Enforcing Compliance in IEA: Investments, Instruments, and Participation

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Motivation

- **Climate** is the ultimate **global public good**
- International cooperation through IEA is the solution to suboptimal level of public good provision
- There is no supra-national authority with the power to enforce participation and respect of treaties obligations
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- **Compliance** is the main challenge
- While full compliance alone is not sufficient for effectiveness, no agreement can succeed without a reasonable level of compliance

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    - **Carrots**: Provision of financial and technological assistance to incentivize participation.
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  - *Technology investments* (e.g., Barrett, 2003; Harstad, Lancia and Russo, 2019, 2022; Battaglini and Harstad, 2020): By investing in cleaner technology upfront, countries reduce their cost of compliance.

Motivation

Scope of this lecture:

- Discuss these potential **ways** to **motivate compliance** using a **dynamic setting**
- Focus on **technology investment**
- Generally on the role of **strategic complement and substitute actions** in repeated interactions

Literature (too long for a summary!)

Fudenberg and Tirole '96: Game Theory

Mailath and Samuelson '06: Repeated Games and Reputations

Bolton and Dewatripont '05: Contract Theory: Quantities and investments

Hart '10: Theory of the Firm: Hold-up problems and organizational responses

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Outline of Lecture

1. Concepts
2. Repeated games and Folk theorem
3. Repeated games with emission and technology
4. Repeated games with imperfect public monitoring
5. Continuous emission levels & Policy instruments
6. Some facts on IEA
7. Dynamic ratification game and structural estimation

1-1. Important Concepts and Equilibria Refinements

Normal form game	Nash equilibrium
Extensive form game	Subgame-perfect equilibrium
Repeated game and stage game	Renegotiation proofness
Stochastic game	Markov-perfect equilibrium

1-2. The Prisonner Dilemma Game

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- Let g_i be the emission of country $i \in \{1, \dots, n\}$, $B(g_i)$ the benefit of polluting, c the marginal cost of greenhouse gases:

$$u_i = B(g_i) - c \sum_{i=1}^{n} g_i.$$

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- When $g \in \{\underline{g}, \overline{g}\}$ with $\underline{g} < \overline{g}$, the first-best agreement is simply $g = \underline{g}$ if:

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$$B(\overline{g}) - B(\underline{g}) < (\overline{g} - \underline{g})cn.$$

- But polluting more is a dominant strategy if:

$$B(\overline{g}) - B(\underline{g}) > (\overline{g} - \underline{g})c.$$

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- The emission game is a PD game if both hold:

$$1 < \frac{B(\overline{g}) - B(\underline{g})}{c(\overline{g} - \underline{g})} < n.$$

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- With (grim) trigger strategies, cooperation $(g = \underline{g})$ is an SPE if:

$$\frac{B(\underline{g}) - cn\underline{g}}{1-\delta} \geq B(\bar{g}) - c\bar{g} - c(n-1)\underline{g} + \delta \frac{B(\bar{g}) - cn\bar{g}}{1-\delta}$$

$$\Longleftrightarrow$$

$$B(\bar{g}) - B(\underline{g}) \leq c(\bar{g} - \underline{g})\left[\delta n + (1-\delta)\right]$$

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$$B(\bar{g}) - B(\underline{g}) \leq c(\bar{g} - \underline{g})\left[\delta n + (1-\delta)\right]$$

- As long as the first best requires $g = \underline{g}$, cooperation is possible for sufficiently high discount factors:

$$\delta \geq \hat{\delta} \equiv \frac{1}{n-1}\left[\frac{B(\overline{g}) - B(\underline{g})}{c(\overline{g} - \underline{g})} - 1\right] < 1$$

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- If $\delta < \hat{\delta}$, the unique SPE is $g = \overline{g}$.

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- Cooperation in a PD game can be sustained when the game is repeated:
  - Countries worry that if one cheats by emitting today, other countries will do the same in the future
- For cooperation on abatement to be enforceable two conditions must be satisfied:
  - Countries must care sufficiently about the future
  - The temptation to emit rather than abate cannot be too large

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- The gains from emitting rather than abating depend on a country's **stocks** of technologies and the **type** of technology
- If a country has renewable energy sources, or if it is able to clean emissions effectively
  - → then the cost of abating relative to emitting is smaller, and the temptation to cheat in the PD game is diminished

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- If a country has renewable energy sources, or if it is able to clean emissions effectively
  - → then the cost of abating relative to emitting is smaller, and the temptation to cheat in the PD game is diminished
- If instead, a country is endowed with a brown industry structure, as after advancements in the extraction of (unconventional) fossil fuels
  - → then the country will be more tempted to emit

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  - then these other countries may also be willing to comply with their promises to prevent cooperation from breaking down
- Thus, to raise the likelihood for compliance and ensure that the treaty is self-enforcing,
  - it may be necessary to require countries to distort investment decisions → **Technology investment as reputation building** (Harstad, Lancia, and Russo, 2019)

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- Beyond setting emission targets, the agreement required EU member states to raise the share of renewable energy to at least 20% of the total energy mix by 2020.
- Member states had to submit national plans for technology investments by 2010, but binding emission limits only came into force in 2013.
- As a result, early technology adoption allowed for enforcement mechanisms based on conditioning cooperation on prior investment in clean technologies.

