Efficient Upgrading to Clean Technology: An Industry Equilibrium Approach

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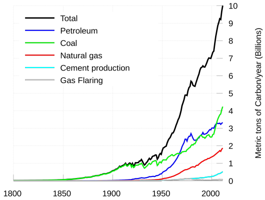
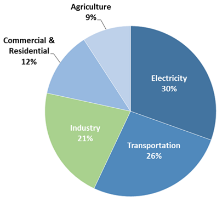
Sustainable Energy Systems

- Future of sustainable energy systems have to rely on clean energy production to reduce greenhouse gas emissions.
- This is not just an engineering problem (i.e., new supply technologies, demand management) since
  - Firms have to be incentivized to upgrade to clean technology.
  - Less efficient firms encouraged to exit.
- Key tool for achieving this: carbon tax programs.
  - Carbon taxes have to be chosen "optimally" to balance costs of reduced production today vs achieving an optimal evolution of industry.





[US Energy Information Administration, Inventory of US Greenhouse Gas Emissions and Sinks]

Questions and Model

- Key elements of such an investigation:
  - An industry equilibrium with heterogeneous productivity (so that there are different generation companies with different efficiencies).
  - Entry and exit decisions.
  - Explicit decision to upgrade to clean technologies (as well as growing supply of renewables).
  - Crucially, it's a nonstationary industry equilibrium.
- Optimal policy (in the form of tax sequences on carbon) chosen taking the industry equilibrium as given.
- This leads to a framework different from any that has been used in either the engineering or the economics literature so far.

Related literature

- Our work relates both to the engineering and economics literatures on optimal climate policy.
- Baseline models of carbon taxation
  - Nordhaus (1994), Stern (2007), Golosov et al. (2013)
  - These are models of exogenous technology in which production (overall output or energy) creates carbon emissions.
  - Augmented with a carbon cycle and a technological relationship between damage to future output (e.g., agricultural output) from carbon concentration.
  - General result: there should be moderate carbon tax today, being "ramped up" over time (because of discounting of future utility).
  - Missing in these models:
    - endogenous technology, no transition to clean technology.
    - industry equilibrium aspects where the efficiency of carbon producing plants evolves endogenously.

Related literature (continued)

- Models of directed technological change and climate policy
  - Acemoglu et al. (2012), Acemoglu et al. (2016)
  - Endogenous evolution of clean technologies (in particular, through R&D directed towards renewables and clean technology).
  - Very different policy prescriptions and predictions about future.
- Models of industry equilibrium
  - Lucas and Prescott (1971), Jovanovic (1982), Hopenhayn (1992), Acemoglu and Jensen (2015)
  - These are models in which equilibrium productivity distribution is endogenously shaped by entry and exit of firms with different productivities.
  - The focus is on stationary equilibria
  - There is relatively little work on nonstationary versions of these models, and **no work**, to the best of our knowledge, on policy taking the evolution of such an industry equilibrium as a constraint.
- Our work necessitates the development of such a model.

Model Outline: Two-Layer Model

- First (lower) layer: a model of industry equilibrium.
  - The consumer side: how consumers decide the amount of energy to consume.
  - The producer side: how the supply of energy involves over time due to entry, exit and upgrading decisions, as well as renewable supply growth.
  - Industry equilibrium: the consumer and producer side coming together.
- Second (upper) layer: the planning problem
  - A social planner wishing to maximize the utility of consumers chooses a tax sequence taking the industry equilibrium as a constraint.

The Consumer Side

- We model the consumer side via a representative consumer with the following optimization problem:

$$\begin{array}{ll} \max & \sum_t \beta^t [u(z_t) + y_t - \phi_t K_t] \\ \text{s.t.} & \underbrace{p_t z_t + y_t}_{\text{consumer expenditure}} \leq (\text{Total income})_t \quad \forall t. \end{array}$$

- z_t is the total amount of energy consumed at time t (and thus in equilibrium produced), $u(\cdot)$ is a strictly concave utility function.
- y_t is the total expenditure on other goods at time t.
- The last term represents costs from environmental degradation (K_t is the total amount of carbon emission at time t, and ϕ_t is the cost of carbon in the atmosphere at time t).
- Key first-order condition:

$$u'(z_t) = p_t$$

where p_t is the price of energy at time t.

