Green Policies, Aggregate Investment Dynamics and Vintage Effects

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Banque de France - July 6, 2018

Research Agenda

- Investment and vintage effects
  - New capital goods are more efficient
  - Investment decision at the microeconomic level non-smooth
- Quantitative macro mostly abstracts from it
- Business cycle dynamics (in progress)
- Energy/emission policy (today)

Energy Policies Today

Range of energy policies across countries and at federal, state, & local levels

- Carbon tax
  - Finland/Netherlands in 1990, Norway/Sweden in 1991, Denmark in 1992, Boulder, CO in 2007, British Columbia in 2008, and Ireland in 2009
  - Variation in implementation and use of tax revenues

Motivation

- Literature mainly employs representative firm model to study environmental policies
- Issue: is firm/plant heterogeneity important for environmental policies?
- Data suggests
  - Plants with higher TFP have lower emission intensities
    Shapiro & Walker (2014)
  - Plants with better management have lower emission intensities
    Bloom, Genakos, Martin & Sadun (2010)
  - Smaller plants have higher emission intensities
    Dasgupta, Lucas, & Wheeler (2002); Qi, Tang & Xi (2015)

This Paper

- Present empirical evidence showing heterogeneity in emission intensities
  - Higher emission intensities for older equipment
  - A flat tax on emissions is effectively heterogeneous across plants
- Formulate general equilibrium model to study aggregate effects of carbon taxes
  - Model timing of firms' decisions to replace old technology with new ones
  - Investment required to upgrade energy efficiency
  - Cross-sectional distribution of firms over energy efficiency and emission intensities
  - Micro-data discipline

Main Results

- The distribution of plants relevant object for policymakers
  - The degree of heterogeneity in emission rates shapes the aggregate response
  - Larger gains from a carbon tax when firms differ in emission rates: no trade-off between $\downarrow$ average energy usage/emissions and $\uparrow$ energy efficiency
- Energy usage versus emissions
- Dynamics differ when policies are uniform or vintage specific
  - Exempting older plants from policy increases average age of capital

Connection to the Existing Literature

- Current general equilibrium analysis employs representative firm models

- Focus on degree firms use energy efficient technology and not on extent to which various technologies adopted by firms
  - Nordhaus (1994, 2007, 2008), Golosov, Hassler, Krusell, & Tsyvinski (2014), Acemoglu, Ackigit, Hanley, & Kerr (2014), Krusell & Smith (2015)

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- Closest connections
  - Putty-clay approach: Diaz & Puch (2013), Atkeson & Kehoe (1999)
  - Bosetti & Maffezzoli (2014): incomplete markets model a la Huggett (1993), Aiyagari (1994) with idiosyncratic characteristics of agents
  - Qi, Tang & Xi (2015), Shapiro & Walker (2014)

Data

Emission Intensities and Capital Age

- Use data on electric generators in the U.S.
  - Emissions data from EPA eGrid (2004,2005,2007,2009,2010)
  - Plant/generator data from EIA-860 survey

- Estimate emissions function via OLS:

$$\ln emr_{it} = \alpha + \beta \ln age_{it} + X_t + \epsilon_{it}$$

- *emr* is output emission rate (SO_2, NO_x, CO_2, CH_4) in lb/MWh
- *age* is the weighted average of plant generator's years since online
- X are controls:
  - state and year fixed effects
  - type of primary fuel input

Emission Intensities and Capital Age

Non-coal

	SO_2 rate	NO_x rate	CH_4 rate	CO_2 rate
ln *age*	0.567***	0.574***	0.103***	0.107***
observations	10,559	12,165	9,384	11,423
Adj R-squared	0.71	0.57	0.65	0.45

Coal

	SO_2 rate	NO_x rate	CH_4 rate	CO_2 rate
ln *age*	0.907***	0.438***	0.045	0.059**
observations	2,809	2,809	2,193	2.809
Adj R-squared	0.28	0.22	0.40	0.44