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5. Who should invest what?

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- Consider next a stage game with both emissions and technology investments ($r_{i,t}$):

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- Linear investment-cost k is a normalization
- Will be added below: Uncertainty, spillovers, and stocks

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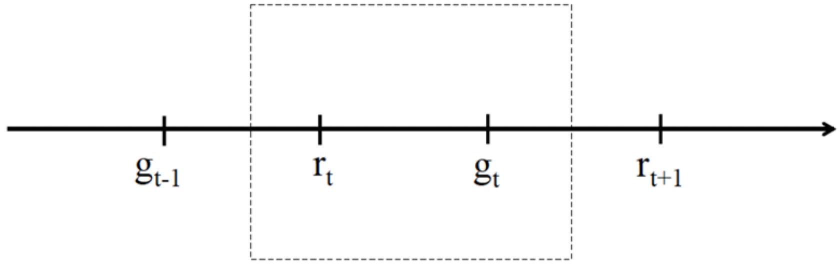

Figura 1: Timing of the Game

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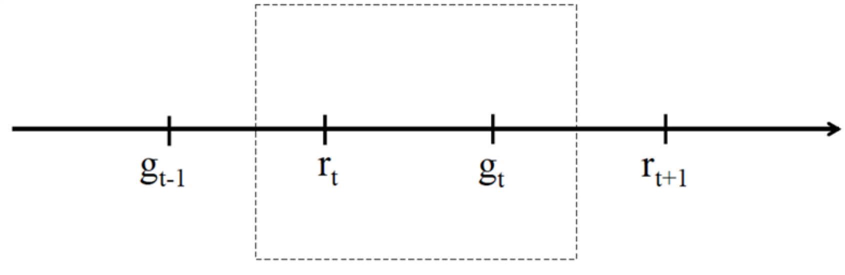

Figura 1: Timing of the Game

- Sequential timing of investment and emissions decisions justified by operational lag
- Technology is assumed to fully depreciate, so countries must invest in each period

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- The business-as-usual (BAU) outcome is (g^b, r^b) satisfying

$$B_g(g^b, r^b) = c(r^b) \text{ and}$$

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Proposition

- *If $g_i \in \{\underline{g}, \bar{g}\}$, the* ***first-best agreement*** *is simply $g_i^* = \underline{g}$ and*

$$r_i^* = \rho_i^*(g_i^*) = argmax_r B(g_i^*, r) - ng_i^* c(r) - kr$$

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- *The* ***unique SPE of the stage game*** *is $g_i^* = \overline{g}$ and $r_i^* = \rho_i^*(g_i^*)$*

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- *The* ***unique SPE of the stage game*** *is $g_i^* = \overline{g}$ and $r_i^* = \rho_i^*(g_i^*)$*
- *Given g, every country will voluntarily invest optimally in $\rho_i^*(g)$*
  - → *Once g has been* ***committed*** *to, there is* ***no need to negotiate*** *r.*

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Definition

An **equilibrium** is referred to as **best** if and only if it supports the **unique Pareto-optimal SPE** outcome involving $g = \underline{g}_i$ for all $i \in N$ and $t \geq 0$ on the equilibrium path.

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- The maximization problem is:

$$\max_{r,g\in\{\underline{g},\overline{g}\}} \frac{B(g,r)-ngc(r)-kr}{1-\delta}$$

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- subject to the two **Compliance Constraints**:

CC-r Compliance constraint at the Investment Stage

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- Let $v^b = \frac{B(g^b,r^b)-ng^b c(r^b)-kr^b}{1-\delta}$ be each country's continuation utility in BAU.

