Emission caps and investments in green technologies

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Can government with limited commitment credibly announce cap on CO2 emissions?

After announcing cap, will government actually implement it, or will it give up because of political opposition ?

Depends on how costly it is to switch to green technology in order to comply with cap

Cost of green technology endogenous due to spillovers:

- Previous investments in green technologies $\Rightarrow$ innovations
- // endogenous technical progress: Aghion et al 2017, Acemoglu et al 2012

Spillover effects in green technologies

Strong empirical evidence of spillovers in green technologies

Samadi (2016) (survey on electricity generation):

> *A large volume of empirical research indicates that specific costs fall as experience gained from production... increases. Initially such learning was investigated at individual firm level, but progressively similar observations were made at the industry level... knowledge gained by individual companies... can ultimately be appropriated by other companies... i.e., the spillover effect"*

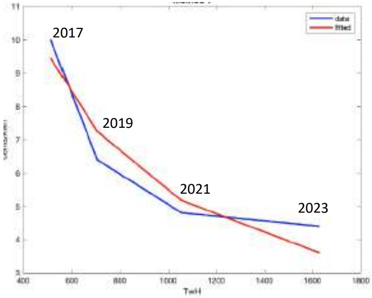
Dechezleprêtre et al (2017) (empirical study of 2 industries: electricity production & electric cars)

> *Clean innovations generate on average 43 % more spillovers than dirty innovations. Knowledge spillovers from clean technologies are comparable in scale to those observed in the IT sector.*

Spillover calibration

Grafström Lindman 2017, Zhou Gu 2019: $cost = \delta_0 capacity^{\delta_1}$
Fit for solar electricity between 2017 and 2023: $\delta_1 = -.69$

Figure 1: Levelized cost of solar electricity in cents per kwh, observed and fitted for power specification, versus total solar electricity production in TWh
Source: our world in data, IRENA



The levelized cost of electricity is a measure of the average net present cost of electricity generation for a generator.
The power specification is cost = delta_0 capacity^delta_L

Investment in green tech $\Rightarrow$ spillovers $\Rightarrow$ lower cost of further investment

Spillovers ⇒ strat. complementarity ⇒ multiple equilibria

Green equilibrium:

- Firms believe government's cap announcement
- invest to reduce emissions
- because of spillovers this reduces the cost of further investment in green tech
- government finds it optimal to cap because not too costly to switch to green for firms that have not invested yet

Brown equilibrium:

- Firms don't believe announcement
- don't invest
- costs remain high
- too costly to implement cap
- government gives up on emission reduction policy

Literature on strategic complementarities

Complementarity between 2 actions: marginal value of one action increases in the level of the other action

When complementary actions chosen by different agents:

- strategic complementarities between these agents (Vives 1985, 1990)
- equilibrium multiplicity

Strategic complementarities in bank runs à la Diamond Dybvig (1983): Goldstein Pauzner (2005), Vives (2014), Schilling (2023)

Difference between our model and classical analyses of strategic complementarities

In Goldstein Pauzner (2005), Vives (2014), Schilling (2023):

- Strategic complementarities between simultaneous actions taken by similar agents
- For one investor, gain from running (relative to gain from staying) increases in mass of investors simultaneously running

In contrast in our model:

- Complementarities between sequential actions: cost of time-2 investment decreases in amount of time-1 investment
- Generate endogenous strategic complementarity between different players: firms' ex-ante investments affect government's ex-post incentives to cap
- Strategic substitutability between firms' simultaneous actions (for given gov policiy): more firms invest at $t = 1 \rightarrow \downarrow$ cost of investment at $t = 2 \rightarrow \uparrow$ incentives to defer investment to $t = 2$

Outline

- Model
- First best
- Implementation of first best as green equilibrium with carbon tax and emission cap, when government can commit
- Green and brown equilibria, when government has limited commitment power

Model

Mass one of firms producing Y at each period $t = 1, 2$

- Period 1: early research & spillover
- Period 2: long term

Each period firm can invest in green tech or not (γ_0 previously invested)

- mass γ_1 invest at t=1 each at cost $c(\gamma_0)$
- mass γ_2 invest at t=2 each at cost $c(\gamma_0 + \gamma_1) < c(\gamma_0)$ (spillover)

