Climate Policy, Industry Concentration and Technology Adoption

Taxes, Subsidies and Rebates

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Motivation - Heavy Industry Pollution

1. 24% of global GHG emissions stem from industrial installations
   → Most polluting industries are classic "heavy industries"

Iron and Steel	Cement	Fertiliser
22% of French industry emissions	15% of French industry emissions	15% of French industry emissions

2. Characteristics of these heavy industries:
   - Fairly homogeneous commodity product
   - High entry fixed cost

   → Prone to market concentration concerns (Koltay et al. 2021; Hoarau et al. 2025)
3. In the EU, these industries are regulated by the EU ETS
   - Goal: Reduce emissions by putting a cost on them
   - Major margin: Upgrading to low-emission technologies

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Research Question - Output Contraction and Technology Adoption

Research Question of the Project

How should we regulate carbon emissions in concentrated industries?
What drives the welfare implications of these regulations?

→ Analysed specifically highlighting the role of green technology adoption

Carbon pricing in concentrated industries:

- Conventional Wisdom: Tax below cost of carbon, as output already suppressed (Buchanan 1969)
- But: Incentives to adopt also interact with imperfect competition (Hoarau et al. 2025)

→ Two conflicting objectives when regulating emissions in heavy industry:

- Limit output suppression
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This Paper

Develop dynamic model of industry behaviour

- Cournot competition (with capacity constraints)
- Investments into emission abatement (low emission technology) Low-carbon options

Estimate the model parameters for the French cement industry

- Administrative data on production and abatement investment Data
- Minimal distance estimator for static Cournot
  → Construct regional markets (in line with demand data) Markets
  → Exploiting demand and production variations over time
- Full-solution nested fixed-point estimator for dynamic game
  → Exploiting investment behaviour observed under EU ETS regulation

Evaluate environmental regulations for the French cement market

1. Carbon tax level   2. Output-based rebating   3. Technology cost subsidy

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This Project - Literature and Contribution

1. Structural IO & Environmental Regulations

Ryan (2012), Fowlie et al. (2016), Toyama (2024), Gowrisankaran et al. (2024a), and Gowrisankaran et al. (2025) a.o.

- Introduce endogenous green technology upgrading to oligopoly models
  → Thus far studied in single-agent settings (Toyama 2024)
- Apply continuous choice framework (Gowrisankaran et al. 2024b) to oligopoly
  → Allows the model to reflect observed behaviour of low-carbon investments
- Framework for estimation of economic abatement cost
  → Quantification of cost and benefits of regulations

2. Carbon Pricing Impact Evaluations

3. Technology Investment - Theory

This Project - Contribution

1. Structural IO & Environmental Regulations

2. Carbon Pricing Impact Evaluations

Fowlie (2010), Fabra et al. (2014), Martin et al. (2014), Calel et al. (2016), Wagner et al. (2016), Calel (2020), Wagner et al. (2023), and Dechezleprêtre et al. (2023) a.o.

- Explain small output and welfare effects under carbon pricing
  $\rightarrow$ Explicitly explained via technology adoption
- Incorporate insights on technology adoption into structural model
  $\rightarrow$ Rich understanding of mechanisms leading to the reduced-form results
  $\rightarrow$ Structural model allows for counterfactual analyses

3. Technology Investment - Theory

This Project - Contribution

1. Structural IO & Environmental Regulations

2. Carbon Pricing Impact Evaluations

3. Technology Investment - Theory

Laffont et al. (1996), Delbono et al. (1991), Yi (1999), Montero (2002), Requate (2005), Fowlie (2010), and Hoarau et al. (2025) a.o.