1-3. Problem: Deriving the best SPE

- The **Compliance constraint** at the **Investment Stage** is

$$\frac{B(\underline{g}, r) - n\underline{g}c(r) - kr}{1-\delta} \geq B(g^b(\tilde{r}), \tilde{r}) - [g^b(\tilde{r}) + (n-1)g^b(r)]c(\tilde{r}) \\ -k\tilde{r} + \delta v^b \quad \forall \tilde{r}$$

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- $\tilde{r}$ is the best country'i deviation at the investment stage

- If a country deviates at the investment stage, this deviation is observed by the other countries who revert to BAU thereafter, conditional on their investments

- When $g_i \in \{\underline{g}, \overline{g}\}$, then $g^b(r) = g^b(\tilde{r}) = \overline{g}$ and $\tilde{r} = r^b$

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- With discrete emissions, then the **Compliance constraint** at the **Investment Stage** simplifies to a **Participation constraint**

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$$\frac{B(\underline{g}, r) - n\underline{g}c(r) - kr}{1-\delta} \geq v^b$$

- If a country deviate at the investment stage the penalty is imposed before the country can benefit from free riding on emissions

1-3. Problem: Deriving the best SPE

- With discrete emissions, then the **Compliance constraint** at the **Investment Stage** simplifies to a **Participation constraint**

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- **CC-r never binds** if an agreement is beneficial

1-3. Problem: Deriving the best SPE

- The **Compliance constraint** at the **Emission Stage** is

$$\frac{B(\underline{g}, r) - n\underline{g}c(r) - \delta kr}{1-\delta} \geq B(\tilde{g}, r) - [\tilde{g} + (n-1)\underline{g}]c(r) + \delta v^b \quad \forall \tilde{g}$$

- $\tilde{g}$ is the best deviation in emission conditional on not having deviated at the investment stage $\rightarrow \tilde{g} = \overline{g}$

- As $\delta \rightarrow 1$, CC-g approaches CC-r, but for any $\delta < 1$, CC-g is harder to satisfy than CC-r

1-3. Problem: Deriving the best SPE

Proposition

Folk theorem: *There exists* $\hat{\delta}^r < 1$ *and* $\hat{\delta}^g < 1$ *such that the first-best can be sustained as an SPE iff* $\delta \geq \max\{\hat{\delta}^r, \hat{\delta}^g\}$

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→ What is the **best SPE** that can be sustained when the **Folk theorem does not hold**?

1-3. Compliance Constraints

- $CC\text{-}g$ can be written as:

$$B(\underline{g}, r) - n\underline{g}c(r) - kr - (1/\delta - 1)[B(\overline{g}, r) - B(\underline{g}, r) - (\overline{g} - \underline{g})c(r)] \geq (1-\delta)v^b$$

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- Maximizing rhs of CC-g wrt r gives **the best compliance technology** $\hat{r}$:

$$\frac{B_r(\underline{g}, \hat{r}) - n\underline{g}c_r(\hat{r}) - k}{1/\delta - 1} = B_r(\overline{g}, \hat{r}) - B_r(\underline{g}, \hat{r}) - (\overline{g} - \underline{g})c_r(\hat{r})$$
$$\approx (\overline{g} - \underline{g})[B_{gr} - c_r] \Leftrightarrow$$
$$\hat{r} > (<) r^* \text{ iff } B_{gr} - c_r < (>) 0.$$

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- Let $\hat{\delta}_i(r_i)$ be the level of δ such that CC-g holds with equality for all i
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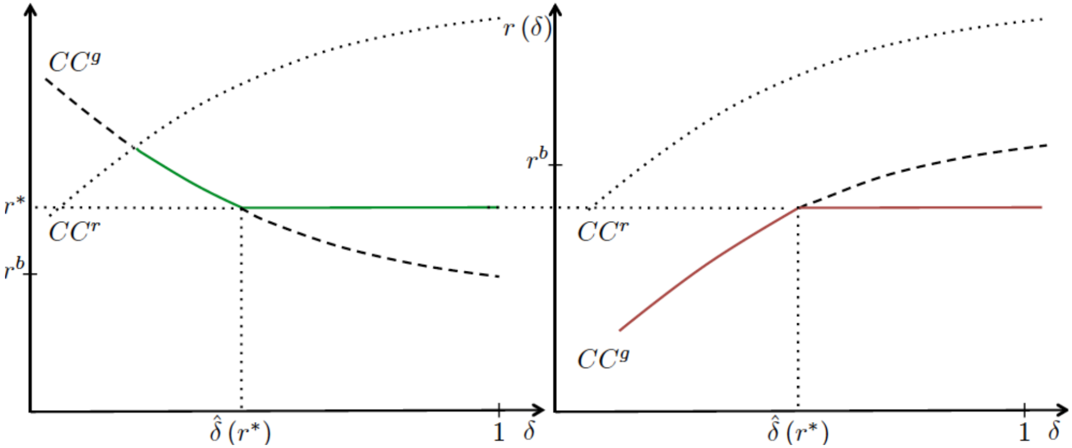

Figura 2: Best SPE: Left Panel for Green Technology. Right Panel for Brown and Adaptation Technology.