Investment in green tech $\rightarrow \downarrow$ emissions (for simplicity $\downarrow 0$)

Emissions increase in brown output ($\eta =$ carbon intensity)

$$E_t = (1 - \sum_{s=0}^{t} \gamma_s)\eta Y, t \in \{1, 2\}$$

Damage flow increasing convex in cumulative emissions:

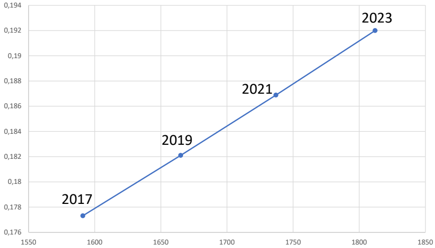
$$\varphi(\sum_{s=1}^{t} E_s), t \in \{1, 2\}$$

Damage from global warming

Climate change $\Rightarrow$ direct $\downarrow$ utility, or $\downarrow$ productivity (e.g., Nordhaus (2018), Bilal Kanzig (2024))

Integrated Assessment Model (DICE, RICE): damage flow increasing in cumulative emissions: $\varphi(\sum_{s=1}^{t} E_s)$

Figure 2: Yearly flow of disutility from global warming in trillion \$ vs cumulative CO2 emissions in Gigatons
Based on Llavador et al 2022



Estimates in Llavador et al (2022) $\rightarrow \varphi$ almost linear

Social cost of carbon as % of GDP

Emissions

$$E = \eta(1-\gamma)Y$$

Linear approximation of social cost of "brown" GDP

$$\phi E = \phi\eta(1-\gamma)Y$$

- $\eta \approx .25$ GT CO2 trio / trillion \$
- $\phi \approx 200\$$ per ton CO2 = .2 trillion \$ / GtCo2

$$\Rightarrow \phi\eta \approx 5\% \text{ to of brown GDP}$$

First best

Utilitarian welfare = PV of utility from consuming output − cost of investing in green technologies − damage from global warming

$$w = \max_{\gamma_1, \gamma_2} Y - \gamma_1 c(\gamma_0) Y - \phi\eta(1 - \gamma_0 - \gamma_1) Y$$
$$+\beta \left(Y - \gamma_2 c(\gamma_0 + \gamma_1) Y - \phi\eta(1 - \gamma_0 - \gamma_1 - \gamma_2) Y \right)$$

β = discount factor between period 1 and period 2

Spillover:

$$c(\gamma_0 + \gamma_1) \leq c(\gamma_0)$$

Optimal government policy at time 2

Dynamic programing problem $\rightarrow$ solve by backward induction $\rightarrow$ first solve at $t = 2$, then solve at $t = 1$ factoring impact of $t = 1$ decisions

$$\frac{\partial w}{\partial \gamma_2} = \eta Y \phi - c(\gamma_0 + \gamma_1) Y$$

benefit (less global warming) $-$ cost of investment in green tech

Define $\bar{\gamma}$ s.t at time 2 benefit of green investment = cost

$$\eta \phi = c(\gamma_0 + \bar{\gamma})$$

If $\gamma_1 \geq \bar{\gamma}$, full investment:

$$\gamma_2 = 1 - \gamma_0 - \gamma_1$$

If $\gamma_1 < \bar{\gamma}$, no investment

$$\gamma_2 = 0$$

$t = 1$ and $t = 2$ decisions complementary: $\gamma_2 > 0$ if γ_1 large enough

Strong Spillovers Assumption

Cost of investment at $t = 2$ after full invest at $t = 1 <$ social cost of brown output $<$ cost after no investment at $t = 1$

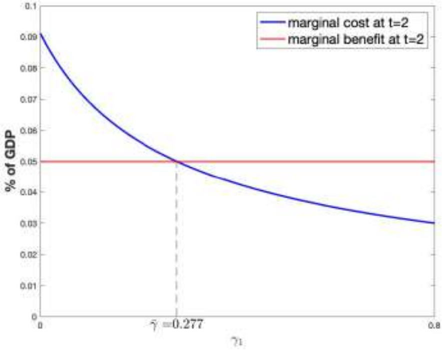
$$c(1) < \eta\phi < c(\gamma_0) \tag{1}$$

In line with literature (e.g., Nordhaus 2018)