- Estimated structural model with data on a regulated industry
  → Quantification of adoption equilibrium and welfare implications

Model Set-up - Dynamic Oligopoly Game

Given - Outside Parameters

- Isoelastic demand per market
- Competitive fringe of small players
- Import supply curve

Static Game - Cournot

- Production cost function
- Environmental compliance cost: $\phi(E, \tau)$
  - $E = q \cdot \eta$ is emissions
  - τ the carbon tax

Dynamic Game - Investment

- Abatement investment cost function

Timing of the model:

1. Technology cost shocks realise
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- Observed:
  - q_i is the annual production by firm i
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  - ϕ the environmental compliance cost (observed under EU ETS, altered in CFs)
- Estimated:
  - δ_1: constant marginal production cost
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Estimation - Abatement Investment Cost

Investment Cost for plant *i* to reach η_i:

$$InvCost_i(\theta_i|\epsilon) = s_i\theta_i\left(\lambda_1 + \lambda_2\theta_i + \lambda_3\epsilon_i\right)$$

- s_i the firm's annual capacity
- $\theta_i \in (0, 100)$ the percentage reduction in emission intensity compared to baseline
- Realised emission intensity: $\eta_i = \frac{100-\theta_i}{100} * \overline{\eta}$ with $\overline{\eta} = 0.63$
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$\rightarrow$ Cost starting from $\theta_i^0 < 100$ to reach $\theta_i > \theta_i^0$:

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$\rightarrow$ To estimate: λ_1, λ_2, λ_3

- Estimation Method - Nested Fixed-Point Estimator
  $\rightarrow$ Match model outcomes to observed investment under EU ETS

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- $\Pi_i^*(\eta, \delta)$ is the per-period profit, given static optimisation
- θ is the vector of θ_i's of all firms (the state variable)
- $P(\theta_{-i}, \sigma(\theta))$ the probability distribution of competitor states
- σ denotes the strategies, mapping the states into action probabilities

$$\sigma : \theta \rightarrow P(\Delta\theta)$$

$\rightarrow$ Equilibrium concept: Markov-Perfect Nash-Equilibrium Details

Counterfactuals - Computation

With the estimated model: Estimation Details

1. Solve the dynamic oligopoly equilibrium for counterfactual policies
2. Simulate the industry path forward, starting at full emission intensity

Value Function Iteration

- Equilibrium invest strategies
- Result: Values of each state

→

Monte-Carlo Simulation

- Simulate forward industry path
- Repeat to compute expected path

Welfare in this economy:

$$W = CS\left(Q^{Dom} + Imports\right) - Damages\left(E^{Dom} + Leakage\right) + \sum Profits - InvCost$$

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Simulation Results - A Taste

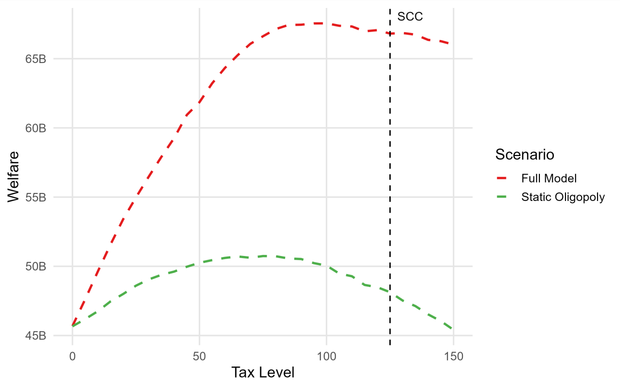

Figure 1: NPV: Total Welfare

- Adoption increases welfare
- Optimal tax between static optimum and SCC

A Taste of Simulation Results - Socially optimal vs. private Investment

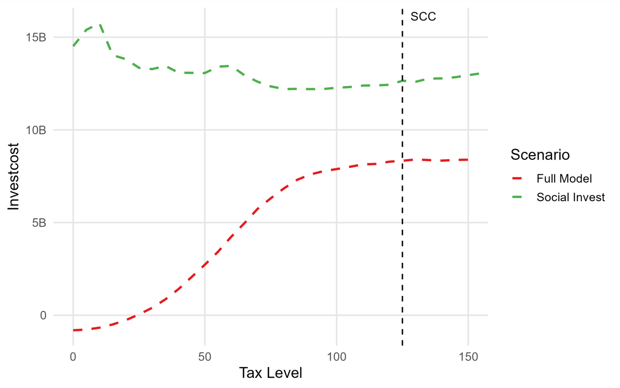

Figure 2: NPV: Socially optimal vs. private investment

Investment under tax stays limited:

- Even an ever-increasing tax cannot reach optimal investment

→ In a dynamic context, solely a tax cannot achieve first-best welfare

Qualitative Results

1. A carbon tax alone cannot achieve welfare optimum
   → Tax needs to be low enough for static efficiency
   → But also high enough for dynamic efficiency
2. Output-based rebate can decouple effective static from dynamic tax
   → High tax with rebating eases the tension between static and dynamic efficiency
   → Allows subsidising the production of even the greenest producers
3. Combining a tax with a technology adoption subsidy allows a similar mechanism
   → Subsidise adoption to mitigate suboptimal incentives
   → Keep tax statically optimal, but cannot subsidise green producers

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Quantitative Results

At SCC of €125/ton:

1. Optimal carbon price between statically optimal tax (Buchanan) and cost of carbon
   → Optimal price of €100/ton (€75/ton implied by a static analysis)
   → Setting the statically optimal tax results in a welfare loss of ≈ 1.6%
2. Output-based rebating can enhance welfare
   → A rebate based on a benchmark of 0.25 can increase welfare by ≈ 6.7% above a tax
3. Combining a tax with a subsidy can enhance welfare
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A Taste of Simulation Results - Market Quantity with OBA

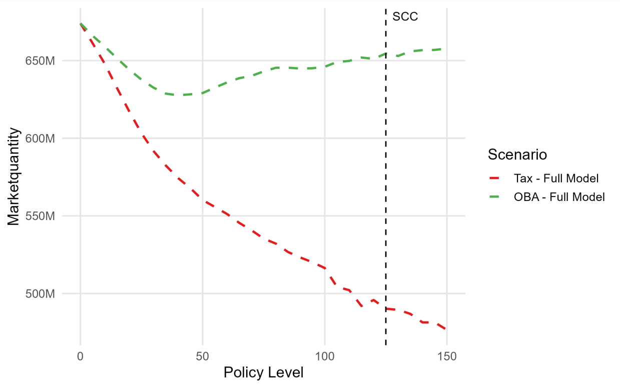

Figure 3: NPV: Quantity (Benchmark at 0.2, varying Tax)

- Production barely suppressed
- Subsidises green producers

→ OBA allows high tax, without strong output suppression

A Taste of Simulation Results - Investment with OBA

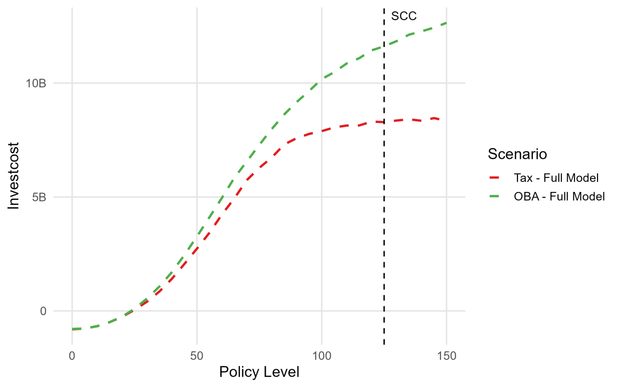

Figure 4: NPV: Investment (Benchmark at 0.2, varying Tax)