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- Reluctant countries should contribute **more!** (i.e., invest more in green technologies and less in brown).
- *True*: One problem is to persuade a reluctant country to *participate*.
- However, the harder problem is to ensure that they are willing to *comply* - once they expect others to comply.
- Reluctant countries should be helped to make such **self-commitment**, and this can be done with technology!

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- Green technologies and brown technologies act as strategic **complements**: The more countries invest in drilling technologies, the more they must invest in green technologies.
- Green technologies and adaptation technologies act as strategic **complements**: The more countries adapt, the more they must invest in green technologies.
- Brown technologies and adaptation technologies act as strategic **substitutes**: The more countries invest in brown technologies, the less they should adapt.

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- The probabilities will depend on the threshold $\hat{g}$:

$$p_I = 1 - F(\hat{g} - n\underline{g}) \text{ and } p_{II} = F(\hat{g} - (n-1)\underline{g} - \bar{g})$$

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- When $p_I > 0$, the best SPE may require $T < \infty$.

1-4. Uncertainty and Imperfect Monitoring: Cooperation

Proposition

- *The triplet* $(\underline{g}, r, T)$ *is an SPE if* $\delta \geq \hat{\delta}(r, T)$ *where* $\hat{\delta}'_T < 0$, $\hat{\delta}'_{p_I} > 0$, $\hat{\delta}'_{p_{II}} > 0$ *and, as before,* $\hat{\delta}'_n < 0$, $\hat{\delta}'_h < 0$ *and*

$$sign\ \hat{\delta}'_r = sign\ (B_{gr} - c_r).$$

1-4. Uncertainty and Imperfect Monitoring: Proof

Proof: Let $V^c(r)$ be the **continuation value** in the **cooperation phase**:

$$V^c(r) = B\left(r, \underline{g}\right) - n\underline{g}c(r) - kr + \delta\left[p_I V^p(r) + (1 - p_I)V^c(r)\right],$$

where the **continuation value** at the start of the **punishment phase** is:

$$V^p(r) = (1 - \delta^T)\nu^b + \delta^T V^c(r) \geq \nu^b$$

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- As before, if the agreement is valuable, **CC-r is never binding**
- **Punishing on the eq. path**: To sustain the max $V^c(r)$, the value in punishment $V^p(r)$ must be as large as CC-g (defined later) permits

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A country may be tempted to pollute a lot to get $V^d(r) =$

$$B(r, \bar{g}) - [(n-1)\underline{g} + \bar{g}]c(r) - kr + \delta[(1-p_{II})V^p(r) + p_{II}V^c(r)]$$

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The best equilibrium maximizes $V^c(r)$ subject to CC-g (called now CC-im):

$$V^c(r) \geq V^d(r) \Rightarrow \tag{CC-im}$$

$$V^c(r)\left[(1-p_{II}-p_I)\delta\left(1-\delta^T\right)+1-\delta\right] \geq$$

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- When T tends to ∞ and $p_I = p_{II} = 0$, CC-im approaches CC-g, as without imperfect monitoring

1-4. Uncertainty and Imperfect Monitoring: Proof

- Let $\hat{\delta}(r, T, p_{II}, p_{I})$ be defined such that CC-im holds with equality
- Doing comparative static w.r.t. this equation completes the proof

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1-4. Uncertainty and Imperfect Monitoring: Optimal r

Taking CC-im holding with equality we get the following continuation value:

$$V^c(r) = \frac{1}{1-\delta}\left(B(r,\underline{g}) - n\underline{g}c(r) - kr - \frac{p_I}{1-p_I-p_{II}}\Psi(r)\right) \quad \text{where}$$

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- The term $\frac{p_I}{1-p_I-p_{II}}\Psi(r)$ is the **efficiency loss** associated with punishment in equilibrium

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- The optimal investment $\tilde{r}$ is determined by maximizing $V^c(r)$:

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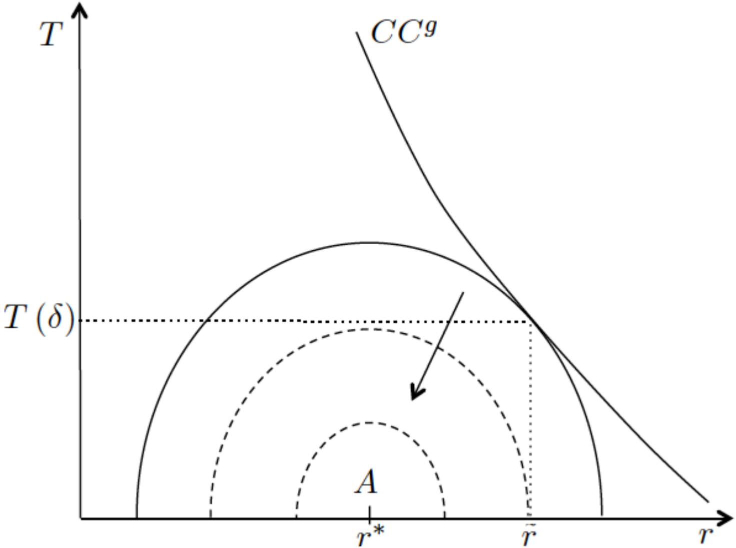

