-cap series are sparse in the downloaded panel, the current Refinitiv market-cap snapshot is used as the size variable. This table is an illustrative disclosure screen, not a causal ETS estimate.

The estimated listed-firm relation is used only as an illustrative disclosure screen. The coefficient on centered log total GHG is -0.0083 and the size-interaction coefficient is -0.0014 , so the fitted emissions–ROA association becomes more adverse for larger firms. At the average listed-firm size in the sample, a 10% increase in reported GHG emissions is associated with an ROA reduction of about 0.08 percentage points; at the 75th percentile of firm size, the implied decline is about 0.09 percentage points. This pattern is directionally consistent with the broader risk-mapping logic of the case study, but it should not be interpreted as independent causal evidence.

Table 25 Illustrative listed-firm carbon-performance sensitivity screen for Thailand

Firm ID	Year	Sector	GHG (kt)	ROA	Carbon ROA gap	10% dGHG ROA
Firm 1	2024	Energy	173,606	2.62%	-10.03 pp	-0.13 pp
Firm 2	2024	Energy	46,728	8.17%	-7.75 pp	-0.12 pp
Firm 3	2024	Energy	87,204	3.69%	-7.32 pp	-0.11 pp
Firm 4	2024	Consumer Non-Cyclicals	36,425	0.74%	-6.80 pp	-0.11 pp
Firm 5	2024	Basic Materials	48,176	-4.62%	-6.74 pp	-0.11 pp
Firm 6	2024	Basic Materials	43,677	-3.56%	-6.47 pp	-0.11 pp
Firm 7	2024	Energy	50,336	2.43%	-6.41 pp	-0.10 pp
Firm 8	2024	Consumer Non-Cyclicals	19,615	2.68%	-6.36 pp	-0.12 pp
Firm 9	2024	Consumer Non-Cyclicals	35,300	2.23%	-6.34 pp	-0.11 pp
Firm 10	2024	Energy	57,641	-0.19%	-6.06 pp	-0.09 pp

Notes: firms are ranked by the most adverse implied carbon-related ROA gap from the paper-style listed-firm regression. The final column reports the implied ROA change from a 10% increase in reported GHG emissions at each firm’s size. These are conditional correlation screens, not causal ETS effects.

Table 26 Projected listed-firm ROA distribution summary under Thailand ETS scenarios

Scenario	Mean proj. ROA	Median proj. ROA	P10	P90	Mean change
P1 Soft transition	4.79%	3.54%	-1.57%	12.07%	-0.06 pp
P2 Balanced ETS	4.50%	3.33%	-1.66%	11.34%	-0.36 pp
P3 Strict ETS	3.68%	2.78%	-2.93%	10.33%	-1.17 pp
P4 Auction with recycling	4.46%	3.33%	-1.64%	11.19%	-0.40 pp
P5 Mature ETS	2.87%	2.45%	-3.80%	9.63%	-1.98 pp

Notes: each scenario projection combines the paper-style listed-firm ROA regression with scenario-specific sector abatement rates and net compliance-cost burdens from the Thailand installation calibration. Results are illustrative fixed-firm scenario screens, not forecasts of realized future ROA or causal treatment effects.