- Higher production
  → Higher direct savings

→ OBA increases investment incentives

A Taste of Simulation Results - Total Welfare with OBA

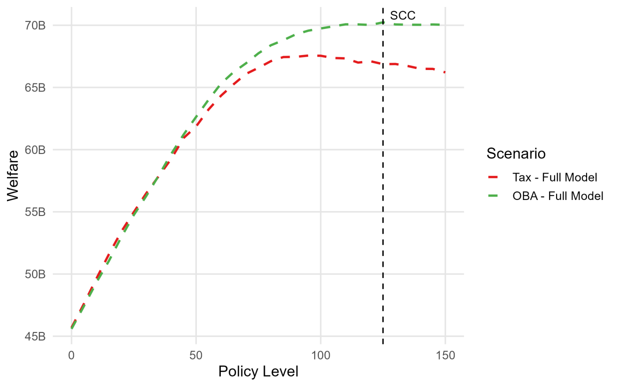

Figure 5: NPV: Welfare (Benchmark at 0.2, varying Tax)

- Decouple static and dynamic tax
- Higher optimal tax

→ OBA even outperforms a direct adoption subsidy

Conclusion

Research question of the project:

- Industry emissions account for a substantial share of emissions
- Technology adoption is necessary to achieve stated reduction goals
- Accounting for technology upgrading and market concentration:
  $\rightarrow$ How should we price carbon in concentrated industries?

Method:

- Documented abatement investment in French Cement sector
- Estimated a dynamic model of industry behaviour
- Computed counterfactual outcomes and welfare

Conclusion:

- Carbon tax needs to balance output suppression and technology adoption
- A technology cost subsidy can deliver welfare gains, but the magnitude is limited
- OBA allows subsidising production, and keeping high tax for dynamic incentives

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Appendix

Abatement Options - Cement Industry

Carbon Capture

→ Capture at exhaust
→ Store or utilise

Calcined Clay

→ Replace limestone with clay
→ Reduce process emissions

Fuel Switch

→ Biofuel feed-in
→ Reduce energy emissions

Characteristics:

1. All options are individually scalable
2. All options are combinable
3. All options require an adjustment of the capital stock

→ Modelling choice: Continuous investment cost function to reduce emissions
→ Approximating this menu of options Back

Empirics - Data

Plant-level:

- Realised abatement investment (2012-2025)
  1. Monetary value reported in Antipol (2012-2022, INSEE)
     → Estimation of the engineering cost function using company reports
     → Translate spending into emission savings
  2. Complemented by hand-collected most recent announcements
- Production capacity (CemNet Global Cement Report; Global Energy Monitor)
  → Hand-collected changes in capacity and ownership since 2012

Firm-level:

- Production
  → Plant-level production inferred from emissions
  → Cross-checked with firm-level administrative data (EAP, INSEE)
- Received subsidies (State Aid Transparency Database, EC)

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Observed (2010-2019) or calibrated:

- q_i is the annual production by firm i
- s_i the firm's annual capacity
- Demand and import elasticities for now taken from the literature (Fowlie et al. 2016)
  $\rightarrow$ Yearly market-specific intercepts fitted given elasticities
- η_i set at 0.63 baseline, with observed investments accounted for

Estimated:

- δ_1: constant marginal production cost
- $\delta_2 \in (0,1)$: capacity utilisation threshold
- δ_3: escalation of cost above the threshold

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Estimation - Production Cost

- I estimate the vector of parameters δ minimising two equally weighted moments (Ryan 2012; Fowlie et al. 2016):
  1. The squared deviation of model-predicted quantities and observed quantities
  2. The squared deviation of marginal revenue and marginal cost at the observed quantities

$\rightarrow$ I identify the cost parameters from the firms' FOCs

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$\rightarrow$ Identifying variation: Demand fluctuations and output response over time (2010-2019)

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Production Cost Estimation - Results

MC (δ_1)	71.74 EUR/ton
Utilisation threshold (δ_2)	77%
Utilisation cost (δ_3)	0.51 EUR

→ Avg. reported price level in my sample period: 109 EUR/ton (≈ 40% mark-up)