The Producer Side

- Total production comes from three sources:

1. Conventional energy producers (based on fossil fuels). The total supply is X_t^d.
    - These producers emit η_d units of carbon per unit of production.
2. Upgraded conventional energy producers (with a cleaner technology). The total supply is X_t^c.
    - These producers emit η_c units of carbon per unit of production.
3. Renewables (which do not emit any carbon). The total supply is R_t.
    - We assume that renewable supply grows over time, in particular

$$R_t = (1+g)^t R_0.$$

The Producer Side: Conventional Power Plants

- Suppose that power plant (firm) i has a variable cost function of the form

$$C\left(\frac{x_{it}}{a_i}\right),$$

where a_i is a productivity term.

- This implies that the greater is a_i, the more productive the plant is, and thus the lower are its costs of producing a given amount of energy. This productivity term is constant throughout the life of the plant.
- $C(\cdot)$ is a continuously differentiable, strictly convex function.
- Each firm incurs a fixed cost of Γ at each instance in which it is in operation (capturing the cost of running an active plant even at zero production).
    - The fixed cost is important, since without it, no reason for exit.
- A plant can decide to exit whenever it likes.

The Producer Side: Dirty and Clean Plants

- In addition to its production and exit decision, a plant can decide to upgrade to clean technology, by incurring the cost Φ.
- For simplicity, we assume that this does not change the cost structure for production, but reduces its emissions of carbon as specified above (from η_d per unit of production to $\eta_c < \eta_d$ per unit of production).

The Producer Side: Production Decision

- Even though firms will solve a dynamic maximization problem in making their exit, entry and upgrading decisions, the level of production (given prices) can be solved statically—because today's level of production does not affect anything in the future.
- This maximization problem can be written as

$$\max_{x_{it}} (p_t - \tau_t \eta_d) x_{it} - C\left(\frac{x_{it}}{a_i}\right)$$

  for dirty plans, where τ_t is the carbon tax.
- This specification clarifies that what matters for the firm is the effective price, $p_t - \tau_t \eta_d$.
- With a simple change of variable, we can write

$$\max_{\tilde{x}_{it}} (p_t - \tau_t \eta_d) \tilde{x}_{it} a_i - C\left(\tilde{x}_{it}\right),$$

  where $\tilde{x}_{it} := x_{it}/a_i$, and obtain the first-order condition

$$C'(\tilde{x}_{it}) = (p_t - \tau_t \eta_d) a_i.$$

The Producer Side: Production Decision (continued)

- Therefore, the level of (equilibrium) profits of firm i using the conventional (dirty) technology at time t can be written as

$$\pi_{it} := \pi(a_i(p_t - \tau_t \eta_d)),$$

  where $\pi(\xi) := \xi(C')^{-1}(\xi) - C((C')^{-1}(\xi))$.

- Similarly, the level of profits for a firm using the upgraded (clean) technology is

$$\pi_{it} := \pi(a_i(p_t - \tau_t \eta_c)),$$

  with the only difference being the effective price faced by such a firm (due to its lower emissions).

The Producer Side: Dynamic Optimization of Firms

- We can now write the dynamic optimization problem of dirty firms as

$$
\begin{aligned}
V_t^d(a) \quad = \quad \max \quad & \{\pi(a(p_t - \eta_d \tau_t)) - \Gamma + \beta V_{t+1}^d(a); \\
& \pi(a(p_t - \eta_d \tau_t)) - \Gamma + \beta V_{t+1}^c(a) - \Phi; \\
& 0\}
\end{aligned}
$$

- The max operator here takes care of the three decisions of the firm:
  1. The first line is for operating as a dirty firm.
  2. The second line is for upgrading to a clean firm by incurring the cost of upgrade, Φ.
  3. The third line is for shutting down and receiving zero thereafter.

