The Structural Determinants of Carbon Prices in the European Union Emissions Trading Scheme

Anouk Faure

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Prepared under the supervision of Marc Baudry, at the University of Paris Nanterre (EconomiX) and the Climate Economics Chair

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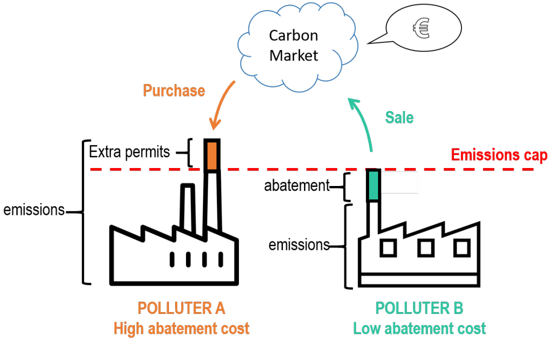
Carbon markets in climate policy

- Market-based emissions trading programs have become inevitable in industrial environmental regulation and climate change mitigation.



- EU-ETS: covers 50% of EU's GHG emissions

Research Question

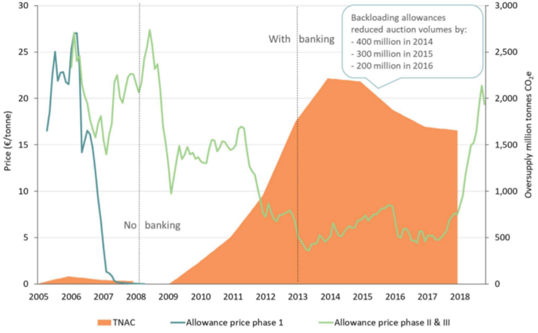
- In the EU-ETS, price trajectory departs from the Hotelling rule
- Little attention given to price drivers related to the internal structure of the carbon market
- **What are they, how do they affect price formation and the design of supply-adjusting policies ?**

Thesis Structure

1. History of **crises and reforms**
2. **Static permit trading** : transaction costs
3. **Dynamic dimension**: technological progress
4. 2021+ EU-ETS design : **carbon price floor**

Chapter 1 - The price is (not) right

- EU-ETS born in 2005 with the Kyoto protocol taken over by Paris Agreement



Notes: *The total number of allowances in circulation (TNAC) reflects the allowance surplus and is determined each year as the total allowances issued minus the allowances surrendered for compliance, taking into account international credits used for compliance and allowances already in the reserve (European Commission, 2015b).*

Source: *Vivid Economics*

- Permit price : main performance indicator, despite compliance with the emission cap

Chapter 1 - A matter of supply and demand ?

- 2009 price drop largely attributed to supply imbalance due to external factors
- Phase 3 reforms: supply-adjusting measures (backloading, MSR)
- Partially worked: prices roses but volatility remains

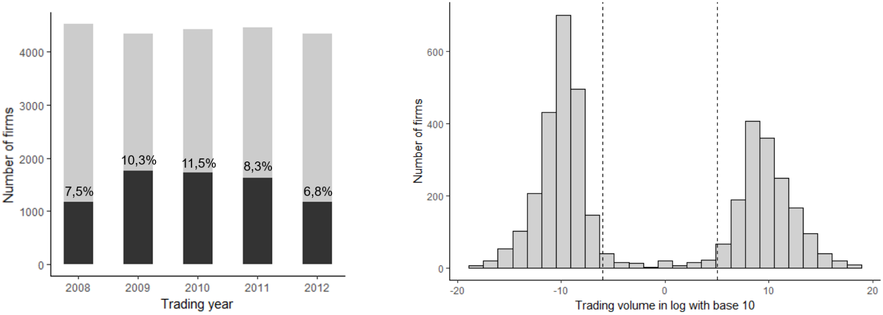
Takeaways

- Price/quantity relationship questionable
- Suggests greater level of complexity in the behavior of market actors

Chapter 2 - Emissions trading with transaction costs

Article with M.Baudry and S.Quemin, R&R in JEEM

- Founding assumption of static permit trading: equi-marginal value principle

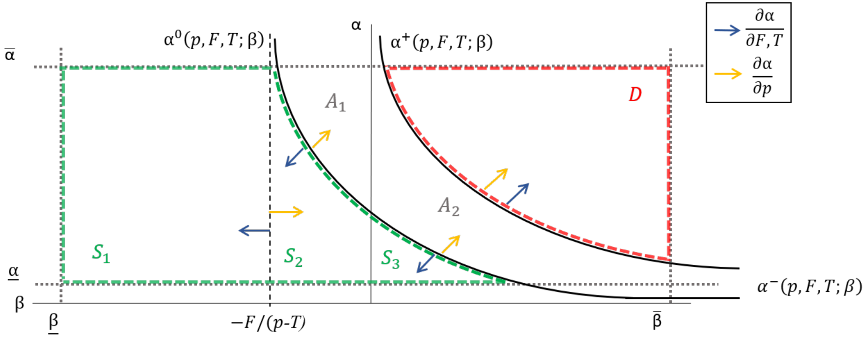


Note: Source: European Union Transaction Log.