→ Carbon price of 75 EUR/ton: ≈ 62% increase in cost (at full emission intensity)

→ Marginal cost increase by ≈ 1 EUR per extra percent of capacity utilisation

→ Standard errors in the working Back

Estimation - Abatement Investment Cost

Investment Cost for plant *i* to reach η_i:

$$InvCost_i(\theta_i|\epsilon) = s_i\theta_i\left(\lambda_1 + \lambda_2\theta_i + \lambda_3\epsilon_i\right)$$

$\rightarrow$ To estimate: λ_1, λ_2, λ_3

- Estimation Method - Nested Fixed-Point Estimator
  $\rightarrow$ Match moments of implied model outcomes to observed investment behaviour
- Solve the model for a guess of parameters, using discretized grid of investment levels
- Map against moments of observed investment

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Abatement Investment Cost Estimation - Identifying variation

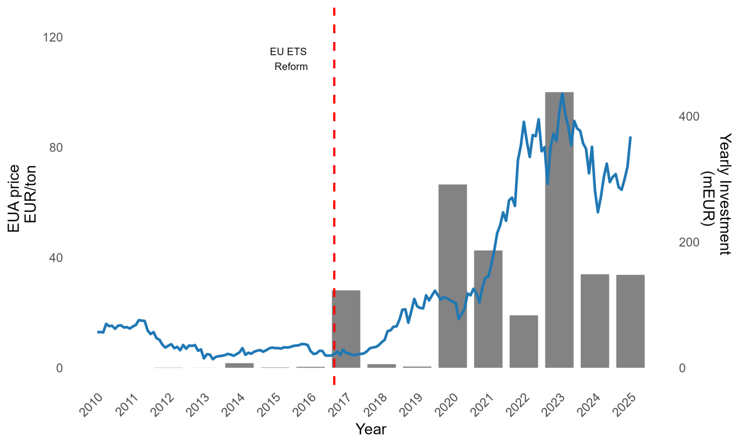

Figure 6: Identifying variation: Which firm invests how much in response to different carbon prices?

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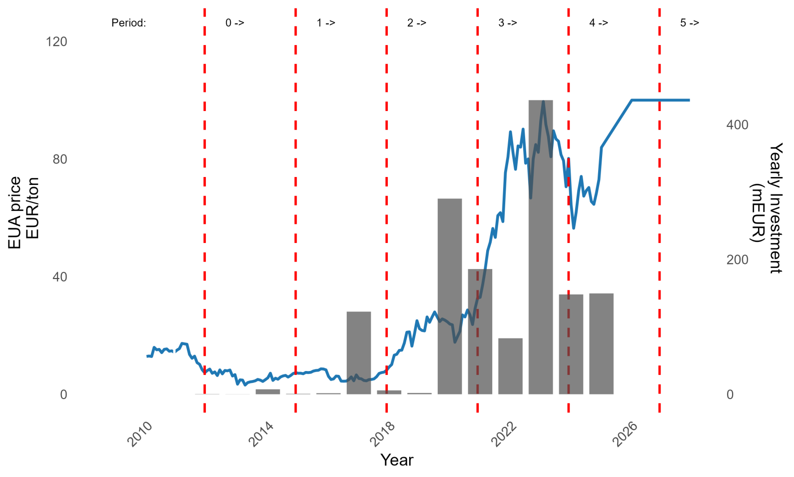
Abatement Investment Cost Estimation - Investment Periods



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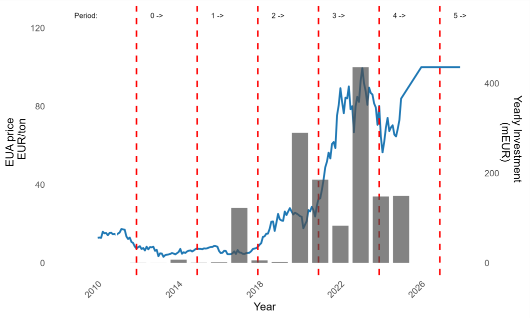
Abatement Investment Cost Estimation - Investment Periods