- The problem of clean firms is similar, except that they can only continue as they are or exit. Thus:

$$V_t^c(a) = \max\{\pi(a(p_t - \eta_c \tau_t)) - \Gamma + \beta V_{t+1}^c(a); 0\}.$$

The Producer Side: Monotonicity and Threshold Rules

- Because the stage payoffs are (strictly) increasing in a_i, the value functions, $V_t^d(a)$ and $V_t^c(a)$, are also increasing in a_i.
- This implies that exit decisions will take the form of a simple threshold rule:
  - Exit if and only if $a_i < \underline{a}_t^{d,exit}$ and $a_i < \underline{a}_t^{c,exit}$ (for dirty and clean plants, respectively).
- Moreover, since $V_t^c(a) - V_t^d(a)$ is increasing in a, upgrade decisions also take the form of a threshold rule:
  - Upgrade if and only if $a_i > \bar{a}_t^{upgrade}$.
  - Intuitively, high productivity firms produce more and thus upgrading is more valuable for them.

The Producer Side: Entry

- In addition, new firms can enter into the conventional energy production sector by incurring a fixed cost of entry given by Ψ.
- We assume that these firms, upon entering, draw their productivity from the distribution $G(a)$.
- Equilibrium must be such that firms are indifferent between entering and not, i.e.,

$$\Psi \geq \int_{\underline{a}_t^{d,exit}}^{\bar{a}_t^{upgrade}} V_t^d(a)dG(a) + \int_{\bar{a}_t^{upgrade}} (V_t^c(a) - \Phi)dG(a)$$

with equality if $M_t > 0$ where M_t is the mass of entrants at t.

  - Intuitively, if its draw of productivity is too low (below $\underline{a}_t^{d,exit}$), the entrant exits and receives zero. If it is intermediate, it stays as a dirty producer and if it is above the threshold $\bar{a}_t^{upgrade}$, it pays the cost of upgrading and becomes a clean producer.

- The sequence of market prices have to be such that this equality is satisfied at all times.

The Producer Side: Endogenous Firm Distributions

- To fully characterize the equilibrium, we need to characterize the (endogenously-determined) firm productivity distributions.
- Denote the measure over productivities of dirty and clean firms at time t as F_t^d and F_t^c, i.e., $F_t^d(A)$ is the mass of dirty firms with productivities in set A.
- These distributions evolve as follows:

$$F_{t+1}^d([0,a)) = F_t^d([\underline{a}_{t+1}^{d,exit}, \min\{a, \bar{a}_{t+1}^{upgrade}\})) + M_{t+1}G(a)$$
$$F_{t+1}^c([0,a)) = F_t^c([\underline{a}_{t+1}^{c,exit}, a)) + F_t^d([\bar{a}_{t+1}^{upgrade}, a))$$

where M_t is the mass of entrants.

  - Intuitively, we start with the distribution from last period, e.g., F_t^d, we then truncate it according to exit and upgrading decisions, and then add new firms with productivity drawn from the entry distribution G.

The Producer Side: Supply Levels

- We can now determine the equilibrium supply levels as follows:

$$\text{dirty production: } X_t^d = \int_{\underline{a}_t^{d,exit}}^{\bar{a}_t^{upgrade}} (C')^{-1}(a_i(p_t - \tau_t \eta_d))dF_t^d(a),$$

  where recall that $(C')^{-1}(a_i(p_t - \tau_t \eta_d))$ is the amount of energy that a dirty plant with productivity a_i will produce when the effective price is $p_t - \tau_t \eta_d$.

- Similarly,

$$\text{clean production: } X_t^c = \int_{\underline{a}_t^{c,exit}} (C')^{-1}(a_i(p_t - \tau_t \eta_c))dF_t^c(a).$$

- Consequently, total carbon emissions is

$$K_t = \eta_d X_t^d + \eta_c X_t^c.$$

Industry Equilibrium

- An industry equilibrium is defined as a sequence of prices such that markets clear at each date.
- Given the renewable supply, market clearing implies

$$z_t = X_t^d + X_t^c + R_t$$

or combining with the first-order condition of the representative consumer:

$$p_t = u'(X_t^d + X_t^c + R_t).$$

Theorem

For any sequence of taxes, $\{\tau_t\}$, an equilibrium exists.