Model

Model Framework

Neoclassical growth model with endogenous technology adoption

- Unit measure of perfectly competitive firms
  - Use capital, energy, and labor to produce output
  - Fixed upgrading cost
  - (S,s) upgrading/investment policies as in Caballero and Engel (1999), Thomas (2001)
  - Endogenous discrete distribution of energy efficiency across firms (that enters the state space of the model)
- Representative household provides labor, consumes, and saves

Model Framework

- Government
  - Consumes final good
  - Taxes labor, consumption, and energy usage/emissions
  - Potentially regulates firms' emissions and energy efficiency
- Energy imported from rest of world at exogenous world price
  - Balanced trade: imported energy offset by exported output
  - Allow world price to potentially respond to demand

The Model - Firms

Production function

- Representative Agent Model:
  : RBC frictionless technology adoption and capital accumulation

$$Y_t = \left[\omega^{\frac{1}{\epsilon}} \left(Z_t K_{t-1}^{\gamma} L_t^{\nu}\right)^{\frac{\epsilon-1}{\epsilon}} + (1-\omega)^{\frac{1}{\epsilon}} (Z_t E_t)^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}$$

  : ϵ is the price elasticity of energy; $1-\omega$ is a quasi-share parameter for energy
  : $\frac{Z_t}{Z_{t-1}} = \Theta_t$, $\gamma + \nu < 1$

The Model - Firms

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- Heterogeneous Agent Model:
  - : RBC with fixed cost to technology upgrade and capital accumulation

$$Y_{j,t} = \left[\omega^{\frac{1}{\epsilon}} \left(Z_{j,t} K_{j,t-1}^{\gamma} L_{j,t}^{\nu}\right)^{\frac{\epsilon-1}{\epsilon}} + (1-\omega)^{\frac{1}{\epsilon}} (\Upsilon_{j,t} E_{j,t})^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}$$

  - : $\Upsilon_{j,t}$ gives energy efficiency
  - : $Z_{j,t} = Z_{0,t-j}$, $\Upsilon_{j,t} = \Upsilon_{0,t-j}$

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  : $\Upsilon_{j,t}$ gives energy efficiency

  : $Z_{j,t} = Z_{0,t-j}$, $\Upsilon_{j,t} = \Upsilon_{0,t-j}$

  : Assume $Z_{0,t}$ grows exogenously at rate $\Theta_{Z_{0,t}} \rightarrow Z_{j,t} = \frac{Z_{0,t}}{\prod_{s=t-j}^{0} \Theta_{Z_{0,s}}}$

  : Assume $\Upsilon_{j,t} = Z_{j,t}$

The Model - Firms

Emission function

- Emissions of firms are proportional to energy $M_{j,t} = \Omega_j E_{j,t}$
  - Equal to energy $\Omega_j = 1$
  - Increasing with age $\Omega_j = f(j)$

The Model - Firms

Upgrading/Investment decision

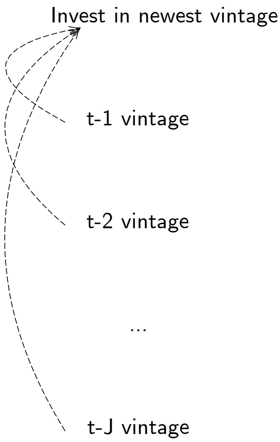
- Firm is defined over vintage $Z_{j,t}$ and $K_{j,t-1}$
- Cost of upgrading $= i_{j,t} +$ fixed cost $(w\xi)$; ξ is $i.i.d. \sim U[0, B]$.
- Upgrade: $V_{investing,t} - V_{notinvesting,t} \geq cost$
- $Z_{0,t+1}$ and $K_{0,t+1} = (1 - \delta - \delta_j^s)K_{j,t} + I_{j,t}$
- Since ξ is the only idiosyncratic uncertainty, $K_{0,t+1}$ is independent of $K_{j,t}$

The Model - Firms

Upgrading/Investment decision

- Firm is defined over vintage $Z_{j,t}$ and $K_{j,t-1}$
- Postpone: $V_{investing,t} - V_{not_investing,t} < cost$
- $Z_{j+1,t+1} = Z_{j,t}/\Theta_{Z_{0,t+1}}$ and $K_{j+1,t+1} = (1-\delta)K_{j,t}$