Research question : impact of trading costs on firms' trading decisions, market price and policy design ?

Chapter 2 - Modeling approach

- Static, competitive carbon market with a market entry cost F and a proportional trading cost T (mark-up on permit price)
- Firms' characteristics: initial permit deficit $\beta_i = u_i - q_i$ (> 0 or < 0); exogenous marginal cost of abatement α_i



Chapter 2 - Illustration in the EU-ETS

- Calibration to EU-ETS Phase II (2008-12): what values of trading costs best replicate observed firms' market participation and trading decisions ?
  - Calibrated F and T vary between 5-18 k€, and 0.55-1.40 €/tCO_2
- Extra compliance costs : 7%
- In the context of a supply-tightening:
  - Trading costs amplify the price reaction
  - All the more (less) when permits are withdrawn from under-allocated firms (proportionally to their allocation)

Chapter 2 - Takeaways

Results

1. Firms take little advantage of static flexibility offered by the EU-ETS : missed gains from trades
2. Compliance costs highly depend on the size of the permit endowment and the allocation method : important source of heterogeneity between economic sectors

Policy implications

1. Mitigate trading costs: monetary help, more transparency & support, e.g. initial training
2. Harmonize allocation method $\longrightarrow$ full auctioning : improve effort sharing

Chapter 3 - Technological progress and price formation

Article with M. Baudry accepted in FAERE WP

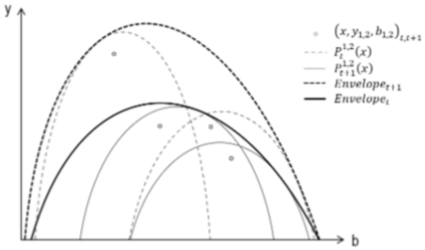
- Chapter 2: permit deficits are important determinants of price formation
  - Baseline emissions unlikely to be constant yet

How does technological progress affect carbon price formation through plants' marginal abatement cost curves ?

- No assumption about the nature of technological progress ex-ante : improvement of total factor productivity
- Characterizing criterion : *strongly directed*, *weakly directed*, *non-directed*

Chapter 3 - Technological frontier framework

Figure 2: Plant and industry technological frontiers



Note: Representation at t and $t+1$ of the production sets $P(x)$ of two producing plants producing one desirable good and one pollutant, y and b, and using x inputs.

- Empirical application : manufacturing/power sector from 2013-17
- Calibration approach : directional distance functions
- Numerical industry m.a.c.c. curves: revenue maximization under pollution constraint

Chapter 3 - Results

- Efficiency analysis : high-carbon intensity plants experience more productivity gains than low-carbon intensity ones
- Technological progress :
  - Baseline-increasing technological progress more frequent, whether directed or non-directed
  - Directed technological progress more often strongly directed in highly carbon intensive industries
  - M.a.c.c. curves influenced by baseline variations
- Market equilibrium :
  - Technological progress inflates equilibrium prices in our samples
  - Transfers from low to high carbon intensity plants

Chapter 3 - Takeaways

Results

1. Environmental regulations do not necessarily lead to 'low-carbon' technological progress
2. EU-ETS often perceived as a relative rather than absolute cap on emissions
3. Technological progress alters the effective emissions ceiling over-time

Policy implications

1. Limits of benchmarking : gives the perception of a carbon intensity target; little dynamic flexibility
2. Full auctioning circumvents these limits
3. d.d.f. : methodological alternative to benchmarking procedure ?

Chapter 4 - Carbon price floor design

Article with M.Pahle and S.Okullo under review in JEEM

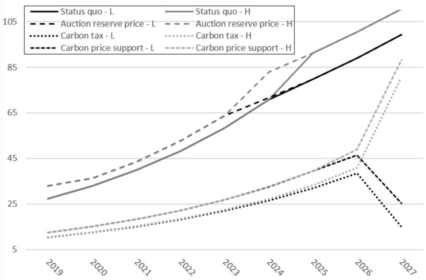
- Which design for the EU-ETS ?
- In this context, MSR may not be an adequate instrument to uphold prices and reduce their volatility
- Carbon price floor: in policy debates for a while, on the table again at the eve of 2021 MSR review
- *Hybrid schemes* proven beneficial

Can a carbon price floor support and stabilize prices in the EU-ETS, and what are design options ?