Summary of Industry Equilibrium

- Let $\mathbf{q}_t = (X_t^d, X_t^c, p_t, F_t^d, F_t^c, V_t^d, V_t^c)$ be the vector of endogenous variables (we have omitted the thresholds).
- Given any sequence of taxes, we end up with an endogenously-determined equilibrium $\mathbf{q}_t(\{\tau_t\})$. We will then use this as a shorthand for representing how the equilibrium depends on policies.

The Second Layer: The Planning Problem

- Now the planner chooses the sequence of (carbon), taking the resulting industry equilibrium as given.
- Note that this is a nonstationary industry equilibrium.
- This gives us a Stackelberg game, which we can write as

$$\max_{\{\tau_t\}} \sum_{t=0}^{T} \beta^t [u(z_t) + y_t - \phi_t K_t]$$

subject to $\mathbf{q}_t(\{\tau_t\})$.

The optimization problem

$$\max_{\{(\tau_t, p_t, M_t)\}} \quad \sum_t \beta^t [u(z_t) - p_t z_t + (\tau_t - \phi_t)K_t + \Pi_t]$$

$$\text{s.t.} \quad V_t^d(a) = \max\{\pi(a(p_t - \eta_d\tau_t)) - \Gamma + \beta V_{t+1}^d(a); \pi(a(p_t - \eta_d\tau_t)) - \Gamma + \beta V_{t+1}^c(a) - \Phi; 0\}$$

$$V_t^c(a) = \max\{\pi(a(p_t - \eta_c\tau_t)) - \Gamma + \beta V_{t+1}^c(a); 0\}, \quad V_T^d = V_T^c = 0$$

$$\Psi \geq \int_{\underline{a}_t^{d,exit}}^{\bar{a}_t^{upgrade}} V_t^d(a)dG(a) + \int_{\bar{a}_t^{upgrade}} (V_t^c(a) - \Phi)dG(a)$$

$$\left(\Psi - \int_{\underline{a}_t^{d,exit}}^{\bar{a}_t^{upgrade}} V_t^d(a)dG(a) - \int_{\bar{a}_t^{upgrade}} (V_t^c(a) - \Phi)dG(a)\right) M_t = 0$$

$$F_{t+1}^d([0,a)) = F_t^d([\underline{a}_{t+1}^{d,exit}, \min\{a, \bar{a}_{t+1}^{upgrade}\})) + M_{t+1}G(a)$$

$$F_{t+1}^c([0,a)) = F_t^c([\underline{a}_{t+1}^{c,exit}, a)) + F_t^d([\bar{a}_{t+1}^{upgrade}, a))$$

$$z_t = X_t^d + X_t^c + R_t$$

$$p_t = u'(z_t)$$

$$X_t^d = \int_{\underline{a}_t^{d,exit}}^{\bar{a}_t^{upgrade}} (C')^{-1}(a(p_t - \tau_t\eta_d))dF_t^d(a)$$

$$X_t^c = \int_{\underline{a}_t^{c,exit}} (C')^{-1}(a(p_t - \tau_t\eta_c))dF_t^c(a)$$

$$K_t = \eta_d X_t^d + \eta_c X_t^c$$

$$\Pi_t = \int_{\underline{a}_t^{d,exit}}^{\bar{a}_t^{upgrade}} \pi(a(p_t - \eta_d\tau_t))dF_t^d(a) + \int_{\underline{a}_t^{c,exit}} \pi(a(p_t - \eta_c\tau_t))dF_t^c(a)$$

A Characterization Theorem

- We can characterize the form of the equilibrium under the condition that effective prices are nonincreasing (which is natural both because of ongoing upgrading to clean technology and renewable supply growth).