- cost of switching to green: between 9% and 1% of GDP
- social cost of brown output $\eta\phi \approx 5\%$

(1) $\Rightarrow$ threshold $\bar{\gamma} \in [0, 1 - \gamma_0]$

Numerical illustration



Starting from $\gamma_0 = 20\%$, decarbonize at $t = 2$ iff $\gamma_1 \geq \bar{\gamma} \approx 27.7\%$

Optimal policy at t=1

- Cost of decarbonizing a bit more at $t = 0$ $c(\gamma_0) <$ cost to delay a bit to to $t = 2$
$$c(\gamma_0) < \eta\phi + \beta c(1)$$
optimal to fully invest at $t = 1$: $\gamma_1^* = 1 - \gamma_0$
- Cost of never decarbonizing $>$ cost of decarbonizing at $t = 1$:
$$(1 + \beta)\eta\phi \geq c(\gamma_0) \geq \eta\phi + \beta c(1)$$
interior optimum $\gamma_1^* \in [\bar{\gamma}, 1 - \gamma_0]$ s.t.
$$c(\gamma_0) = \eta\phi + \beta c(\gamma_0 + \gamma_1^*) - \beta(1 - \gamma_0 - \gamma_1^*)c'(\gamma_0 + \gamma_1^*)$$
followed by full investment at $t = 2$: $\gamma_2 = 1 - \gamma_0 - \gamma_1^*$
- Large initial cost:
$$c(\gamma_0) > (1 + \beta)\eta\phi$$
Objective not quasi-concave: optimum either $\gamma_1^* = 0$ or $\gamma_1^* \geq \bar{\gamma}$

Optimal investment at $t = 1$ $\uparrow$ with social cost of carbon

$\uparrow$ social cost of brown output $\eta\phi \Rightarrow$

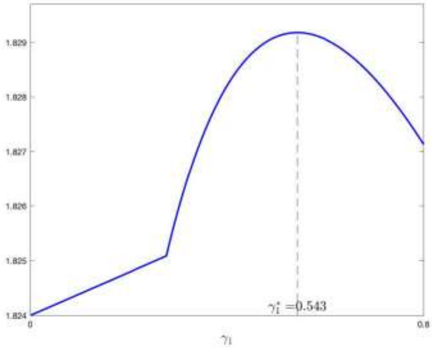
- Relax condition for full investment: $c(\gamma_0) < \eta\phi + \beta c(1)$
- $\uparrow$ interior γ_1^*, since right-hand side of

$$c(\gamma_0) = \eta\phi + \beta c(\gamma_0 + \gamma_1^*) - \beta(1 - \gamma_0 - \gamma_1^*)c'(\gamma_0 + \gamma_1^*)$$

  decreasing in γ_1^*

Interior optimum in numerical illustration

If $(1+\beta)\eta\phi \geq c(\gamma_0) \geq \eta\phi + \beta c(1)$ then $\gamma_1^* \in [\bar{\gamma}, 1-\gamma_0]$



In our numerical illustration: $\gamma_1^* \approx .5138 > \bar{\gamma} \approx .277$

Information asymmetry about early stage research

At $t = 1$:

- gov cannot observe/control early stage research (see Akcigit, Hanley, Stancheva (2022), Scotchmer (1999))
  $\rightarrow$ gov cannot observe/control if firms really invest in green technologies at $t = 1$ (firms claiming they invest could actually be greenwashing)
  $\rightarrow$ γ_1 not directly set by government, results from firms' decision
- to incentivize firms, gov sets carbon tax τ, contingent on observable time 1 emissions

At $t = 2$:

- gov can observe/control implementation of mature technologies developed at $t = 1 \rightarrow$ set γ_2
- to set γ_2, gov can cap emissions: if cap, firms that did not invest at $t = 1$ must do so at $t = 2$ (equivalently, could levy additional carbon tax on time 2 emissions)

Equilibrium when government can fully commit

If gov can commit to emission caps and carbon taxes/green subsidies

- Beginning of period 1, government announces policy: carbon tax τ, and whether emissions will be capped or not
- Firms invest, at cost $c(\gamma_0)$ or not
- End of period 1, emissions observed: government implements announced carbon tax policy: tax $= \tau Y$ on firms that did not invest at $t = 1$
- Beginning of period 2, government implements announced emission cap policy
- End of period 2, emissions observed: government implements announced carbon tax policy: again tax $= \tau Y$ on firms that did not invest at $t = 1$