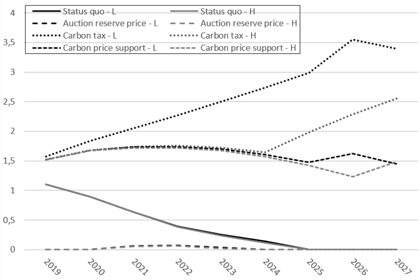
Chapter 4 - Modeling approach

- Numerical inter-temporal optimization model calibrated on the EU-ETS power sector & current MSR rules (Mauer&Okullo 2019)
- Electricity producer maximizes sales revenue over $T \in (2019:2027)$
  - Electricity can be produced from fossil or renewable generation source
  - Producer can buy allowances to cover emissions from carbon input
  - She can invest in both generation capacities
- Exogenous energy demand with linear growth (1% or 0-2% in stochastic simulations)
- Status quo vs. policy scenarios : secure minimum price of 30€/tCO_2
  - **Auction reserve price** (implemented as a buyback mechanism)
  - **Flat tax on emissions**
  - **Carbon Price Support (CPS)** : top-up levy

Chapter 4 - Results



(a) Effective price of pollution (€/tCO_2e)



(b) Permit bank (bn EUA)

- Supply-adjusting policies (MSR, Auction Reserve): higher market prices, less price volatility
- Consequences on green investment and cumulative emissions

Chapter 4 - Takeaways

Results

1. Initial size of surplus matters for the choice of an instrument
2. Supply-adjusting policies outperform extra taxes to uphold and stabilize EUA prices in the power sector...
3. ...and to steer investment in renewable capacity, and accelerate fossil decommissioning

Policy implications

1. Extra taxes could be counterproductive in the long run
2. Drastic permit cancellations put pollution costs at risk of rising uncontrollably
3. MSR 2021 review: 'Price stability reserve' ?

Conclusion

Policy implications

1. Much greater level of complexity than the "simple" model of inter-temporal permit trading
2. Limited participation on the part of polluters & ambiguous incentives
3. Calls for a massive simplification of the system
   - Restrict carbon market to polluters/ financial actors acting on their behalf
   - Same allocation rule for everyone: auctioning
   - Leave aids to the discretion of member states/ solidarity funds financed by auction revenues
4. MSR 2021 review: transparency & consistency seem fundamental
   - Difficult compromise between certainty on prices or on quantities

Conclusion

Thank you for your attention !

Chapter 2 - Calibration details

1. Infer firms' m.a.c. slopes $\alpha_{i,t}$ and net deficits $\beta_{i,t}$
   - $\alpha_{i,t} = EMVP$ corrected with T
   - $u_{i,t} =$ rolling average of t-3 emissions
   - $q_{i,t}$ corrected with bank increments
2. Find $\hat{p}_t$ for a range of F, T pairs
3. Yearly fixed effect η_t neutralises $p_t^r - \hat{p}_t$: in firm-level permit deficits $\beta = u_{i,t} + \eta_t / \alpha_{i,t} - q$
4. Choice criterion for F, T: minimize discrepancies between modeled and observed trading decisions. Weighted Shannon's entropy: $\left(\mathcal{H}/\log(6)\right) \times \left(1 - \sum_{i=1}^{6} |\mathcal{E}_i|/N\right) \in [0;1]$

Observations

Model	Autarkic	Buyer	Seller
Autarkic	–	$\mathcal{E}_1$	$\mathcal{E}_2$
Buyer	$\mathcal{E}_3$	–	$\mathcal{E}_5$
Seller	$\mathcal{E}_4$	$\mathcal{E}_6$	–

Chapter 2 - Calibration results

Table 2: Annual calibration results (2008-2012)

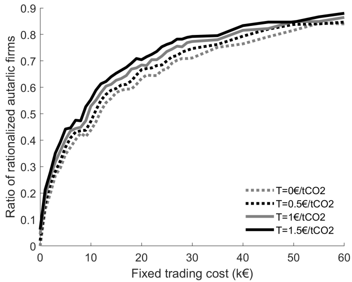
	p_t^r	η_t	F	T	T/p_t^r	$\mathcal{H}/\log(6)$	$1-\sum_{i=1}^{6}\lvert\mathcal{E}_i\rvert/N$
2008	19.6	4.1	10	0.55	2.8%	0.74	0.90
2009	13.3	-0.3	18	1.40	10.5%	0.66	0.85
2010	14.3	8.1	5	0.55	3.8%	0.76	0.89
2011	13.1	0.3	16	1.30	9.9%	0.66	0.87
2012	7.4	0.3	8	0.60	8.1%	0.67	0.90

Note: p_t^r, η_t and T given in €/tCO_2. F given in k€.