- Periods to reflect carbon pricing regimes
- Final period after 2025: price at €125/ton
  $\rightarrow$ Solve for infinite continuation value at €125/ton
- Backward induction to t=0, decisions taken for the next period
  $\rightarrow$ Implicit assumption: Correct price expectations

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Abatement Investment Cost Estimation

- Issue: Solving the full dynamic game is computationally expensive
- Solution: Reduced-form policy functions - BBL-style (Bajari et al. 2007)
  $\rightarrow$ Estimate competitor strategy as a simple function of market observables

$$\theta_{i,(t+1)} = \beta_1 \, \text{MarketShare}_{i,t} + \sum_{k=0}^{4} \gamma_k \, \mathbf{1}\{\text{Period}_t = k\} + \beta_2 \, \text{stateExAnte}_{i,t} + \varepsilon_{i,t}.$$

- Let firms optimise against this response
- Turn computation into a single-agent problem

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Abatement Investment Cost Estimation - Investment Periods

- Result: Full set of state-contingent CCP vectors for each firm in each period
- For each firm and period: Extract the correct state-contingent strategy
  $\rightarrow$ Reflect the realised situation each firm found itself in
- I estimate the vector of parameters λ minimising two equally weighted moments
  1. Squared deviation of model-implied expected and observed investment level
  2. Squared deviation of model-implied and observed investment standard deviation

$$InvCost_i(\theta_i|\epsilon) = s_i\theta_i\left(\lambda_1 + \lambda_2\theta_i + \lambda_3\epsilon_i\right)$$

	λ_1	λ_2	λ_3
Estimate	3.73	0.084	4.43

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Dynamic Cost Estimation - Results

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Estimate	3.73	0.084	4.43

Sanity check:

→ Techno-economic estimate: 3.3 €bn for 50% emission reduction (ADEME 2021)

→ Model cost are economic cost (incl. opportunity cost, overhead cost, downtime)

→ My estimates imply: 7.5 €bn (in expectation)

→ Annual turnover French Cement Industry: ≈ 12.5 €bn in 2024

→ Implicit opportunity cost from downtime: ≈ 4 months

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Simulating Counterfactuals - Computation

Two steps:

1. Solve the dynamic oligopoly equilibrium for counterfactual tax levels
2. Simulate the industry path forward, starting at full emission intensity

Value Function Iteration

- Equilibrium invest strategies Details
- Result: Values of each state

→

Monte-Carlo Simulation

- Simulate forward industry path
- Repeat to compute expected path

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Counterfactuals - Welfare Components

- Welfare components in this economy:

$$W = CS\left(Q^{Dom} + Imports\right) - Damages\left(E^{Dom} + Leakage\right)$$
$$+ \sum Profits - InvCost$$

- Simulate forward industry path
- Set emission damages constant at €100/ton: $D(E) = 100 * E$
- Plot NPV of variables of interest
- Comparing: Full dynamic model and static oligopoly
- Carbon revenues are rebated lump-sum

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Model Set-up - Static Components

- Hockey-stick production cost function (Ryan 2012; Fowlie et al. 2016):

$$C(q_i;\delta) = \delta_1 q_i + \mathbb{1}\left[q_i > \delta_2 s_i\right]\delta_3 s_i (q_i/s_i - \delta_2)^2 + \phi(q_i \cdot \eta_i, \tau)$$

- q_i is the annual production by firm i
- s_i the firm's annual capacity
- δ_1: constant marginal production cost
- $\delta_2 \in (0,1)$: capacity utilisation threshold
- δ_3: escalation of cost above the threshold
- $\phi(q_i \cdot \eta_i, \tau)$ the compliance cost, η_i the emission intensity and τ the carbon tax