Taxing time 1 emissions both at $t = 1$ and $t = 2$ maximizes the power of incentives (but for some parameter values enough to tax at $t = 1$)

Green equilibrium conditions

Green equilibrium : eventual full decarbonation: $\gamma_2 = 1 - \gamma_0 - \gamma_1$

Government sets carbon tax which incentivizes investment in green tech $\gamma_1 \in [\bar{\gamma}, 1 - \gamma_0]$, and announces cap which implies $\gamma_2 = 1 - \gamma_0 - \gamma_1$

Government budget balance: green subsidies funded by carbon taxes

$$(1 - \gamma_0 - \gamma_1)\tau = (\gamma_0 + \gamma_1)s$$

Firms indifferent between investing at $t = 1, 2$

$$(1 + \beta)(1 + s) - c(\gamma_0) = (1 + \beta)(1 - \tau) - \beta c(\gamma_0 + \gamma_1)$$

$\uparrow$ Pigovian tax $\rightarrow \uparrow$ relative profitability of early investment
$\rightarrow \uparrow$ incentive to generate positive externality ($\downarrow$ emissions, $\uparrow$ spillovers)

First best can be implemented as equ with tax & cap

Pigovian taxation and caps incentivize optimal investment in green technology (could also be achieved with cap and trade)

To implement interior first best $\gamma_1^* \in [\bar{\gamma}, 1 - \gamma_0]$, set carbon tax s.t. firms indifferent between investing at $t = 1$ and $t = 2$, when anticipating that $\gamma_1^* \geq \bar{\gamma}$ firms invest at $t = 1$ and emissions capped at $t = 2$

$$\tau(\gamma_1^*) = \frac{\gamma_0 + \gamma_1^*}{1 + \beta}(c(\gamma_0) - \beta c(\gamma_0 + \gamma_1^*))$$

LHS: cost of delaying investment. RHS: cost of investing early.

$\tau(\gamma_1^*)$ increasing in γ_1^*, which is itself increasing in $\eta\phi$:

larger social cost $\Rightarrow$ invest more in green tech $\Rightarrow$ larger carbon tax

If government cannot commit to ex-post dominated policy (subgame perfection)

Assume gov cannot commit to ex-post inefficient cap: no cap if $\gamma_1 < \bar{\gamma}$ but can commit to purely redistributive carbon tax which does not $\downarrow w$

If

$$\hat{\gamma}_1 \equiv \frac{1+\beta}{c(\gamma_0)}\tau(\gamma_1^*) - \gamma_0 \leq \bar{\gamma} \tag{2}$$

then, when gov credibly announces $\tau(\gamma_1^*)$, $\exists$ brown equilibrium:

- low time 1 investment $\hat{\gamma}_1 \leq \bar{\gamma}$
- no time 2 cap: $\gamma_2 = 0$

$\hat{\gamma}_1$ is such that firms indifferent between investing at $t = 1$ and $t = 2$ (when anticipating no cap)

$$c(\gamma_0) = \frac{1+\beta}{\gamma_0 + \bar{\gamma}_1}\tau(\gamma_1^*)$$

Multiple equilibria

If gov cannot commit to cap, green equilibrium implementing γ_1^* with

$$\tau(\gamma_1^*) = \frac{\gamma_0 + \gamma_1^*}{1+\beta}(c(\gamma_0) - \beta c(\gamma_0 + \gamma_1^*))$$

coexists with brown equilibrium if

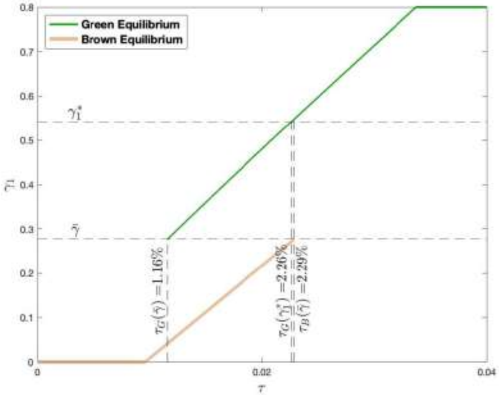
$$\hat{\gamma}_1 = \frac{1+\beta}{c(\gamma_0)}\tau(\gamma_1^*) - \gamma_0 \leq \bar{\gamma}$$