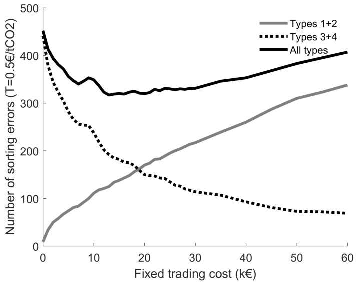
- η_t large in 2010: baseline need to be shifted up (increased permit deficit) to replicate observed price
- Product of right columns = final index, maximum when equal to 1

Chapter 2 - Sensitivity of indexes

Figure: Selection criteria as functions of F and T (2009 sample)



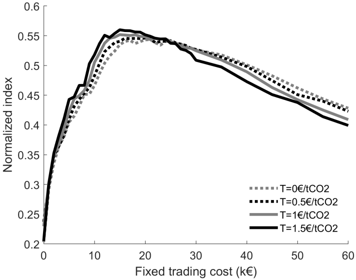
(a) Ratio of rationalized autarkic firms



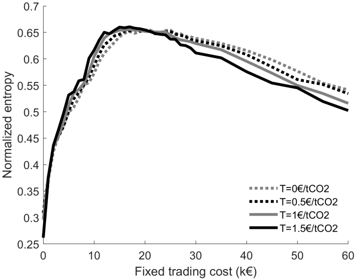
(b) Number of sorting errors (T=0.5/tCO_2)

Chapter 2 - Sensitivity of indexes

Figure: Selection criteria as functions of F and T (2009 sample)



(a) Normalized index



(b) Normalized entropy

Chapter 2 - Supply control

Table 3: Price responses to a $\frac{1}{6}$ supply tightening with different incidence scenarios

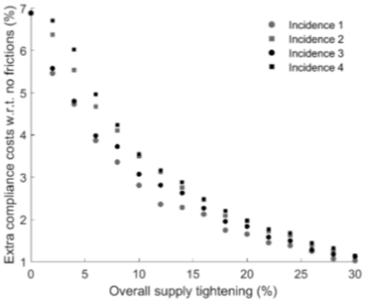
		Incidence scenario			
		(1)	(2)	(3)	(4)
2009 (p^r=13.3)	$(p^\star - p^r)/p^r$	0.70	0.70	0.70	0.70
	$(\hat{p} - p^r)/p^r$	1.11	1.29	1.19	1.59
	$(\hat{p} - p^r)/(p^\star - p^r)$	1.59	1.84	1.70	2.27
2012 (p^r=7.4)	$(p^\star - p^r)/p^r$	1.04	1.04	1.04	1.04
	$(\hat{p} - p^r)/p^r$	2.14	2.47	2.27	2.79
	$(\hat{p} - p^r)/(p^\star - p^r)$	2.06	2.38	2.18	2.68

Note: p^r is the pre-tightening reference price in €/tCO_2, $p^\star$ (resp. $\hat{p}$) is the post-tightening price without (resp. with calibrated) trading costs. Incidence scenario: permits are withdrawn (1) proportionally to firms' allocations, uniformly across all (2), overallocated (3) or underallocated (4) firms in the annual samples.

- Lower price to begin with $\longrightarrow$ more sellers in the market $\longrightarrow$ greater price increase

Chapter 2 - Welfare

Figure 5: Compliance costs for a 0–30% supply tightening with different incidence scenarios



Note: Based on the 2009 select sample of firms. Incidence scenario: permits are withdrawn (1) proportionally to firms' allocations, (2) uniformly across all, (3) overallocated or (4) underallocated firms.

Comparative statics

- Change in the trading cost

$$\frac{\mathrm{d}\hat{p}}{\mathrm{d}K} = -\frac{\partial V(\hat{p},F,T)/\partial K}{\partial V(\hat{p},F,T)/\partial p} \gtrless 0, \tag{1}$$

where

$$\frac{\partial V(\hat{p},F,T)}{\partial K} = \frac{\partial S(\hat{p},F,T)}{\partial K} - \frac{\partial D(\hat{p},F,T)}{\partial K}$$

- Impact of a supply cutback

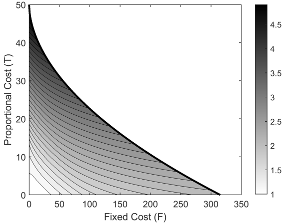
$$\frac{\mathrm{d}\hat{p}/\mathrm{d}\mathcal{Q}}{\mathrm{d}p^\star/\mathrm{d}\mathcal{Q}} = \underbrace{\left(|\mathcal{S}(\hat{p},F,T)| + |\mathcal{D}(\hat{p},F,T)|\right)}_{\text{distribution effect } \leq 1} \underbrace{\frac{\partial V(p^\star,0,0)/\partial p}{\partial V(\hat{p},F,T)/\partial p}}_{\text{price effect } \gtrless 1} \gtrless 1. \tag{2}$$

$$\begin{aligned}\partial V(\hat{p},F,T)/\partial p =& \partial V(p^\star,0,0)/\partial p - \nearrow \text{ in net supply of autarkic firms} + \\ & \nearrow \text{ in net supply due to new entries and exits}\end{aligned} \tag{3}$$