For Clean Technology

Figura 3: Best SPE when Clean Technology Investment

1-4. Uncertainty and Imperfect Monitoring: Optimal T

- The optimal T is obtained from $\hat{\delta}(\tilde{r}, T) = \delta$ as long as $T < \infty$ (i.e., $\delta > \bar{\delta}$)
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- $T(\delta, \tilde{r})$ is such that $T'_{\delta} < 0$
- If $\delta < \bar{\delta}$, then there exists no finite T without violating CC-im if $r = \tilde{r}$
  - $\rightarrow$ need to further distort r

1-4. Uncertainty and Imperfect Monitoring: r vs. T

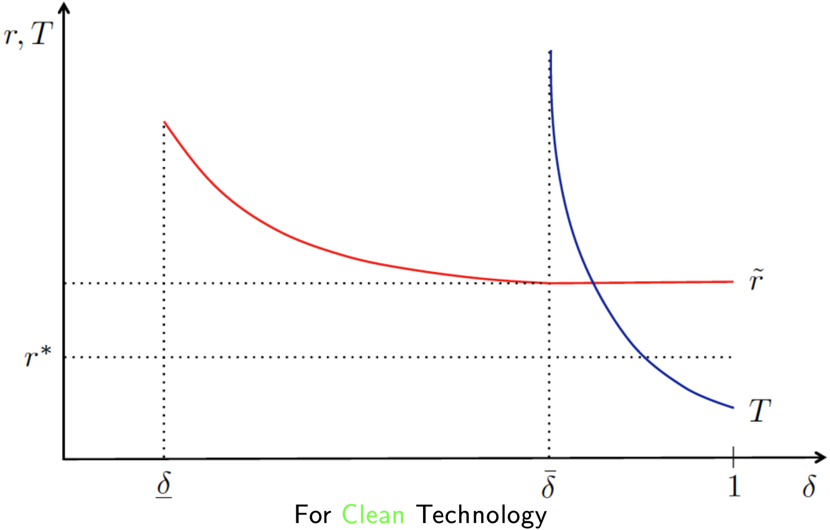

Figura 4: Best SPE when Clean Technology Investment

1-4. Uncertainty and Imperfect Monitoring: r and T

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- In the baseline model (without uncertainty), strategic technology investments were necessary in order to **motivate compliance** when the discount factor is small
- With uncertainty and imperfect monitoring, strategic investments **reduced the length of the punishment** period needed to discourage defections
- Errors p_I and p_{II} are here considered as exogenous, but they can be endogenized (find the optimal emission threshold)
  - → new role of technology is to **reduce the probability of punishment** triggered by mistake, i.e., type I error.

1-4. Further Extensions and Application

- **Technological spillovers**:

$$z_i = (1-e)r_i + \frac{e}{n-1}\sum_{j\neq i} r_j$$

where $1-e$ proxies the strength of IPR.

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- **Present bias in politics** (Harstad and Kessler, 2025):

$$v_{it} = u_{it} + \beta \sum_{j=1}^{\infty} \delta^j u_{it+j}$$

Smaller β implies greater disagreement across governments.

$\Rightarrow$ Stronger incentives to pre-commit via investments.

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- **Continuous emissions** & policy implementation via **prices vs. quantities**:

  ⇒ Harstad, Lancia, Russo (2022)

1-5. Continuous emission levels

- As before, n countries i or $j \in N \equiv \{1, \ldots, n\}$ and infinite periods $t \in \{1, 2, \ldots, \infty\}$;

- Each country i's actual emissions are $g_{i,t} = y_{i,t} - r_{i,t}$, where $y_{i,t}$ are units of energy and $r_{i,t}$ are abated units from **renewable energy investment**;

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- Each country i's per-period payoff is:

$$u(\mathbf{g}_t, r_{i,t}) \equiv B(g_{i,t} + r_{i,t}) - c \sum_{j \in N} g_{j,t} - K(r_{i,t}),$$

where $B(y_{i,t}) = -(b/2)(\bar{y} - y_{i,t})^2$ and $K(r_{i,t}) = (k/2) r_{i,t}^2$;

- Each country discounts future payoffs at a common rate $\delta \in (0, 1)$.