Multiplicity due to strategic complementarity

Brown and green equilibria in our numerical illustration

Define:

$$\tau_G(\bar{\gamma}) = \frac{\gamma_0 + \bar{\gamma}}{1+\beta}(c(\gamma_0)_\beta c(\gamma_0 + \bar{\gamma})) \leq \tau_B(\bar{\gamma}) = \frac{c(\gamma_0)}{1+\beta}$$



Hard to commit to carbon tax

Difficult to implement emission reductions that are costly for businesses

- 2014: Repeal of 2012 Australian carbon tax, motivated by large cost on businesses
- 2018: Ontario withdraws cap-and-trade program, due to concerns over costs to consumers and businesses
- 2020: US withdraw from the Paris Climate Agreement, because of cost on American businesses
- 2025: Europe waters down clean car policy

$\Rightarrow$ when carbon tax announced, not sure it will be implemented

$\Rightarrow$ we hereafter assume carbon tax implemented with probability λ

Offshoring limits carbon tax

Carbon tax in one country $\Rightarrow$ relocation of brown production to countries without carbon tax

Li and Zhou (2017)

> *U.S. plants located in counties with greater institutional pressure for environmental performance offshore more*

Coster, di Giovanni, Mejean (2024)

> *French firms shifted their imports of dirty products to non-ETS country suppliers over time*

$\Rightarrow$ hereafter assume carbon tax $\tau \leq \theta =$ cost of offshoring

If $\tau > \theta$, offshoring: operate brown technology in country with slack environmental policy

Sequence of actions with limited carbon taxation

- Beginning of period 1: Government announces policy: carbon tax τ, and emission caps. Then firms invest, at cost $c(\gamma_0)$ or not.
- End of period 1, emissions observed. With probability λ, government has political clout: implement announced carbon tax policy. Firms can decide to remain and pay tax, or offshore at cost θ.
- Beginning of period 2, government caps if efficient. If cap, firms that did not invest at $t = 1$ must invest now, at cost $c(\gamma_0 + \gamma_1)$
- End of period 2, emissions observed: if government has political clout, it implements announced carbon tax policy.

Option to offshore $\Rightarrow$ government cannot set $\tau > \theta$

Green equilibrium condition with limited carbon taxation

When gov can perfectly commit to taxation ($\lambda = 1$), to implement green equilibrium γ_1 gov must set $\tau_{\lambda=1}(\gamma_1)$ s.t.

$$\tau_{\lambda=1}(\gamma_1) \geq \frac{\gamma_0 + \gamma_1}{1+\beta}(c(\gamma_0) - \beta c(\gamma_0 + \gamma_1))$$

With limited commitment to taxation ($\lambda < 1$), to implement green equilibrium γ_1 gov must set $\tau_{\lambda<1}(\gamma_1)$ s.t.

$$\lambda \tau_{\lambda<1}(\gamma_1) \geq \frac{\gamma_0 + \gamma_1}{1+\beta}(c(\gamma_0) - \beta c(\gamma_0 + \gamma_1)) \iff \tau_{\lambda<1}(\gamma_1) = \tau_{\lambda=1}(\gamma_1)/\lambda$$

No offshoring $\Rightarrow \tau_{\lambda<1}(\gamma_1) < \theta$

So γ_1 can be implemented as green equilibrium iff

$$\tau_{\lambda=1}(\gamma_1) \leq \lambda\theta$$

$\Rightarrow \gamma_1$ can be implemented iff λ and θ not too low: for $\theta = 5\%$, $\lambda \geq .13$

Conclusion

Spillover $\Rightarrow$ complementarity between investment at $t = 1$ and $t = 2$

$\Rightarrow$ strategic complementarity between firms' investment in green technologies and government's cap policy

$\Rightarrow$ multiple equilibria: green and brown

Good to invest early in renewable energy

- because damage increase in cumulative emissions (Nordhaus, 2018)
- because makes further investments more politically acceptable (new)

Strategic complementarity among policy tools: carbon tax $\rightarrow$ incentive for early investment $\rightarrow$ cap