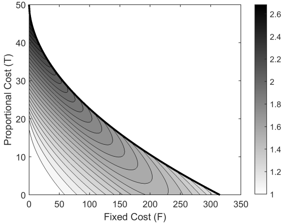
- Last term disappears if $F = 0$

Chapter 2 - Numerical examples I

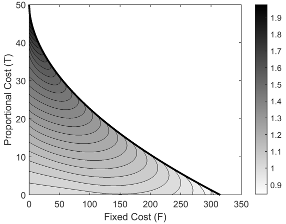
Figure: Ratios $\hat{p}_0/p_0^\star$



(a) $\alpha_\alpha = \beta_\alpha = \alpha_\beta = \beta_\beta = 1$ ($p_0^\star = 9.8$)



(b) $\alpha_\alpha = 3,\ \beta_\alpha = \alpha_\beta = \beta_\beta = 1$ ($p_0^\star = 18.0$)

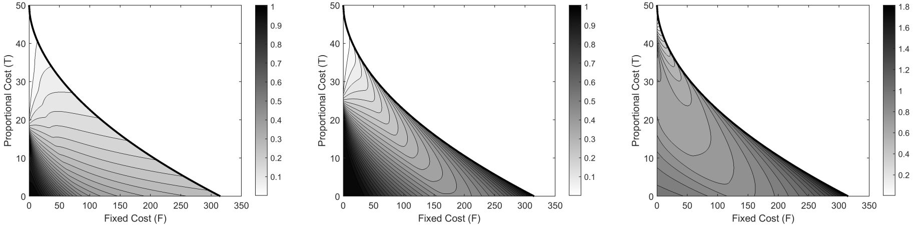


(c) $\alpha_\beta = 3,\ \alpha_\alpha = \beta_\alpha = \beta_\beta = 1$ ($p_0^\star = 24.4$)

- (a): $\hat{p} > p^\star$ always; (b) $\hat{p} > p^\star$; (c) $\hat{p} \gtrless p^\star$
- $\hat{p}$ increases less in (b) and (c) due to demand being relatively more constricted

Chapter 2 - Numerical examples II

Figure: Ratios $\frac{\hat{p}_t - \hat{p}_0}{\hat{p}_0} \Big/ \frac{p_t^\star - p_0^\star}{p_0^\star}$



(a) $\alpha_\alpha = \beta_\alpha = \alpha_\beta = \beta_\beta = 1$ ($p_t^\star = 13.7$)

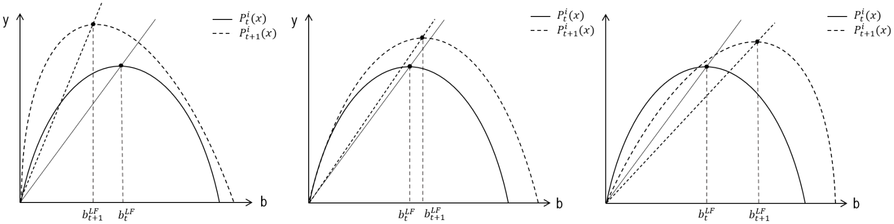
(b) $\alpha_\alpha = 3$, $\beta_\alpha = \alpha_\beta = \beta_\beta = 1$ ($p_t^\star = 25.2$)

(c) $\alpha_\beta = 3$, $\alpha_\alpha = \beta_\alpha = \beta_\beta = 1$ ($p_t^\star = 28.3$)

- (a): $\nearrow \hat{p} < \nearrow p^\star$ always; (b) $\nearrow \hat{p} < \nearrow p^\star$ always ; (c) $\nearrow \hat{p} \gtrless \nearrow p^\star$
- (a) and (b): increase in net supply due to new entries & exists (extensive margin) $>$ loss in net supply due to autarkic firms (intensive margin) $\longrightarrow$ price effect < 1
- (c): net supply less reactive with TC $\longrightarrow$ price effect > 1

Chapter 3 - Technological frontier framework

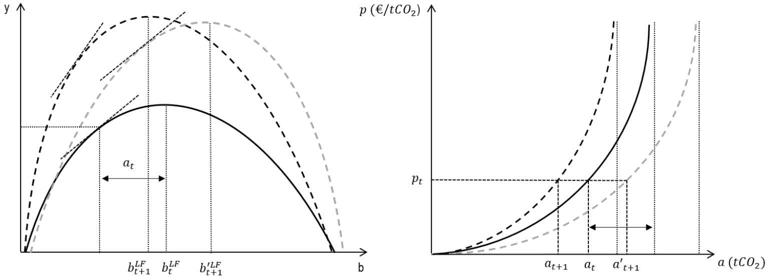
Figure: Nature of technological progress