Firms' Upgrading Cycle



Evolution of Firms' Distribution

Plants' cross-section

Given continuity of the fixed cost

- $V_{investing,j,t} - V_{not\_investing,j,t} = cost \rightarrow$ marginal guy is indifferent
- $V_{investing,j,t} - V_{not\_investing,j,t} = I_{j,t} + W_t f(\alpha_{j,t})$
- $\theta_{j,t} =$ fraction of firms with vintage capital j
    - : $\theta_{0,t+1} = \sum_{j=0}^{J} \alpha_{j,t}\theta_{j,t}$
    - : $\theta_{j,t+1} = (1 - \alpha_{j,t})\theta_{j,t}$

Individual Firm's Problem

A firm maximizes expected discounted profits:

$$V_{j,t} = \begin{array}{c} Y_{j,t} - W_t L_{j,t} - P_t^e (1 + \tau_t^e \Omega_j) E_{j,t} \\ -\mathcal{I}_{t+s}(I_{j,t} + W_t \xi_{j,t}) + E_t V_{j,t+1} \end{array}$$

subject to laws of motion for $K_{j,t}$ and $Z_{j,t}$; $\mathcal{I}_t$ indicator for investment

The Model - Representative Household

Preferences given by

$$\max E_t \left\{ \sum_{s=0}^{\infty} \beta^{s-t} \frac{C_{t+s}^{1-\gamma}}{1-\gamma} - \psi \frac{L_{t+s}^{1+\eta}}{1+\eta} \right\}$$

subject to

$$(1+\tau_t^c)C_t + A_t = (1-\tau_t^l)W_t L_t + R_{t-1}A_{t-1} + TR_t + \Pi_t$$

The Model - Government

Government budget constraint:

$$G_t + TR_t = \tau_t^l W_t L_t + \tau_t^c C_t + \tau_t^e P_t^e \sum_{j=0}^{J} \Omega_j \theta_{j,t} E_{j,t}$$

- Fiscal instruments are set exogenously
- Assume one instrument endogenous to ensure balanced budget
- Energy tax τ_t^e set through policy experiments

Aggregation

Aggregate variables are given by

$$E_t = \sum_{j=0}^{J} \theta_{j,t} E_{j,t}, \; L_t = \sum_{j=0}^{J} \theta_{j,t} \left[L_{j,t} + R\left(\alpha_{j,t}\right) \right], \; K_t = \sum_{j=0}^{J} \theta_{j,t} K_{j,t}$$

The aggregate resource constraint is given by

$$G_t + C_t + \sum_{j=0}^{J} \theta_{j,t} \alpha_{j,t} I_{j,t} + P_t^e \sum_{j=0}^{J} \theta_{j,t} E_{j,t} = \sum_{j=0}^{J} \theta_{j,t} Y_{j,t}$$

The Stationary Model

We denote by lower case variables that are in deviation from their trend.
Trends of variables:

$$\Theta_{Y,t} = \Theta_{W,t} = \Theta_{K,t} = \Theta_{Z_0,t}^{\frac{1}{1-\gamma}},\ \Theta_{E,t} = \Theta_{Z_0,t}^{\frac{\gamma}{1-\gamma}},\ \Theta_{P^e,t} = \Theta_{Z_0,t}$$

Stationary production function:

$$y_{j,t} = \left[\omega^{\frac{1}{\epsilon}} \left(\frac{z_{j,t}}{\Pi_{s=t-j}^{0} g_{Z_0,s}} \frac{1}{g_{K,t}^{\gamma}} k_{j,t-1}^{\gamma} L_{j,t}^{\nu} \right)^{\frac{\epsilon-1}{\epsilon}} + (1-\omega)^{\frac{1}{\epsilon}} \left(\frac{1}{\Pi_{s=t-j}^{t} g_{Z_0,s}} e_{j,t} \right)^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}};$$