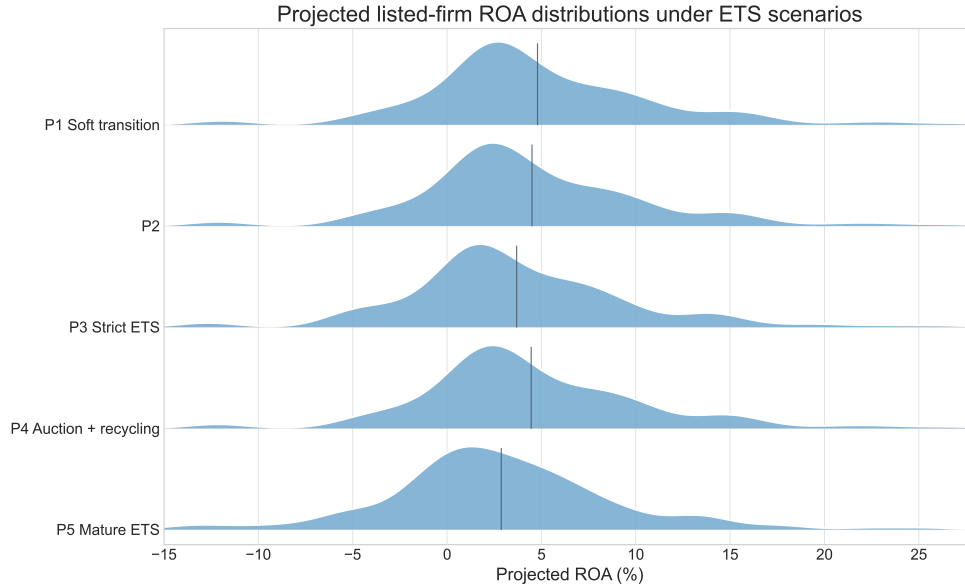


Fig. 9 Projected listed-firm ROA distributions under Thailand ETS scenarios. Notes: each ridge shows the cross-sectional ROA distribution implied by combining the listed-firm ROA regression with scenario-specific sector abatement rates and net compliance-cost burdens from the Thailand calibration. The exercise is illustrative and should be interpreted as a fixed-firm stress screen, not a causal treatment effect or a forecast of realized future ROA.

7.7 Causal firm-treatment design for future implementation

The stronger causal version of this Thailand paper is conceptually clear, but it requires data that are not yet publicly available. The current paper delivers predictive screening and policy calibration. A future causal paper would estimate firm-treatment effects only after constructing a matched facility–firm panel that links regulated factories to listed-company ownership, verified facility emissions, output, energy use, and compliance dates.

The most natural design is a threshold-based causal strategy around ETS designation. If Thailand assigns mandatory coverage using an emissions threshold such as 20,000 tCO₂e, firms or facilities just above and just below that cutoff can be compared using a regression-discontinuity design or a fuzzy regression-discontinuity design if compliance is imperfect. The running variable would be pre-policy verified emissions, the treatment would be ETS designation, and the outcomes would include emissions intensity, ROA, EBITDA margin, capex, market valuation, and allowance-purchase exposure. A credible implementation would also need manipulation checks around the threshold, bunching or density tests, bandwidth sensitivity, covariate-balance checks, and explicit treatment of multi-facility firms whose exposure may not map cleanly to a single plant-level cutoff. Such a design would identify local causal treatment effects near the designation cutoff and would fit the institutional logic of the proposed Thai system.

If Thailand instead phases the system in by sector, estate, or year, a difference-in-differences or event-study design would be a natural alternative. In that setting, treated firms would be those linked to covered facilities in the implementation phase, while matched uncovered firms would form the comparison group. Firm and year fixed effects, sector-specific trends, pre-trend diagnostics, treatment-timing estimators robust to staggered adoption, and sensitivity checks for supply-chain spillovers would then be needed to separate ETS treatment from broader energy-price or macroeconomic shocks.

Under either design, four data conditions are essential: a verified factory-to-listed-company crosswalk, facility-level verified emissions and compliance status, timing of designation and surrender obligations, and firm-level outcomes observed before and after treatment. Once these conditions are met, the present screening framework can be upgraded into a causal firm-treatment study. Until then, the correct interpretation of Section 7 is that the current results are predictive and supervisory, while the causal design is a clearly specified next empirical step.

Auction revenue is small in P1 but material once auctioning expands. It reaches 756 million baht/y under P2, 1.86 billion baht/y under P4, and 5.06 billion baht/y under P5. Revenue should not be treated only as fiscal income; it can be earmarked for energy audits, boiler replacement, waste-heat recovery, electrification, solar rooftops, MRV systems, and concessional finance so that future abatement costs fall. In the current scoring framework, this is one reason P4 ranks above P3: both tighten scarcity relative to P2, but the assumed recycling rule keeps firm burden more manageable while preserving the carbon-price signal. That comparison remains conditional on the paper’s lump-sum recycling assumption and does not yet model a dynamic investment response.

8 Discussion

The analysis highlights that ETS design is a joint problem of environmental coverage, firm-level burden, administrative feasibility, revenue use, and competitiveness risk. A system that maximizes coverage without sufficient MRV capacity may fail administratively. A system that minimizes short-run burden without creating meaningful

scarcity may fail environmentally. A system that relies heavily on grandfathering may protect inefficient firms and weaken allocation credibility. A system that auctions too much too soon may provoke avoidable political resistance. A firm-level simulation framework is useful because it makes these trade-offs observable before implementation, even when the available data are still incomplete. In sustainable development terms, that matters because climate policy in industry must be implemented in a way that reduces emissions while preserving feasible pathways for industrial upgrading, investment, employment, and cleaner production.