(a) Strongly directed (b) Weakly directed (c) Non-directed

Chapter 3 - Industry m.a.c. curves

Figure: Technological change and m.a.c. curves



Chapter 3 - Data

- Data collection : inputs (labor, capital and energy in €), good output (production in €) and bad output (CO_2) emissions at the plant level, binned by NACE rev.2 4-digit code
- Orbis (Amadeus) and EUTL

Industry	NACE rev. 2	Activity description
Baked clay	23.32	Manufacture of bricks, tiles and construction products, in baked clay
Cement	23.51	Manufacture of clinkers and hydraulic cements, including Portland, aluminous cement, slag cement and superphosphate cements
Chemicals	20.1(2-3-4)	Manufacture of organic and inorganic basic chemicals, dyes and pigments
Electricity	35.11	Production of electricity, including operation of generation facilities that produce electric energy
Metallurgy	24.1	Manufacture of basic iron and steel and of ferro-alloys
Paper	17.12	Manufacture of paper and paperboard
Plaster	23.52	Manufacture of plasters of calcined gypsum or calcined sulphate, and manufacture of quicklime, slacked lime and hydraulic lime

Chapter 3 - DDF

1. Directional distance function:

$$\vec{D}_i(x, y, b; g_y, -g_b) = \sup\{\beta : (y + \beta g_y, b - \beta g_b) \in P(x)\}$$

2. Translation property

$$\vec{D}_i(x, y, b; g_y, -g_b) = \vec{D}_i(x, y + s \times g_y, b - s \times g_b; g_y, -g_b) + s$$

3. $\longrightarrow$ Parametric, quadratic technological frontier, $g = (1; -1)$

$$D_{i,t}(x_{i,k,t}, y_{i,t}, b_{i,t}) = \alpha_0 + \sum_{k=1}^{3} \alpha_k x_{k,i,t} + \beta_1(y_{i,t} + b_{i,t}) + \frac{1}{2}\sum_{k=1}^{3}\sum_{k'=1}^{3} \alpha_{kk'} x_{k,i,t} x_{k',i,t} + \frac{1}{2}\beta_2(y_{i,t} + b_{i,t})^2 + \sum_{k=1}^{3} \delta_k x_{k,i,t}(y_{i,t} + b_{i,t}) + b_{i,t} \tag{4}$$

with parameter restrictions: (i) $\gamma_1 = \beta_1 + 1$, (ii) $\beta_2 = \gamma_2 = \mu_2$, (iii) $\delta_n = \eta_n$ and (iv) $\alpha_{nn'} = \alpha_{n'n}$

Chapter 3 - Calibration details

- Linear minimization program.

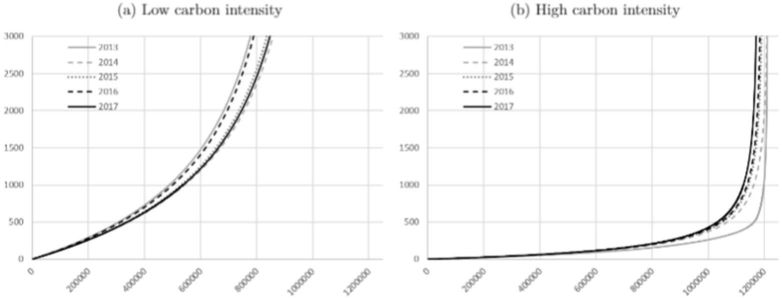
$$
\begin{aligned}
& Min\ \left[\vec{D}_{i,t}(x_{i,k,t}, y_{i,t}, b_{i,t}; g)\right] \quad \text{such that} \\
& (a) \quad \vec{D}_{i,t}(x_{i,k,t}, y_{i,t}, b_{i,t}; g) \geq 0 \\
& (b) \quad \partial \vec{D}_{i,t} / \partial y_{i,t} \leq 0 \\
& (c) \quad \partial \vec{D}_{i,t} / \partial b_{i,t} \geq 0 \\
& (d) \quad \partial \vec{D}_{i,t} / \partial x_{i,t} \geq 0 \\
& (e) \quad \vec{D}_{i,t}(x_{i,k,t}, 0, 0; g) < 0
\end{aligned}
$$

- Sequential production possibility set approach

Chapter 3 - Marginal abatement cost curves

- Industry m.a.c. curves generated with fixed inputs (2013)

Figure 5: Marginal abatement cost curves, baked clay (23.32)



Note: The y-axis reports the marginal cost of abatement in €/tCO_2 and the x-axis reports abatement levels.