1-5. Price vs Quantity

- In each period, domestic firms invest in renewables *before* consumers choose energy consumption;
- Each country's government can regulate domestic emissions and investment by means of:
  - Q. **Quantity mandates**: Government sets emission and investment levels;
  - P. **Price instruments**: Government sets an emission tax $\tau_{i,t}$ to be paid by consumers and an investment subsidy $\varsigma_{i,t}$ to be paid to firms;
- Governments cannot commit to future policies and set each period policy before private sector's decisions.

1-5. Price vs Quantity: Timing

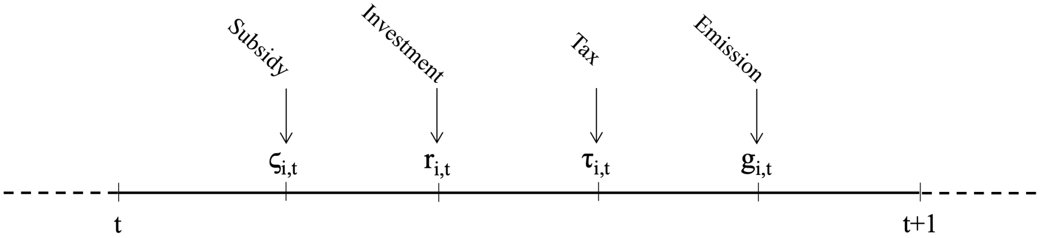

Figura 5: *Timing of the Game*

⇒ Price instruments allow firms to *flexibly* adjust investment to the anticipation of future policies, while quantity mandates do not.

1-5. Emission and Investment levels

- **Consumers** choose $g_{i,t}$ to max. the benefit of consumption net of taxes $B\left(y_{i,t}\right) - \tau_{i,t} g_{i,t}$:

$$B'\left(y_{i,t}\right) = \tau_{i,t} \Leftrightarrow g\left(\tau_{i,t}, r_{i,t}\right) = \overline{y} - \frac{\tau_{i,t}}{b} - r_{i,t}.$$

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- **Firms** choose $r_{i,t}$ to max. the benefit of production net of investment costs and subsidies $B(y^e_{i,t}) - K\left(r_{i,t}\right) + \varsigma_{i,t} r_{i,t}$, where $\tau^e_{i,t} = B'(y^e_{i,t})$ is the foreseen emission tax:

$$K'\left(r_{i,t}\right) = B'\left(y^e_{i,t}\right) + \varsigma_{i,t} \Leftrightarrow r\left(\tau^e_{i,t}, \varsigma_{i,t}\right) = \frac{\tau^e_{i,t} + \varsigma_{i,t}}{k}.$$

▸ Price Agreement

1-5. Benchmarks

Business as Usual: Each country's climate policies are set non-cooperatively to maximize the country's payoff.

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Q. **Optimal Quotas**:

$$r^b = \frac{c}{k} \quad \text{and} \quad g_b\left(r_{i,t}\right) = \overline{y} - \frac{c}{b} - r_{i,t}, \quad \text{then} \quad g^b = \overline{y} - \frac{b+k}{bk}c.$$

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A self-enforcing agreement implies that optimal climate policies satisfy:

CC-r: A **compliance constraint** at the **investment stage**:

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- However, since they invested $r \geq r^b$ (see later), then $g_b(r) \leq g^b$
- Hence, there is one period gain from deviating and CC-r possibly binding

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- When $\delta \to 1$, both CC-r and CC-r approaches $u(\mathbf{g}, r) \geq u^b$ when $r = r^*$ and $g = g^*$ and the Folk Theorem applies
- Which compliance constraint is harder to satisfy?

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- If $k/b \geq 1/2$, high cost of investment makes emission reduction more cost effective $\longrightarrow$ more tempting to defect at the emission stage
- If $k/b \geq 1/2$, low cost of investment prioritizes high investment $\longrightarrow$ more tempting to defect at the investment stage

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Proposition

i. *If* $\delta \geq \max\left\{\overline{\delta}_q^g, \overline{\delta}_q^r\right\}$, ***all quantities are first best.***

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$$g = g^* + \Lambda_q(\delta) > g_*(r) \quad \textit{and} \quad r = r^* = r_*(g) + \frac{b}{b+k}\Lambda_q(\delta), \textit{ where}$$

$$\Lambda_q(\delta) \equiv \frac{c(n-1)}{b}\left(1 - \delta - \sqrt{\frac{\delta(b+\delta k)}{k}}\right) > 0.$$

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- Since CC-g binds, emissions are allowed to be larger than g^* with $\Lambda_q(\delta)' < 0$
- Two countervailing effects for investment: (i) more emissions less investment (ii) more mandated investment less emissions → net effect is null

