Flattening the carbon extraction path:
Unilateral versus cooperative cost-effective action

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1 Motivation

Policy issue

- Greenhouse gas emissions generate global negative climate externalities
- Fighting climate change requires curbing carbon (dioxide) emissions

Insights from externality literature

- Internalize climate externalities by flattening the carbon extraction path. Policy instrument here: emission taxes ($\approx$ energy taxes)

- Literature dealing with full cooperation in world growth models:

  Flattening requires high emission tax rates early on and low rates later

  "High does nothing and rising is worse" (Sinclair 1992)

1 Motivation

- To date: Several countries take (some) action, other major countries don't.

  Prospects for a fully cooperative climate policy are bleak

- Problems with unilateral (= less than global) emission reduction:
  - Free riding, carbon leakage, green paradox …
  - Little reduction in total world emissions, if any …
  - High cost for abating countries, little benefit

- Challenge for *rational* unilateral action:

  - Flatten the *world* emission path, although you have regulatory control only over *domestic* emissions

  - Domestic emission reduction **not** ultimate *goal* of unilateral climate policy. Rather: It is a *means* to put some ceiling on total medium-term emissions

1 Motivation

Ceiling policy = Intertemporal regulation of carbon emissions such that cumulated world emissions at some future time (say 2050) do not exceed a politically fixed limit (= ceiling)

- Ceiling policy may be carried out
  - either by a global climate coalition (full cooperation)
  - or ‘unilaterally’ by a sub-global climate coalition

- Unilateral action:

  Suppose it is feasible to implement some ceiling, which we will do. Then there is, in general, a large set of feasible ceiling policies that differ in tax rates and overall costs for the sub-global coalition

1 Motivation

- Aim of the present paper:

  - Characterize unilateral ceiling policies, that is
  - the set of *feasible* policies as well as the *cost-effective* ceiling policy,
  - and compare them with the global cost-effective ceiling policy

1 Preview of main conclusions

- Unilateral cost-effective ceiling policy …
  - requires regulating emissions of the sub-global coalition in *all* periods
  - may require emission *subsidies* (!) rather than taxes
  - depends on the share of the world stock of fossil energy owned by the sub-global climate coalition

- *In contrast*: With full cooperation, the cost-effective allocation of world resources is unique. It can be implemented (inter alia) through a uniform worldwide emission tax in the first period

1 Outline of the paper

1 Motivation (done)

2 The competitive two-country economy with ceiling regulation

3 Cooperative cost-effective ceiling policy

4 Unilateral ceiling policy

   4.1 Characterization of unilateral *feasible* ceiling policies

   4.2 The unilateral *cost-effective* ceiling policy

5 Concluding remarks

2 The competitive two-country economy with ceiling regulation

- Two-period two-country 'world economy'
- Both countries produce the same consumption good
  Fossil fuel is the only variable input
- Each country owns a stock of fossil energy resources
- All agents optimize over both periods as price takers
  Discount rate is zero
- Competitive world markets exist for fossil fuel and the consumption good
- Policy instruments are sign-unconstrained emission taxes for each period

2 The structure of the formal model

$x_{it}^{s} = X^{i}\left(e_{it}\right),\quad i = A, B;\quad t = 1, 2$	production functions	(1)
$u_i = U^{i}\left(x_{i1}, x_{i2}\right)\quad i = A, B$	utility functions	(2)
$x_{At}^{s} + x_{Bt}^{s} = x_{At} + x_{Bt}\quad t = 1, 2$	consumption-good market equilibria	(3)
$\overline{e} = e_{A1} + e_{B1} + e_{A2} + e_{B2}$	intertemporal fossil-fuel market equilibrium	(4)
$\overline{e}_1 = e_{A1} + e_{B1}$	emission ceiling (ultimate policy goal)	(5)

2 Price-taking optimizing agents

- Representative consumer's optimum: $\dfrac{U^i_{x_{i2}}}{U^i_{x_{i1}}} = p_x, \quad i = A, B$