Static payoff:

$$\Pi_i(q_i;\delta,\eta) = P(Q)\cdot q_i - C(q_i;\delta)$$

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Model Set-up - Dynamic Components

Investment cost for plant i:

$$InvCost_i(\theta_i|\epsilon_i) = s_i\theta_i\left(\lambda_1 + \lambda_2\theta_i + \lambda_3\epsilon_i\right)$$

- s_i the firm's annual capacity
- $\theta_i \in (0, 100)$ the percentage reduction in emission intensity compared to baseline
  $\rightarrow$ Realised emission intensity: $\eta_i = \frac{100-\theta_i}{100} * \overline{\eta}$ with $\overline{\eta} = 0.63$
- ϵ the cost shock, with $\epsilon \sim N(0, 1)$
- Cost starting from $\theta_i^0 < 1$ to reach $\theta_i > s\theta_i^0$:

$$InvCost(\theta_i^0, \theta_i) = InvCost_i(\theta_i) - InvCost_i(\theta_i^0)$$

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Model Set-up - Dynamic Components

Dynamic problem of firm *i*:

$$\max_{\theta_i} V_i(\theta; \delta, \lambda, \epsilon_i, \sigma(\theta)) = \Pi_i^*(\eta, \delta) - InvCost(\theta_i^0, \theta_i) + \beta \int E_{\epsilon_i}[V_i(\theta; \delta, \lambda, \epsilon_i)]\, dP(\theta_{-i}, \sigma(\theta))$$

- $\Pi_i^*(\eta, \delta)$ is the per-period profit, given static optimisation
- θ is the vector of θ_i's of all firms (the state variable)
- $P(\theta_{-i}, \sigma(\theta))$ the probability distribution of competitor states
- σ denotes the strategies, mapping the states into action probabilities

$$\sigma : \theta \to P(\Delta\theta)$$

$\rightarrow$ Equilibrium concept: Markov-Perfect Nash-Equilibrium

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French Cement Market - Four segmented markets

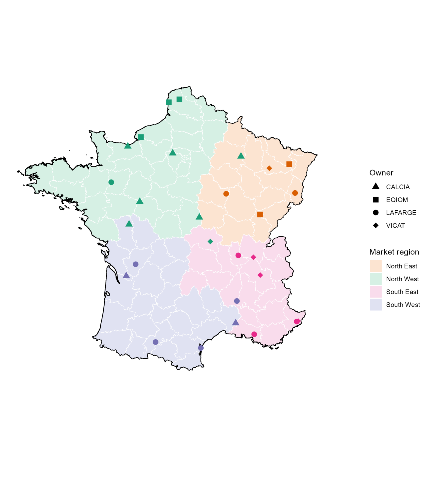

Figure 7: Regions according to France Ciment

- Regionally segregated competition (EC 2014; Miller et al. 2014)
  → But: Import competition via ship (Fowlie et al. 2016)
- France is divided into four regions
- Each region will be a market
- Four large players:
  → VICAT, HolcimLafarge, EQIOM, Calcia
  → Multiple plants each
- Allocation of plants to market:
  → Nearest urban centre
- Competition individually per market

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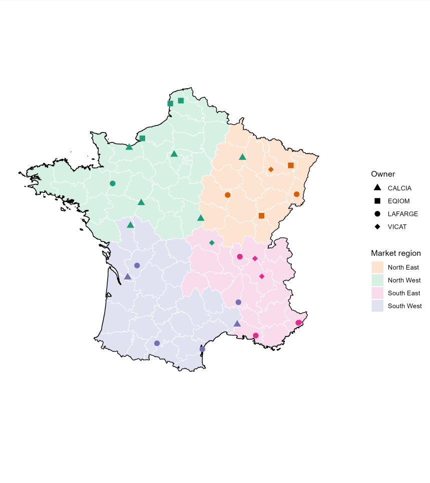

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