Chapter 3 - Results

Table: Summary of abatement dynamics

Industry	Carbon intensity	Nature of T.P.	Ave. abatement, EUA prices	Ave. abatement, 100/tCO_2	%Δ in abatement, 100/tCO_2
Baked clay	0.4	*weakly directed*	0.5%	8.1%	+10.4%
	3.6	*strongly directed*	4.2%	48.8%	-10.9%
Cement	5.1	*non-directed*	5.8%	55.7%	+57.1%
Chemicals	0.3	*strongly directed*	1.1%	13.4%	-11.3%
Electricity	1.1	*weakly directed*	1.3%	19%	+7.2%
Metallurgy	0.1	*non-directed*	0.1%	2.2%	+16.7%
	0.5	*non-directed*	0.6%	10.2%	+30.4%
Paper	0.1	*weakly directed*	0.1%	2.6%	+3.9%
	0.5	*strongly directed*	0.5%	8.1%	-13.3%
	1.1	*strongly directed*	1.2%	18.7%	-28.4
Plaster	2.8	*non-directed*	3.2%	39.4%	+17%

Chapter 3 - Market equilibrium

Industry	Emissions share	Carbon intensity	Net demand ($mtCO_2$)				
			2013	2014	2015	2016	2017
Baked Clay (23.32)	14.2%	0.4 3.6	0.388 0.676	0.507 0.698	0.499 0.619	0.415 0.437	0.504 0.438
Cement (23.51)	14.1%	5.1	11.318	12.159	11.596	11.819	13.561
Chemicals (20.1)	4.8%	0.3	6.779	5.579	6.132	6.154	6.225
Electricity (35.11)	1,2%	1.1	32.733	33.752	33.203	31.894	31.745
Metallurgy (24.1)	3.1%	0.1 0.5	1.934 2.483	1.988 2.900	2.358 3.557	2.582 4.144	2.642 3.533
Paper (17.12)	13.9%	0.1 0.5 0.9	0.389 0.988 5.221	0.647 0.897 3.452	0.643 0.952 2.916	0.640 0.976 4.224	0.515 0.886 3.071
Plaster (23.52)	12.4%	2.8	3.301	3.643	3.739	2.927	3.085
Clearing price ($/tCO_2$)			4	7	19.9	44.2	45.1
Price gap ($/tCO_2$)			**/**	**+3**	**+12.9**	**+24.3**	**+0.9**

- (Baseline(t) - Allocation(t)) + AutonomousDemand(2013) = Abatement(t,p)
- Net demand(t) = (Baseline(t) - Allocation(t)) - Abatement(t,p)

Chapter 3 - Counterfactual

- 2013 inputs & allocation, current technology

Fixed inputs (2013), fixed allocation (2013), current technology

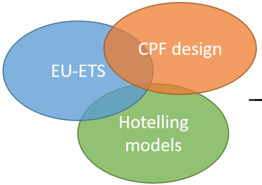
	2013	2014	2015	2016	2017
Net demand (mtCO2)	67 997 322	67 503 431	72 278 371	85 825 780	85 642 341
Baseline emissions (mtCO2)	103 684 731	103 190 840	107 965 780	121 513 189	121 329 750
Agg. Allocation (mtCO2)	35 687 409	33 898 256	32 819 540	33 272 244	32 033 849
Clearing price (€/tCO2)	650	641	645	667	634

- Baseline ↗ due to weakly directed/non-directed technological progress
- Market permit deficit increases (nuanced by industry)

Chapter 3 - Porter Hypothesis

- "Weak" version: properly designed environmental regulation may spur innovation (R&D expenditure or patents) cf Calel and Dechezleprêtre (2014)
  - Our approach: no causality, reverse argument - effect of TP on price formation?
- "Strong" version: impact of environmental regulation on the business performance
  - Our approach: pollution constraint implies a revenue sacrifice which can be mitigated by directed TP (more revenue for same level of pollution)...
  - ...but one has to account the indirect effect of TFP improvement on market prices
  - Only strongly directed TP mitigates "compliance costs" on the carbon market
- Productivity analysis: no clear link between productivity gains & nature of TP

Chapter 4 - Modeling approach I



Schopp et al (2015 – pre-reform):
- Dynamic, deterministic partial equilibrium model
- Emitter minimizes abatement costs, hedgers & speculators
- Macc curves: Landis (2015)
- Test 3 MSR designs and a price stability reserve (CPF 10/20€/tCO2) with 5% increase annually
- Performance criteria : efficiency, credibility, consistency

Fell (2016 – pre-reform)
- Stochastic dynamic model of cap and trade
- Firm minimize abatement cost
- Shocks on BAU emissions, macc curves: Landis (2015)
- Tests MSR + PSR (floor + hard/soft collar with width 20 or 40€/tCO2)
- Price triggers implemented as a buyback mechanism