Theorem

Suppose that there exits $t' \in \{0, \cdots, T-1\}$ such that for $t \geq t'$ the effective prices are monotonically nonincreasing over time, i.e.,

$$p_t - \eta_d \tau_t \geq p_{t+1} - \eta_d \tau_{t+1}, \quad p_t - \eta_c \tau_t \geq p_{t+1} - \eta_c \tau_{t+1} \quad \forall t \geq t'.$$

Then, the exit thresholds are given by

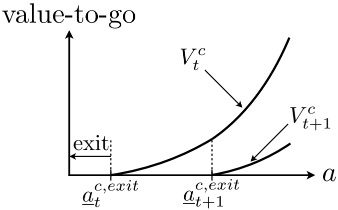
$$\underline{a}_t^{d,exit} = \frac{\pi^{-1}(\Gamma)}{p_t - \eta_d \tau_t}, \quad \underline{a}_t^{c,exit} = \frac{\pi^{-1}(\Gamma)}{p_t - \eta_c \tau_t} \quad \forall t \geq t'.$$

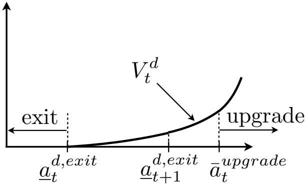
Corollaries

- This implies exit thresholds are monotonically nondecreasing over time, i.e.,

$$\underline{a}_t^{d,exit} \leq \underline{a}_{t+1}^{d,exit}, \quad \underline{a}_t^{c,exit} \leq \underline{a}_{t+1}^{c,exit} \quad \forall t;$$

- When effective prices are nonincreasing over time, exit thresholds both for dirty and clean firms increase, meaning that more and more firms will exit.
- Moreover, since $\eta_c < \eta_d$, we have $\underline{a}_t^{c,exit} < \underline{a}_t^{d,exit}$.





A Further Characterization Result

Theorem

There exists $\underline{g}$ such that if $g > \underline{g}$, effective prices are nonincreasing over time (i.e., $p_t - \eta_d \tau_t \geq p_{t+1} - \eta_d \tau_{t+1}, \quad p_t - \eta_c \tau_t \geq p_{t+1} - \eta_c \tau_{t+1} \quad \forall t$), and the characterization in the previous theorem applies.

- Intuitively, if there is sufficient growth of the supply of renewables, this will ensure that prices decline over time, enabling us to obtain this particular characterization of the structure of the nonstationarity industry equilibrium.
- To make further progress on the second layer optimization (the planning problem), we will now use numerical methods with realistic parameter values.

Simulation setting

Parameter selection (data from US Energy Information Administration (EIA), International Energy Agency (IEA)

- Time horizon: 250 years
- Consumer utility function: $u(z) = 2.3 \times 10^{12} \log z$ based on the fact that the average electricity price is approximately $100 per MWh and the total electricity generation in 2013 is 23×10^9 MWh [IEA (2015)]
- Production cost function: $C(x) = 50x + \frac{10^{-5}}{2}x^2$
- Renewable energy: $R_0 = 5.131 \times 10^9$ MWh (in 2013) [IEA (2015)]
- Renewable energy growth rate: $g = 1\%/\text{yr}$ [IEA (2015)]
- Carbon emission rate: $\eta_d = 319\text{kg}/\text{MWh}$ for a typical coal-based power plant and $\eta_c = 31.9\text{kg}/\text{MWh}$ for a coal power plant with carbon capture and storage (10 times lower emissions) [EIA (2013)]

Simulation setting (continued)

Parameter selection (data from US Energy Information Administration, International Energy Agency, MATPOWER)

- Operation cost: $\Gamma = \$24.6 \times 10^6/\text{year}$ [EIA (2013)]
- Capital cost of a 650MW coal power plant: $\Psi = \$2.11 \times 10^9$ [EIA (2013)]
- Cost to upgrade to carbon capture systems: $\Phi = \$1.29 \times 10^9$ [EIA (2013)]
- The firms initial distributions F_0^d and F_0^c are chosen as the stationary equilibrium level under zero tax
- Productivity: $a \in [1, 10]$
- Entry distribution is chosen as $G(a) = \text{Pareto}(1, 1.1)$.