$\forall j = 1, ..., J$

The Stationary Model

Value of the average j firm:

$$\begin{aligned} \varphi_{j,t} &= \beta E_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \left[\begin{array}{c} y_{j,t+1} - w_{t+1} \left[L_{j,t+1} + R\left(\alpha_{j,t+1}\right)\right] \\ -p^e_{t+s}(1+\tau^e_{t+s}\Omega_j)e_{j,t+s} - \alpha_{j,t+1} i_{j,t+1} \\ +\varphi_{j+1,t+1}\left(1-\alpha_{j,t+1}\right) + \alpha_{j,t+1}\varphi_{0,t+1} \end{array} \right] \right\}. \\ \forall j &= 0, ..., J. \end{aligned}$$

Investment decision:

$$\begin{aligned} \varphi_{0,t} - \varphi_{j+1,t} &= i_{j,t} + wG^{-1}(\alpha_{j,t}). \\ \forall j &= 0, ..., J. \end{aligned}$$

Optimality Conditions

Capital demand:

$$\mu_{j,t} = \beta E_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \frac{1}{g_{C,t+1}} \left[\begin{array}{c} MPK_{j,t} + \\ (1-\delta-\delta_j^s)\alpha_{j,t+1} + \\ (1-\delta)\mu_{j+1,t+1}(1-\alpha_{j,t+1}) \end{array} \right] \right\}$$

$$\forall j = 0, ..., J$$

Labor demand:

$$w_t = (1-\alpha)(\omega y_{j,t})^{\frac{1}{\epsilon}} \left(\frac{z_{j,t}}{\Pi_{s=t-j}^{0} g_{Z_0,s}} \right)^{\frac{(\epsilon-1)}{\epsilon}} \gamma_{K,t}^{-\frac{\alpha(\epsilon-1)}{\epsilon}} k_{j,t-1}^{\frac{\alpha(\epsilon-1)}{\epsilon}} L_{j,t}^{\frac{(1-\alpha)(\epsilon-1)}{\epsilon}-1}; \forall j = 0, ..., J$$

Energy demand:

$$p_t^e(1+\tau_t^e\Omega_j) = \frac{1}{\Pi_{s=t-j}^{0} g_{Z_0,s}} \left(\frac{(1-\omega)y_{j,t}}{\frac{e_{j,t}}{\Pi_{s=t-j}^{t} g_{Z_0,s}}} \right)^{\frac{1}{\epsilon}} ; \forall j = 0, ..., J$$

The Model - Solution

Iterative algorithm to solve for steady state:

- Guess the number of vintages J in the economy
- Given J, guess w, k_0, α_j, e_j
- Solve the model
- Verify the guess using
  - : Labor supply for w
  - : Euler equation for capital k_0
  - : Indifference investment equation for hazard rates α_j
  - : Energy demand for e_j
- Verify if J is the endogenous number of vintages; If not, update to $J+1$ and repeat until convergence.

Given unanticipated policy change at time 0,

- : solve for dynamics by first solving for terminal condition (steady state)
- : calculate transition path by solving nonlinear forward-looking deterministic system

