# Technology Choice Under Emissions Regulation

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# Before Proceeding

# Q

How should we design emission limiting policies? Taxes or caps?

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## EU Emissions Trading System has reduced emissions in the sectors covered by 50% since 2005

In 2024, emissions under the EU Emissions Trading System (EU ETS) were further reduced. The power sector was again the most important driver of the decarbonisation progress.


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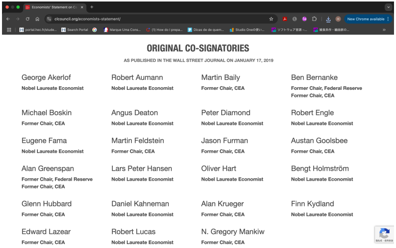
NEWS ARTICLE | 3 December 2024 | Directorate-General for Climate Action | 1 min read

## Emissions Trading System for buildings, road transport and small industry (ETS2): cap adopted for 2027



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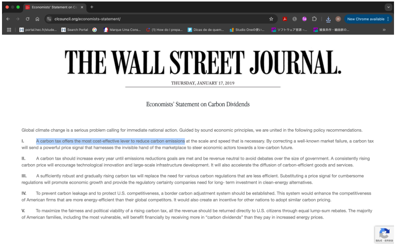


# THE WALL STREET JOURNAL.

THURSDAY, JANUARY 17, 2019

Economists' Statement on Carbon Dividends

Global climate change is a serious problem calling for immediate national action. Guided by sound economic principles, we are united in the following policy recommendations.

**I.** A carbon tax offers the most cost-effective lever to reduce carbon emissions at the scale and speed that is necessary. By correcting a well-known market failure, a carbon tax will send a powerful price signal that harnesses the invisible hand of the marketplace to steer economic actors towards a low-carbon future.

**II.** A carbon tax should increase every year until emissions reductions goals are met and be revenue neutral to avoid debates over the size of government. A consistently rising carbon price will encourage technological innovation and large-scale infrastructure development. It will also accelerate the diffusion of carbon-efficient goods and services.

**III.** A sufficiently robust and gradually rising carbon tax will replace the need for various carbon regulations that are less efficient. Substituting a price signal for cumbersome regulations will promote economic growth and provide the regulatory certainty companies need for long- term investment in clean-energy alternatives.

**IV.** To prevent carbon leakage and to protect U.S. competitiveness, a border carbon adjustment system should be established. This system would enhance the competitiveness of American firms that are more energy-efficient than their global competitors. It would also create an incentive for other nations to adopt similar carbon pricing.

**V.** To maximize the fairness and political viability of a rising carbon tax, all the revenue should be returned directly to U.S. citizens through equal lump-sum rebates. The majority of American families, including the most vulnerable, will benefit financially by receiving more in "carbon dividends" than they pay in increased energy prices.

# Context

1. Firms choose **capacity** portfolios and production but face **demand uncertainty** and **emission limiting policy**
2. If tax, know before-hand the price of production. If cap, the price of production is also uncertain
3. Serve-to-order model (70% of Europe's power generators)
4. Uncertainty known in the short-run

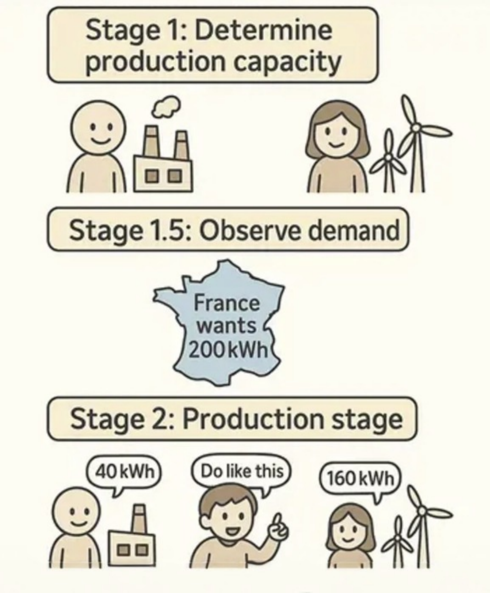
## Emission Tax Problem

## Cap-and-Trade Problem

### Dominant Second Stage Technology

### No Dominant Second Stage Technology

## Implications


Stage 1: Determine production capacity
Stage 1.5: Observe demand
France wants 200kWh
Stage 2: Production stage
40kWh
Do like this
160kWh