1-5. Self-Enforcing Quota Agreement

Proposition

iii. *If $k/b < 1/2$, then* ***CC-r binds first*** *and for $\delta < \bar{\delta}_q^r$:*

$$g = g_*(r) = g^* + \Xi_q(\delta) \quad \text{and} \quad r = r^* - \Xi_q(\delta) < r_*(g) < r^*, \text{ where}$$

$$\Xi_q(\delta) \equiv \frac{c(n-1)}{k}\left(1 - \delta - \sqrt{\frac{k+\delta^2 b}{b}}\right) > 0.$$

- With binding CC-r, clean investment must fall below r^* and $\Xi_q'(\delta) < 0$

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Proposition

iii. *If* $k/b < 1/2$*, then* ***CC-r binds first*** *and for* $\delta < \bar{\delta}_q^r$:

$$g = g_*(r) = g^* + \Xi_q(\delta) \quad \text{and} \quad r = r^* - \Xi_q(\delta) < r_*(g) < r^*, \text{ where}$$

$$\Xi_q(\delta) \equiv \frac{c(n-1)}{k}\left(1 - \delta - \sqrt{\frac{k+\delta^2 b}{b}}\right) > 0.$$

- With binding CC-r, clean investment must fall below r^* and $\Xi_q'(\delta) < 0$
- Emissions rise, but g remains optimal given r

1-5. Self-Enforcing Quota Agreement

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- With binding CC-r, clean investment must fall below r^* and $\Xi_q'(\delta) < 0$
- Emissions rise, but g remains optimal given r
- Counterintuitive result: Countries must face punishment when $r = r_*(g)$; otherwise, non-deviators cannot credibly punish excessive emissions!

1-5. Self-Enforcing Quota Agreement

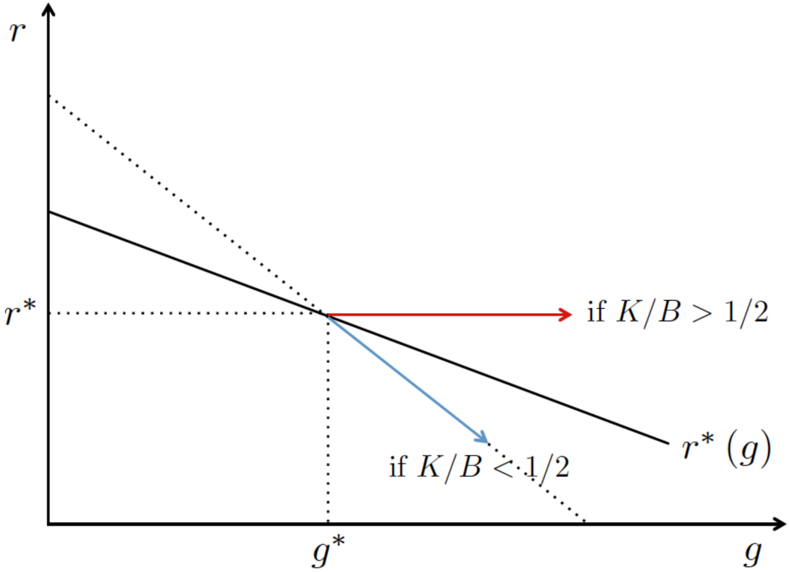

Figura 6: Self-Enforcing Quota Agreement

1-5. Self-Enforcing Price Agreement

- **CC-g is equivalent to** that under **quotas** because, for any given r, there is a one-to-one mapping between τ and g; ▸ Private Choices

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- Hence, CC-r is:

$$\frac{u(\mathbf{g}, r)}{1-\delta} > c(n-1)\frac{\varsigma}{k} + \frac{u^b}{1-\delta} \quad \Rightarrow \quad u(\mathbf{g}, r) > u^b \quad for \quad \varsigma \to 0.$$

1-5. Self-Enforcing Price Agreement

Proposition

Compliance constraint at the ***investment*** *stage* ***never binds first****.*

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Compliance constraint at the ***investment*** *stage* ***never binds first***.

- If a country defects at CC-r, the subsequent emissions in a non-deviating country is larger than under a quantity agreement
- A price agreement allows for *more flexibility* of investment adjustments and thus stronger punishments
  - → It is less tempted to defect at the CC-r under a price agreement than under a quantity agreement

1-5. Self-Enforcing Price Agreement

Let $\bar{\delta}_p^g$ be the threshold of δ above which CC-g is satisfied if $\tau = \tau^*$ and $\varsigma = \varsigma^*$

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Proposition

i. *If $\delta \geq \overline{\delta}_p^g$, the emission tax is Pigouvian and investments are unregulated:*

$$\tau = \tau^* \quad \textit{and} \quad \varsigma = \varsigma^*.$$

ii. *If $\delta < \overline{\delta}_p^g$, the emission tax is smaller than the Pigouvian level, and investments are subsidized:*

$$\tau = \tau^* - \Lambda_p(\delta) \quad \textit{and} \quad \varsigma = \Lambda_p(\delta), \textit{ where } \Lambda_p(\delta) = b\Lambda_q(\delta).$$