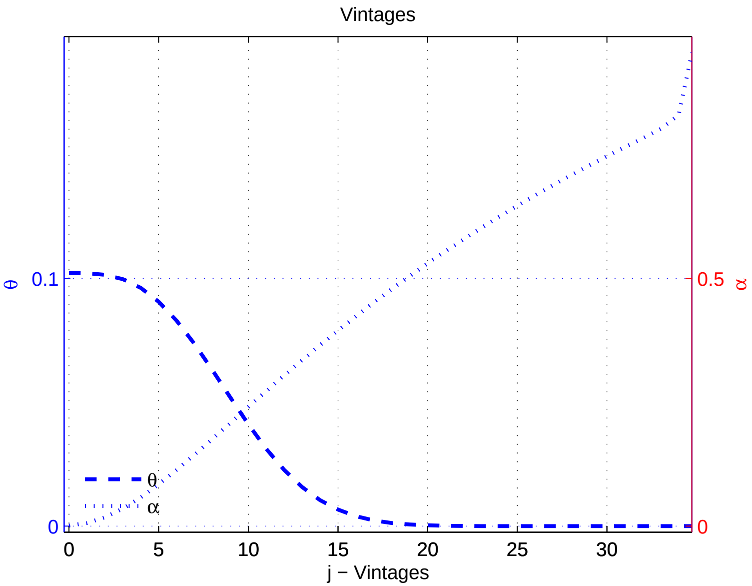
The Model - Calibration

Targets for U.S. economy

Parameter	Value
β, discount factor	0.99
δ, depreciation	0.015
δ_j^s, % scrapped capital	0
g_Y, growth rate of Y	1.0035
ϵ, energy price elasticity	0.25
G/Y, gov spending-output ratio	0.2
τ^l, labor tax	0.2
τ^c, labor tax	0.07
η, inverse of Frisch elasticity	1
Ω_j, relation of energy/emission	1 or $exp(0.05)j$

Parameter	Matching
$1-\omega$, firm distribution parameter	$\frac{P^e E}{Y} = 0.05$
B, upper bound of fixed cost	8% of firms have $\frac{i_j}{k_j} > 30\%$
ψ, preference distribution	$L = 0.2$

Firms' Steady-State Distribution



Results

Policy Experiments

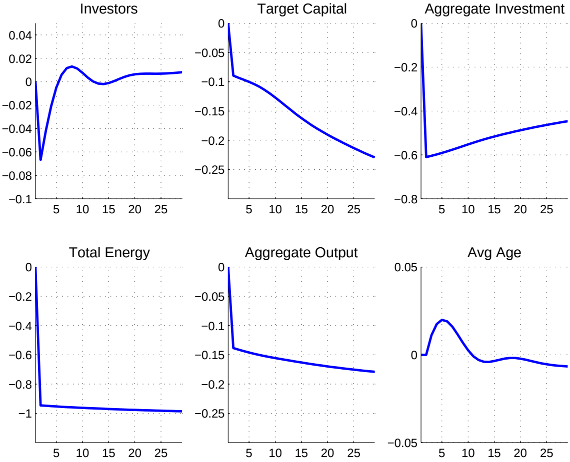
Examine effects of carbon tax

1. Common to all plants
2. Exempting older plants or grand-fathering
3. In conjunction with various revenue recycling scenarios

Calibrate tax rate to achieve 1% reduction in energy usage (or emissions) in long-run