# Overall Decision Problem

**1. Capacity Choice**

1. Choose: $K_1, K_2$ (with total cost $K_1\beta_1 + K_2\beta_2$)
2. Maximize: Expected Profit

**1.5. Uncertainty solving $\tilde{D} = d$**

**2. Production Choice**

1. Choose: $q_1, q_2$
2. Subject to: $q_i \leq K_i, \sum_{i=1}^{2} q_i \leq d$
3. Maximize: Total Operating Margin

Technologies $i \in N = \{1, 2\}$

- $\beta_i \geq 0$ Fixed investment cost/unit of capacity
- $\gamma_i \geq 0$ Fixed operating and maintenance (O&M) cost
- $b_i \geq 0$ Variable operating cost
- $\alpha_i \geq 0$ Emission intensity parameter; $\alpha_1 \geq \alpha_2$

1. $p^B$ Baseline price, $\tau$ emission tax rate, $\omega$ pass through of portion of the expensive technology
2. $p(\tau) = p^B + \max_i(b_i + \alpha_i \tau)\omega$ Price

# Second Stage

1. Unmet demand penalty $r$
2. Per unit margin $\eta_i(\tau) = p(\tau) + r - b_i - \alpha_i \tau$
3. Total Operating Margin

$$\pi(K_1, K_2, d, \tau) = \max_{q_1, q_2} \left( \sum_{i=1}^{2} \eta_i(\tau) q_i - \gamma_i K_i \right) - rd$$

$$s.t.\ 0 \leq q_i \leq K_i, \forall i$$

$$\sum_{i=1}^{2} q_i \leq d$$

# More Notation

Enumerate the production by merit order:

$$b_{[1]} + \alpha_{[1]}\tau \leq b_{[2]} + \alpha_{[2]}\tau$$

Optimal production quantities $q_{[1]} = \min\{K_{[1]}, d\}$ and $q_{[2]} = \min\{K_{[2]}, (d - K_{[1]})^+\}$

# First Stage: Optimal Capacity Investment

**Problem:**

$$\Pi(\tilde{D},\tau) = \max_{K_1,K_2} \mathbb{E}[\pi(K_1,K_2,\tilde{D},\tau)] - \sum_{i=1}^{2} \beta_i K_i$$

- $\tilde{D}$ Uncertain demand
- Assume $\eta_i(\tau) - \beta_i - \gamma_i > 0 \ \forall i$
- Define upper bound $\overline{K}_{[i]} = F_{\tilde{D}}^{-1}(1 - \frac{\beta_{[i]}+\gamma_{[i]}}{\eta_{[i]}(\tau)})$ (which is equaivalent to the optimal decision when $K_{[-i]} = 0$)

# Optimal Capacities

## Proposition

***Optimal capacities under emission tax:***

*Let* $\rho_{[i]} = \frac{\eta_{[i]}(\tau)}{\beta_{[i]}+\gamma_{[i]}}$ *and* $\delta_{[i]} = \eta_{[i]}(\tau) - \beta_{[i]} - \gamma_{[i]}$ *be the return on capital per unit delivered and profit per unit*

$$\textbf{\textit{Dominating tech:}} \quad K^*_{[1]}(\tau) = \begin{cases} \overline{K}^T_{[1]}(\tau) & \textit{if } \rho_1 \geq \rho_2 \\ 0 & \textit{if } \delta_2 \geq \delta_1 \\ F^{-1}_{\tilde{D}}\left(1 - \frac{\delta_1 - \delta_2}{\eta_{[1]}(\tau) - \eta_{[2]}(\tau)}\right) & \textit{otherwise} \end{cases}$$

$$\textbf{\textit{Dominated tech:}} \quad K^*_{[2]}(\tau) = \begin{cases} 0 & \textit{if } \rho_1 \geq \rho_2 \\ \overline{K}^T_{[2]}(\tau) & \textit{if } \delta_2 \geq \delta_1 \\ \overline{K}^T_{[2]}(\tau) - K^*_{[1]}(\tau) & \textit{otherwise} \end{cases}$$