Simulation setting (continued)

Numerical methods:

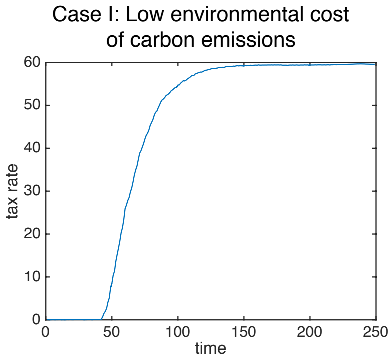
- To obtain an optimal pre-commitment tax policy path, we optimize the tax sequence to maximize the consumer utility (in an open-loop fashion) subject to the industry equilibrium.
- The industry equilibrium $\mathbf{q}_t = (X_t^d, X_t^c, p_t, F_t^d, F_t^c, V_t^d, V_t^c)$ should satisfy the following constraints:
  1. dynamic programming equations for optimal firms' exit and upgrade decisions, $\{(\underline{a}_t^{d,exit}, \bar{a}_t^{upgrade}, \underline{a}_t^{c,exit})\}$, and optimal values, $\{(V_t^d, V_t^c)\}$;
  2. dynamics of firm distributions, $\{(F_t^d, F_t^c)\}$;
  3. supply levels:

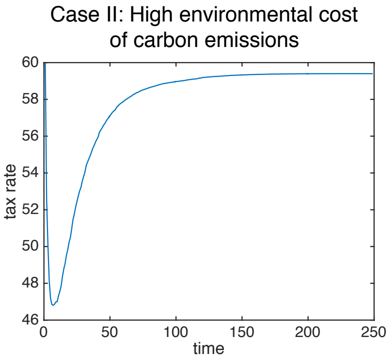
$$\text{dirty production: } X_t^d = \int_{\underline{a}_t^{d,exit}}^{\bar{a}_t^{upgrade}} (C')^{-1}(a(p_t - \tau_t \eta_d))dF_t^d(a),$$

$$\text{clean production: } X_t^c = \int_{\underline{a}_t^{c,exit}} (C')^{-1}(a(p_t - \tau_t \eta_c))dF_t^c(a);$$

  4. market clearing condition: $p_t = u'(X_t^d + X_t^c + R_t)$.

Path of Carbon Tax

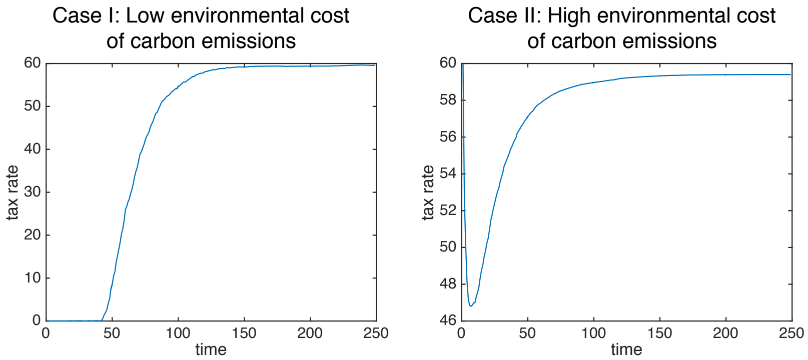




Path of Carbon Tax: Intuition

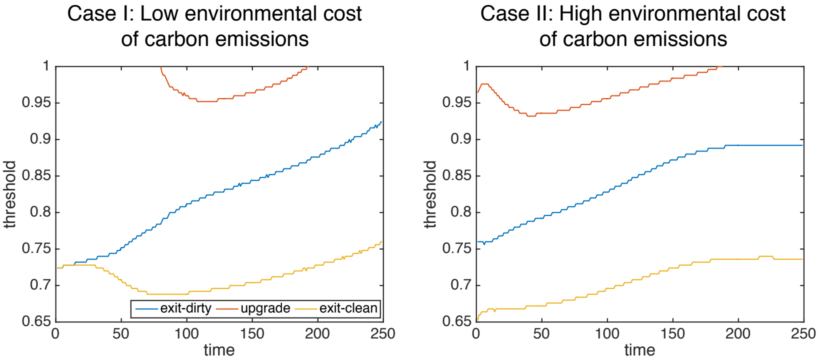
- What explains the time path of carbon taxes?
- Three economic forces:
  - Discounting: the social planner prefers incurring costs later rather than sooner, which implies higher taxes in the future.
  - Frontloading: It is better to upgrade to clean technology sooner rather than later since the cost of upgrading is fixed, and sooner switching means more periods during which society will benefit from lower emissions.