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- If δ is sufficiently small, countries are tempted to defect by lowering τ
- To mitigate this temptation, the required emission tax must be reduced $\tau < \tau^*$
- To maintain incentives to invest, it becomes necessary to increase ς
- Since higher investment sustained by subsidies weakens incentives to increase emissions
  - $\rightarrow$ the reduction of τ needed to provide incentives is smaller than without investment subsidies

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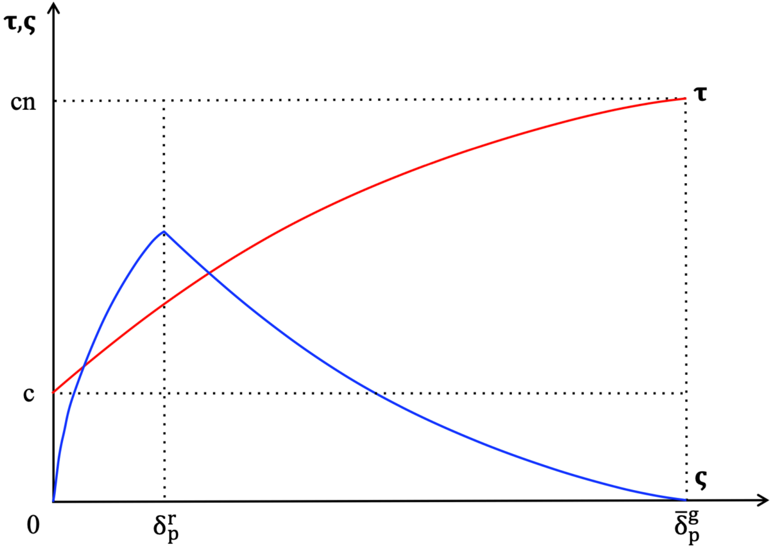

Figura 7: Self-Enforcing Price Agreement

1-5. Self-Enforcing Quantity vs Price Agreements

Proposition

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  - $\longrightarrow$ *Price and quantity agreements yield identical payoffs.*

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- When $k/b > 1/2$, **CC-g binds first** under a quantity agreement, and both agreements impose the same constraint.
  - → *Price and quantity agreements yield identical payoffs.*
- When $k/b < 1/2$, **CC-r binds first** under a quantity agreement, but the price agreement enables stronger punishments due to greater *flexibility*.
  - → *The price agreement delivers a strictly higher payoff.*

1-5. Discussion

- Novel insight about the divergence between price instruments and quantity mandates in terms of welfare;

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- Novel insight about the divergence between price instruments and quantity mandates in terms of welfare;
- From Weitzman (1974), analyses of performance of the two types of regulation with abatement cost shocks when authority has committed to an instrument;
- This framework highlights influence of climate policies on the self-enforcement of an agreement

1-5. Extensions and Further Applications

- **Role of Timing**: If simultaneous choices, technology investments do not influence compliance incentives with emission abatement

  → no strategic scope to be internalized and prices equivalent to quotas

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- **Role of Timing**: If simultaneous choices, technology investments do not influence compliance incentives with emission abatement

  → no strategic scope to be internalized and prices equivalent to quotas

- **Role of Transparency**: Under imperfect transparency of domestic climate policies, a quantity agreement can dominates a price agreement

  → Under a price agreement, firms can mistakenly reduce investment in renewables even if all countries cooperate, implying an unduly strong punishment.

1-5. Extensions and Further Applications

- **Multiple technologies and technological transitions**
  - Golosov et al. (2013): optimal taxation and investment subsidies from a *social planner's perspective*
  - Besley and Persson (2023): the *political economy* of the green transition

⇒ The proposed framework can be extended to study the green transition from the perspective of an *international social planner*, or to explore the interaction between *domestic and supranational* institutions in coordinating climate policy.

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  - ⇒ The proposed framework can be extended to study the green transition from the perspective of an *international social planner*, or to explore the interaction between *domestic and supranational* institutions in coordinating climate policy.
- **Policy instruments and the role of expectations**
  - ∗ Monasterolo et al. (2024): green bonds and green quantitative easing (QE) to foster clean investments
  - ⇒ The framework can also be used to analyze the complementary role of green bonds alongside carbon taxes, and to assess their effectiveness depending on the elasticity of substitution between brown and green technologies.

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- If $\delta < \hat{\delta}$: **Distort investments**.
- Even with no technological spillovers, countries should **cooperate** also on technology, to motivate compliance.

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- Strategic technologies **reduce punishment phase**.
- Strategic motives shape role of **prices versus quantity instruments** to implement low emissions.

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