# Intuition

- Use only the dominating
- Fixed cost

# Flow

- Emissions are capped
- Uncertainty in the demand $\tilde{D}$ and price of technology $\tilde{e}$
- Firms buy and sell permits, generating price $\tilde{e}$ which collapses to $e$
- Profitable technology $\eta(e) \geq 0$

# Problem

## Second Stage Problem

$$\hat{\pi}(\hat{K}_1, \hat{K}_2, d, e) = \max_{\hat{q}_1, \hat{q}_2} \left( \sum_{i=1}^{2} \eta_i(e)\hat{q}_i - \gamma_i \hat{K}_i \right) - rd$$

$$s.t. 0 \leq \hat{q}_i \leq \hat{K}_i$$

$$s.t. \sum_{i=1}^{2} \hat{q}_i \leq d$$

## First Stage Problem

$$\hat{\Pi}(\tilde{D}, \tilde{e}) = \max_{\hat{K}_1, \hat{K}_2} \mathbb{E}_{\tilde{D}, \tilde{e}}[\hat{\pi}(\hat{K}_1, \hat{K}_2, \tilde{D}, \tilde{e})] - \sum_{i=1}^{2} \beta_i \hat{K}_i$$

$$s.t. \ \hat{K}_i \geq 0, \forall i$$

## Optimal production at stage 2

$$q_{[i]} = \begin{cases} \min\left(\hat{K}_{[i]}, \left(d - \sum_{k=1}^{i-1} \hat{K}_{[k]}\right)^+\right) & \forall i \in \ddot{N} \\ 0 & \forall i \in N \setminus \ddot{N} \end{cases}$$

where $\ddot{N}$ represents feasible technologies. Determine

- Merit order $\eta_{[i]}(e) \geq \eta_{[-i]}(e)$
- $\tilde{e}_i$ interval such that type i capacity is preferred, $i = 1, 2$, and $\tilde{e}_3$ one type unprofitable, $\tilde{e}_{3,i}$ indicating which one is unprofitable and $\tilde{e}_4$ neither is profitable
- $\overline{K}_i^C(\tilde{e}) = F_{\tilde{D}}^{-1}\left(1 - \frac{\beta_i+\gamma_i}{\overline{\eta}_i(\tilde{e}_i)+\overline{\eta}_i(\tilde{e}_{-i})+\overline{\eta}_i(\tilde{e}_{3,i})}\right)$ upper bound of $\hat{K}_i$, where $\overline{\eta_i}(\tilde{e}_j)$ is the weighted average operating margin per unit produced with $i$ over interval $\tilde{e}_j$

## Proposition

***Optimal capacities under cap-and-trade with $i$ merit order domination:***

*Let* $\rho_i = \frac{\overline{\eta}_i(\tilde{e}_i)+\overline{\eta}_i(\tilde{e}_{3,i})}{\beta_i+\gamma_i}$, $\rho_{-i} = \frac{\overline{\eta}_{-i}(\tilde{e}_i)}{\beta_{-i}+\gamma_{-i}}$ *and* $\delta_i = \overline{\eta}_i(\tilde{e}_i) + \overline{\eta}_i(\tilde{e}_{3,i}) - \beta_i - \gamma_i$,
$\delta_i = \overline{\eta}_i(\tilde{e}_i) - \beta_i - \gamma_i$ *and* $Pr(\overline{\eta}_i(\tilde{e}) \geq \overline{\eta}_i(\tilde{e})) = 1$