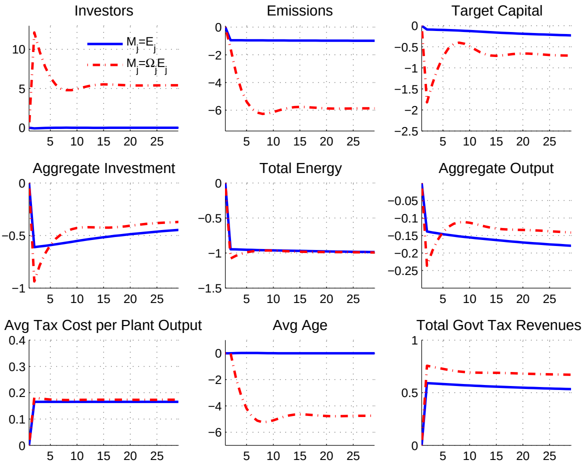
Carbon Tax: uniform emission rates

Tax rate set to reduce energy consumption by 1%



Carbon Tax: heterogeneous emission rates

Tax rate set to reduce energy consumption by 1%



Carbon Tax: heterogeneous emission rates

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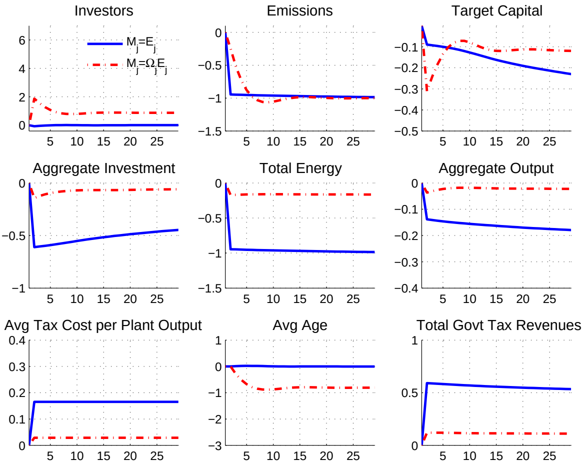
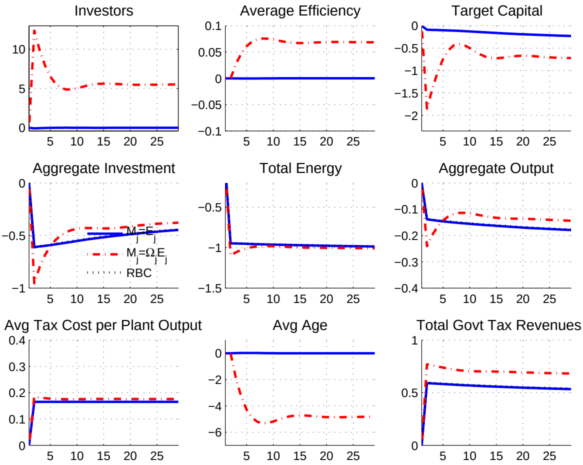


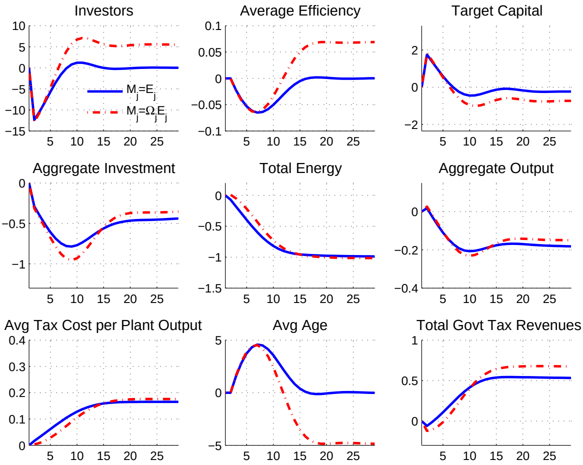
Comparison to Representative Firm Model

Tax rate set to reduce energy consumption by 1%



Energy Policy & "Grandfathering"

Tax rate set to reduce energy consumption by 1%



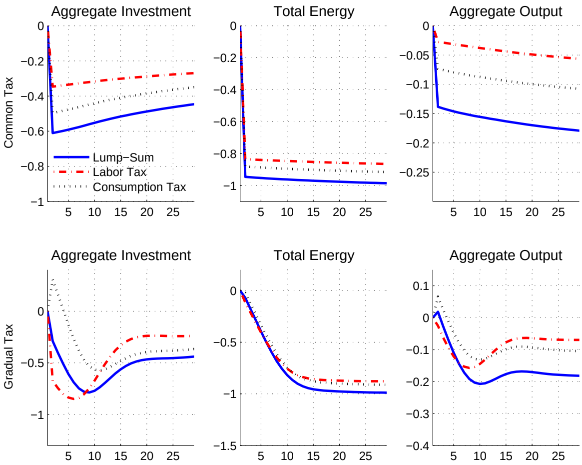
Energy Policy & "Grandfathering"

Tax rate set to reduce energy consumption by 1%

- Vintage-differentiated regulations in U.S.
  - "Grandfathering" permits and regulations
  - Example: U.S. New Source Review Program from Clean Air Act of 1970
  - Result consistent with empirical findings,
    Bushnell & Wolfram (2012), Heutel (2011), Nelson, Tietenberg, & Donihue (1993)

Alternative Revenue Recycling Scenarios

Tax set to reduce energy consumption by 1%



Robustness

- Capital irreversibility $\delta_j^s > 0$
- Idiosyncratic productivity shock (in progress)

Conclusions

- Developed a model to account for plant heterogeneity and plant decision to upgrade technology
- Quantitative predictions of carbon tax reform depend on how policy affects distribution of plants
  - Carbon tax more effective with compositional effect, i.e. when larger dispersion in plant emission rates
  - Exempting older plants from policy decreases benefits in short run
  - Specific implementation of carbon tax affects ability to generate revenues and can even create short term revenue losses