Path of Carbon Tax



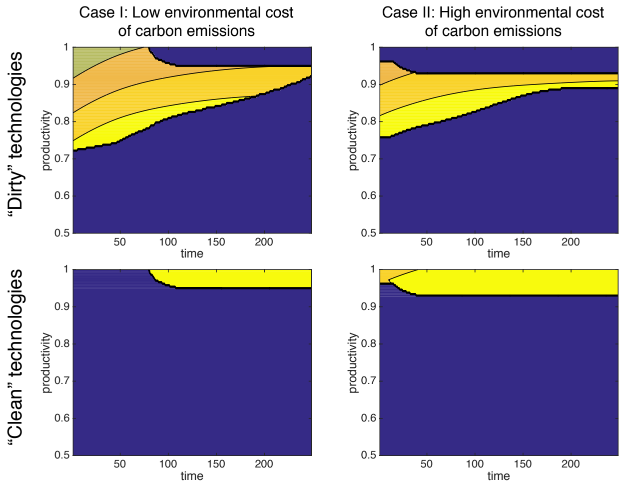
- Case I (low cost of carbon): the first force dominates, and we have the time path for carbon taxes increasing over time.
- Case II (high cost of carbon): the second force dominates and we initially have frontloaded carbon taxes.

Firms' exit and upgrade decisions over time



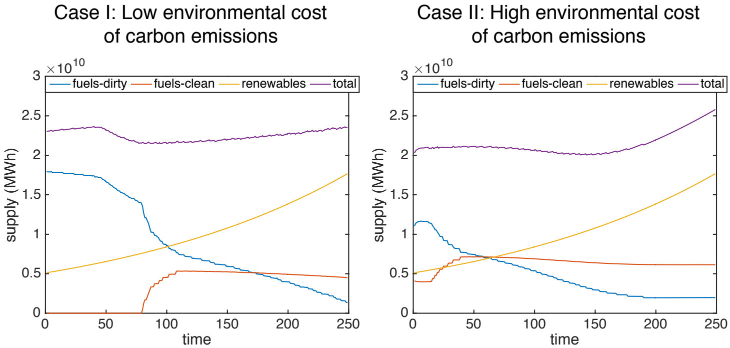
- In Case II, because the damage from carbon is high, the optimal policy induces very rapid upgrading. In fact, we can see that the upgrade threshold is considerably lower in Case II than in Case I.
- We confirm that the effective prices are decreasing after 100 years and thus the exit thresholds are increasing after 100 years.

Firms' distributions



- Because of the low upgrade threshold in Case II, the measure of firms with clean technologies is higher in Case II.

Supply by dirty, clean and renewable technologies



- In Case II, due to rapid upgrading under optimal policy, the supply of energy from clean technologies is higher throughout.
- In both cases, the supply from dirty technologies is decreasing throughout, but the initial drop is greater in Case II.
- In both cases, supply diminishes in late stages because of lower prices (due to the growth of renewables).

Conclusions

- We presented an industry equilibrium model with dynamic decisions on entry, exit, production and technological upgrading.
- We used this model to determine the optimal time-varying carbon tax that maximizes utility of consumers subject to equilibrium.
- The model can be enriched in multiple dimensions:
  - Carbon cycle and an environmental constraint.
  - Endogenize renewable integration with the engineering constraints.
- Once the optimal carbon tax (i.e., social cost of carbon) is determined, we can evaluate the social desirability of any carbon reducing technology (including IoT-based Carbon Capture and Storage (CCS)).