***Dominant tech:*** $$\hat{K}_i^*(\tilde{e}) = \begin{cases} \overline{K}_i^C(\tilde{e}) & \text{if } \rho_i \geq \rho_{-i} \\ 0 & \text{if } \delta_{-i} \geq \delta_i \\ F_{\tilde{D}}^{-1}\left(1 - \frac{\beta_i+\gamma_i-\beta_{-i}-\gamma_{-i}}{\overline{\eta}_i(\tilde{e}_i)+\overline{\eta}_i(\tilde{e}_{3,i})-\overline{\eta}_{-i}(\tilde{e}_i)}\right) & \text{otherwise} \end{cases}$$

***Dominated tech:*** $$\hat{K}_{-i}^*(\tilde{e}) = \begin{cases} 0 & \text{if } \rho_i \geq \rho_{-i} \\ \overline{K}_{-i}^C(\tilde{e}) & \text{if } \delta_{-i} \geq \delta_i \\ F_{\tilde{D}}^{-1}\left(1 - \frac{\beta_{-i}+\gamma_{-i}}{\overline{\eta}_i(\tilde{e}_i)}\right) - \hat{K}_i^*(\tilde{e}) & \text{otherwise} \end{cases}$$

# No Dominant Second Stage Technology

Suppose there is $e, e' \in supp(\tilde{e})$ such that $\eta_i(e) \geq \eta_{-i}(e)$ and $\eta_{-i}(e') \geq \eta_i(e')$.

# Optimal Capacities under Cap-and-Trade

## Conditions

**Condition 1:** $\mathbb{E}_{\tilde{e}}[\eta_i(\tilde{e})] - \beta_i - \gamma_i \leq F_{\tilde{D}}(\overline{K}^C_{-i}(\tilde{e}))(\overline{\eta_i}(\tilde{e}_{-i}) - \overline{\eta}_{-i}(\tilde{e}_i))$

**Condition 2:** $\mathbb{E}_{\tilde{e}}[\eta_{-i}(\tilde{e})] - \beta_{-i} - \gamma_{-i} \leq F_{\tilde{D}}(\overline{K}^C_i(\tilde{e}))(\overline{\eta_{-i}}(\tilde{e}_i) - \overline{\eta}_i(\tilde{e}_{-i}))$

## Proposition

***No merit order domination case:***

$$\hat{K}^*_i(\hat{K}_{-i}, \tilde{e}) = \begin{cases} 0 \textit{ if } \textbf{\textit{Condition 1}} \\ \overline{K}^C_{[i]}(\tilde{e}) \textit{ if } \textbf{\textit{Condition 2}} \\ F^{-1}_{\tilde{D}}\left[\left(1 - \frac{\beta_i+\gamma_i-\beta_{-i}-\gamma_{-i}}{\overline{\eta}_i(\tilde{e}_i)+\overline{\eta}_i(\tilde{e}_{3,i})-\overline{\eta}_{-i}(\tilde{e}_i)}\right) - \left(1 - F_{\tilde{D}}\left(\hat{K}_{-i}\right)\right) \\ \frac{\overline{\eta}_{-i}(\tilde{e}_{-i})+\overline{\eta}_{-i}(\tilde{e}_{3,-i})-\overline{\eta}_{-i}(\tilde{e}_{-i})}{\overline{\eta}_i(\tilde{e}_i)+\overline{\eta}_i(\tilde{e}_{3,i})-\overline{\eta}_{-i}(\tilde{e}_i)}\right] \textit{ otherwise} \end{cases}$$

# Conditions and Convergence

Strict concavity is $f_{\tilde{D}}(x) > 0,\ \forall x \in [0, \max\{\overline{K}_1^C(\tilde{e}), \overline{K}_2^C(\tilde{e})\}]$, where $f_{\tilde{D}}(\cdot)$ is the probability density of demand.