Brink et al (2016 – pre-reform)
- Multi-region/sector dynamic CGE model WordlScan
- Test CPF at 20€/tCO2: AR price, top-up tax, fixed tax
- Macc derived from bottom-up models (end-of-pipe technologies)

Hintermayer et al (2020 – post-reform)
- Discrete dynamic optimization model with current MSR
- CPF designs: auction reserve as a buyback + top-up tax (40€/tCO2)
- Quadratic Macc curves calibrated with ad-hoc method
- r=8%, constant BAU
- Explore impact of CPF on market outcomes, state revenues, cancellation

- ❖ "Classic" numerical model of permit trading
- ❖ Exogenous macc curves
- ❖ Uncertainty: shocks on BAU
- ❖ CPF designs: 20-40€/tCO2
- ❖ Performance indicators

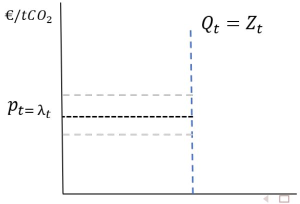
- ❖ Maximization of electricity sales
- ❖ Endogenous abatement costs (foregone revenue from fossil generation), exogenous investment costs
- ❖ Uncertainty: shocks on electricity demand
- ❖ CPF designs: 30€/tCO2
- ❖ Investment in generation capacity

Chapter 4 - Modeling approach II

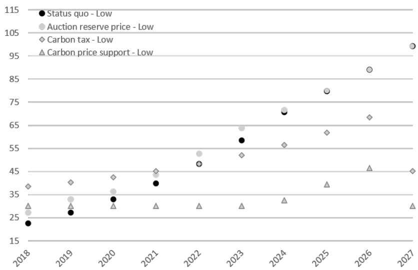
- Typical model : $\min \sum_{t=0}^{T} \beta^t [C(u_t - e_t) + p_t Z_t] \longrightarrow C'(u_t - e_t) = p_t$ (1)
  Z_t is a transfer within the secondary market
- Us : $\min \sum_{t=0}^{T} \beta^t [-ElecSupply \times P_{elec} + CarbonInput + InvCost + p_t Z_t]$
  FOC : $-$Marg. revenue product from fossil-based elec. $= p_t \longrightarrow$ similar to (1)
  Z_t is a transfer from the primary to secondary market
- Market clearing

$$\mathcal{L}^W = \sum_{t=0}^{T} \beta^t \{p_t(Z_t - Q_t) + \mu_t(C_t - Q_t) + \lambda_t\big(B_t + Z_t - F_t - B_{t+1}\big) + \dots\}$$

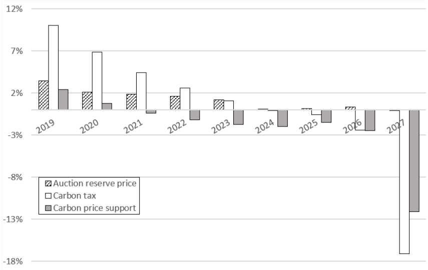
$$FOC : (Q_t)\ p_t = \mu_t \quad ; \quad (Z_t)\ p_t = \lambda_t \tag{5}$$



Chapter 4 - Market outcomes

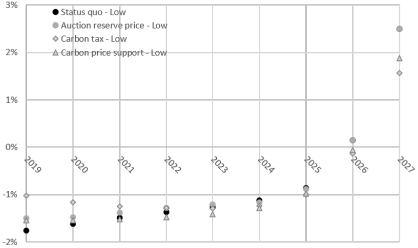


(a) Effective cost of pollution (€/tCO_2)

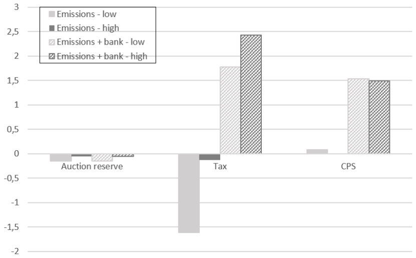


(b) Investment in RE (%)

Chapter 4 - Emissions and fossil decommissioning



(c) Low demand



(d) Cumulative emissions savings (bn EUA)

Chapter 4 - Main assumptions

- Marginal investment cost :

  Financing of initial capacity (€) + inv. cost (€/MW) × new inv. (MW)

  - Calibrated to match observed investment expenditures levels in 2018
- Electricity demand :
  - Linear specification : $p =$ choke price $-$ elasticity $\times$ demand
  - Autonomous demand grows (upward shift) at 1%
  - Shocks on demand : 0 or 2% growth rate with equal chances
- Discount rate : 10% - upper range
- Depreciation rate : 2,5% - inverse of ave. lifetime of power plant
- Initial quantities (MSR, ceiling, trigger threshold, bank) adjusted with 0.73 factor