For Thailand, the current calibration points to an illustrative benchmark package rather than a definitive policy prescription. The main components are to begin with S2, use 20,000 tCO₂e as the early-design threshold benchmark, apply benchmark-style transitional free allocation rather than permanent grandfathering or immediate full auctioning, increase auctioning gradually, earmark at least part of auction revenue for an industrial-estate transition fund, allow domestic T-VER offsets under a tight quantitative and quality screen, and connect ETS preparation to listed-company climate disclosure. This package is relevant to sustainable development because it links SDG 13 Climate Action to industrial transition capacity, investment in cleaner production, and more credible governance of emissions-intensive manufacturing. Because price-stability tools are not activated in the baseline simulation, they should be treated as a later design choice to be assessed with an explicit reserve or corridor mechanism rather than inferred from the current ranking.

For other emerging economies, the Thailand case suggests that a credible ETS need not begin as a comprehensive economy-wide system. It can start with large industrial emitters, build MRV capacity, test allocation rules, introduce limited trading, recycle revenue into abatement investment, and expand gradually as data and institutions mature.

9 Conclusion

This study develops a firm-level ETS simulation framework and applies it to Thailand’s industrial estates. The implemented Thailand calibration integrates coverage thresholds, cap trajectories, allowance allocation, offset limits, a shadow price from direct-abatement clearing, abatement behavior, administrative costs, revenue recycling, and competitiveness risk, while treating banking and explicit price-stability tools as optional extensions. Its purpose is to support regulatory impact assessment, listed-company transition-risk supervision, and ETS design before full implementation in a way that is directly relevant to sustainable industrial transition.

The Thailand case illustrates how the proposed framework can organize ETS design information under incomplete data. The current calibration supports only conditional scenario comparison. Previous industrial-estate evidence shows that partial threshold-based coverage can regulate a relatively small number of factories while capturing a large share of emissions. Building on that evidence, the current proxy-calibrated scenario results are, within the stated assumptions, most consistent with an initial design centered on Scope 1 emissions from large non-power industrial emitters, benchmark-style transitional free allocation, gradual auctioning, limited domestic offsets, and

targeted recycling of auction revenue into energy-efficiency and low-carbon investment. In sustainable development terms, that combination is most closely aligned with climate mitigation that remains implementable for industrial firms and regulators, particularly in relation to SDG 13 Climate Action, SDG 9 Industry Innovation and Infrastructure, and SDG 12 Responsible Consumption and Production.

A policy recommendation requires observed facility-level emissions, output, firm financials, validated marginal abatement costs, verified offset supply, and robustness analysis over score weights and uncertainty parameters. Until official ETS data become available, the framework should be interpreted as a structured ex-ante tool for policy calibration, transition-risk assessment, and disclosure design rather than as a substitute for ex-post causal evidence.

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Declarations

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Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability. This study uses a combination of licensed commercial data and open-source materials. The open-source inputs used in the calibration are cited in the manuscript. The licensed data are subject to provider access restrictions and therefore cannot be shared publicly, but derived non-restricted analytical outputs are available from the corresponding author on reasonable request.

Author contributions. Wanyok Atisattapong: Resources, Methodology, Investigation, Project administration, Supervision, Funding acquisition and Conceptualization.

Pasin Marupanthorn: Writing – original draft, Investigation, Validation, Resources, Formal Analysis, Data curation, Quantitative Modeling and Conceptualization.

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Consent for publication. Not applicable.

Materials availability. Not applicable.

Code availability. Not specified in the source manuscript.

A Variable Definitions

Table 27: Core variables in the firm-level ETS model

Variable	Definition
E_{i0}^c	Baseline emissions of firm or installation i under coverage boundary c .
E_{it}	Emissions of firm i after abatement in year t .
$D_i^{c,\tau}$	Coverage indicator equal to 1 if firm i is regulated under boundary c and threshold τ .
C_t	Total emissions cap in year t .
r_t	Cap reduction rate relative to covered baseline emissions.
A_{it}^F	Free allowances allocated to firm i in year t .
A_t^Q	Allowances auctioned by the regulator in year t .
O_{it}	Eligible offsets used by firm i in year t .
ω	Maximum offset-use ratio.
N_{it}	Net allowance position after free allocation and offsets; positive for buyers and negative for sellers.
P_t	Shadow price from direct-abatement clearing in the implemented Thailand baseline.
q_{it}	Emissions-reduction rate chosen by firm i .
λ_{is}	Firm- or sector-specific abatement-cost parameter.
C_{it}^{ab}	Abatement cost incurred by firm i .
C_{it}^{adm}	Administrative compliance cost.
C_{it}^{tot}	Total carbon-policy compliance cost.
R_{it}	Firm revenue.
M_{it}	Operating earnings, measured by EBITDA when available.
ξ_{it}^R	Total compliance cost as a share of revenue.
ξ_{it}^M	Total compliance cost as a share of operating earnings.
x_i^E	Emissions-intensity exposure.
x_i^T	Trade exposure.
x_i^P	Cost pass-through ability.