## Proposition

*Let $\hat{K}_i^0, \hat{K}_{-i}^0$ be strict concave feasible solutions. Define the sequence:*

$$\hat{K}_i^{t+1} = \hat{K}_i^*(\hat{K}_{-i}^t), \quad \hat{K}_{-i}^{t+1} = \hat{K}_{-i}^*(\hat{K}_i^t)$$

*Then $^t$ converges to $(\hat{K}_i^* \hat{K}_{-i}, \tilde{e})$ and $\hat{K}_{-i}^*(\hat{K}_i, \tilde{e})$.*

Emission Tax Problem

Cap-and-Trade Problem

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Implications

# Implications

## Proposition

*If $\tau = \mu_e$, the mean emissions price under cap-and-trade, then emission price uncertainty under cap-and-trade results in greater expected profit than a constant rate under an emissions tax; that is $\hat{\Pi}(\tilde{D}, \tilde{e}) \geq \Pi(\tilde{D}, \tau)$.*

**Not to Operate option**

1. Non-zero probability of emission price $\tilde{e}$ being unprofitable, $p(\tau) + r - b_i - \alpha_i e < 0$
2. Non-zero probability of demand exceeding the firm's capacity of the alternative type if that alternative technology is favored in merit order.

In both cases, firms pay the fixed costs of facilities because they are advantageous

# Dispatch Flexibility

1. Firm's owns capacities of both technologies
2. Expect less-than-full utilization
3. Each type is preferred in merit order at some emissions price over the support of $\tilde{e}$

Then, the firm can decide which one to use given the price

# Extra Results

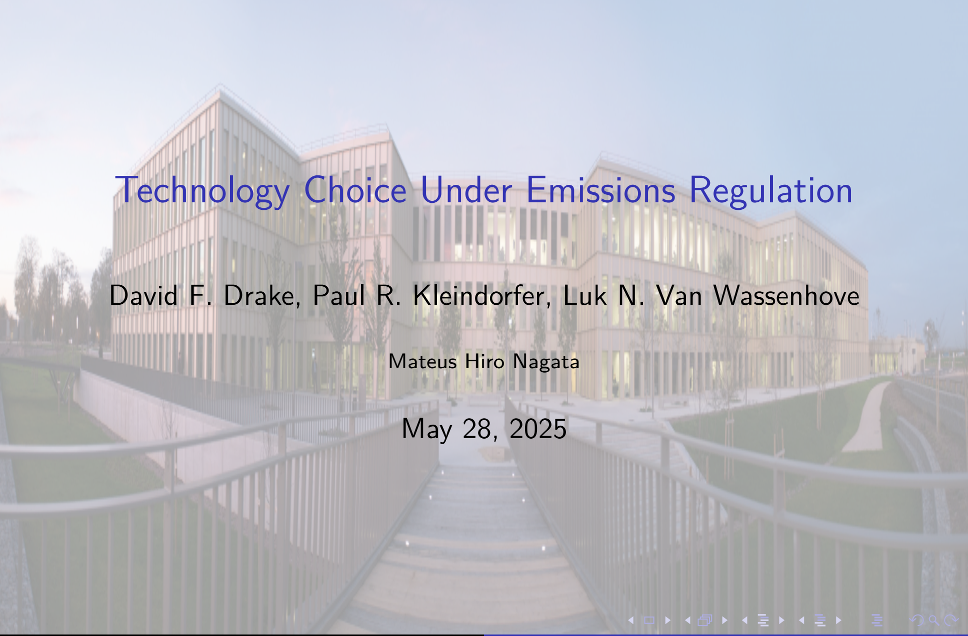
- Production subsidies for high-cost technologies (e.g. carbon capture) do not change total capacity when both clean and dirty technologies are used.
- Investment subsidies for these same high-cost technologies increase total capacity, which can raise expected emissions.
- For low-cost clean technologies, neither production nor investment subsidies affect total capacity when the firm uses multiple technologies.

# Possible Extensions

- Competition between firms
- Incorporation of Knightian uncertainty/ambiguity (Hill, 2024)
- Actual emissions under cap-and-trade and tax policy
- Speed of production
- Risk-aversion

# Conclusion

- Cap-and-trade is superior as it induces bigger profits with same level of emissions
- Induced by the flexibility in **operation** and **dispatch**
- The uncertainty in the capacity problem and



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