Variable	Definition
x_i^S	Sector emissions-share exposure used in the Thailand leakage screen.
L_i	Composite leakage-risk indicator.
$\bar{O}_t$	Aggregate eligible offsets after applying the offset ratio, available supply, and remaining compliance requirement.
Q_t^{ab}	Direct-abatement target after deducting exogenously available offsets.
w_1, w_2, w_3	Weights on emissions intensity, trade exposure, and pass-through in the generic leakage-risk indicator.
β_k	Policy-score weights on normalized scenario components.
S_{jk}	Normalized value of score component k for scenario j .

B Regression Specifications for the Thailand Firm Extension

This appendix records the regression forms underlying the current listed-firm screening exercise and the future causal designs proposed in Section 7.

B.1 Current predictive screening model

The current listed-firm extension is a predictive screening regression, not a causal treatment model. The estimated specification is

$$\begin{aligned} \text{ROA}_{it} = & \alpha + \beta_1 \log(\widetilde{\text{MCAP}}_i) + \beta_2 \log(\widetilde{\text{GHG}}_{it}) + \beta_3 \text{PF}_{it} + \beta_4 \text{IF}_{it} \\ & + \beta_5 \log(\widetilde{\text{MCAP}}_i) \times \log(\widetilde{\text{GHG}}_{it}) + \gamma_t + \delta_s + \varepsilon_{it}, \end{aligned} \quad (40)$$

where ROA_{it} is return on assets for firm i in year t , MCAP_i is the available Refinitiv market-cap snapshot, GHG_{it} is total reported greenhouse-gas emissions, PF_{it} is revenue divided by assets, IF_{it} is capex divided by assets, γ_t are year fixed effects, and δ_s are sector fixed effects. Tildes denote centered logarithms. Standard errors are clustered by firm. Because annual market-cap histories are incomplete in the downloaded panel, MCAP_i is fixed at the current snapshot across 2022–2024. The specification therefore serves only as an exploratory disclosure screen; it does not include firm fixed effects and should not be interpreted causally.

B.2 Future regression-discontinuity design

If Thailand assigns ETS coverage using a verified emissions threshold τ , a natural local causal design is

$$\begin{aligned} Y_{it} = & \alpha + \theta D_i + f(E_{i,t_0} - \tau) + D_i \times g(E_{i,t_0} - \tau) \\ & + \gamma_t + \delta_s + u_{it}, \end{aligned} \quad (41)$$

where Y_{it} is a post-designation outcome such as emissions intensity, ROA, EBITDA margin, capex, or valuation, $D_i = \mathbf{1}(E_{i,t_0} \geq \tau)$ is the ETS designation indicator, and E_{i,t_0} is verified pre-policy facility emissions. The functions $f(\cdot)$ and $g(\cdot)$ allow flexible slopes on either side of the threshold. If treatment compliance is imperfect, this design becomes a fuzzy regression discontinuity using threshold crossing as an instrument for actual compliance status.

B.3 Future difference-in-differences and event-study design

If Thailand phases in the ETS by sector, estate, or year, a natural causal alternative is a panel difference-in-differences:

$$Y_{it} = \alpha_i + \gamma_t + \theta (\text{Treated}_i \times \text{Post}_t) + X'_{it}\beta + \varepsilon_{it}, \quad (42)$$

where α_i are firm fixed effects, γ_t are year fixed effects, Treated_i identifies firms linked to covered facilities, Post_t identifies post-implementation periods, and X_{it} includes time-varying controls such as firm size, leverage, or energy-price exposure.

The corresponding event-study form is

$$Y_{it} = \alpha_i + \gamma_t + \sum_{k \neq -1} \theta_k \mathbf{1}\{t - T_i = k\} + X'_{it}\beta + \varepsilon_{it}, \quad (43)$$

where T_i is the firm-specific treatment year. The coefficients θ_k allow pre-trend diagnostics and dynamic treatment-effect measurement before and after ETS designation.

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