- Representative final-good firms maximize profits

$$\sum_t \left[p_{xt} X^i(e_{it}) - (p_{et} + \pi_{it}) e_{it} \right], \quad i = A, B$$

F.o.c.: $p_{xt} X^i_{e_{it}} = p_{et} + \pi_{it}, \quad i = A, B, \quad t = 1, 2$

- Fossil-energy extraction firm maximizes profits $\sum_t p_{et} e_t$ subject to $e_1 + e_2 = \overline{e}$ (no extraction costs)

F.o.c.: $p_{e1} = p_{e2} \equiv p_e$ (*Hotelling rule*)

3 Cooperative cost-effective ceiling policy

- The social planner solves the Lagrangean

$$L = \sum_{i=A,B} \omega_i U^i\left(x_{i1}, x_{i2}\right) + \sum_{t=1,2} \lambda_{xt}\left[X^A\left(e_{At}\right) + X^B\left(e_{Bt}\right) - x_{At} - x_{Bt}\right]$$
$$+\lambda_e\left(\overline{e} - e_{A1} - e_{A2} - e_{B1} - e_{B2}\right) + \overline{\lambda}\left(\overline{e}_1 - e_{A1} - e_{B1}\right)$$

- F.o.c. (with $\lambda_{x1} \equiv 1$):

$$\frac{U^i_{x_{i2}}}{U^i_{x_{i1}}} = \lambda_{x2}, \qquad X^i_{e_{i1}} = \lambda_e + \overline{\lambda}, \qquad \lambda_{x2} X^i_{e_{i2}} = \lambda_e \qquad i = A, B$$

3 Cooperative cost-effective ceiling policy

Result 1

The cooperative ceiling policy is cost-effective, if and only if $\pi \in \Pi$*,*
where $\pi := (\pi_{A1}, \pi_{B1}, \pi_{A2}, \pi_{B2})$ *and*

$$\Pi := \left\{ \pi \in \mathbb{R}^4 \,\middle|\, \pi_{A1} = \pi_{B1}, \pi_{A2} = \pi_{B2}, \pi_{A1} = \bar{\lambda} + \pi_{A2}, \pi_{A2} \in \left]-\infty, \lambda_e\right] \right\}.$$

The corresponding equilibrium prices are $p_x = \lambda_{x2}$ *and* $p_e = \lambda_e - \pi_{A2}$.

- Properties of $\pi \in \Pi$:
    - In each period taxes are uniform across countries
    - Tax rate in period 1 is higher than in period 2 by the positive constant $\bar{\lambda}$

3 Cooperative cost-effective ceiling policy

Interpretation of Result 1

- There are multiple cost-effective ceiling policies and multiple associated equilibria, but all equilibrium allocations are the same

- There are cost-effective ceiling policies satisfying for *i* = A, B
  - either (i) $\pi_{i1} > 0$ and $\pi_{i2} = 0$
  - or (ii) $\pi_{i1} = 0$ and $\pi_{i2} < 0$
  - or (iii) $\pi_{i1} > \pi_{i2} > 0$ or $\pi_{i1} > 0 > \pi_{i2}$ or $0 > \pi_{i1} > \pi_{i2}$

- Shifts in $\pi's$ are exactly compensated by opposite shifts in p_e

3 Cooperative cost-effective ceiling policy

Result 2

The equilibrium allocation associated to the cost-effective ceiling policy $\pi \in \Pi$ *is characterized by*

$$\frac{X^A_{e_{A1}}}{X^B_{e_{B1}}} = \frac{X^A_{e_{A2}}}{X^B_{e_{B2}}} = 1, \qquad \frac{X^A_{e_{A1}}}{X^A_{e_{A2}}} = \frac{X^B_{e_{B1}}}{X^B_{e_{B2}}} = \left(1 + \frac{\bar{\lambda}}{\lambda_e}\right) p_x \quad \textit{production efficiency}$$

$$\frac{U^A_{x_{A2}}}{U^A_{x_{A1}}} = \frac{U^B_{x_{B2}}}{U^B_{x_{B1}}} = p_x \qquad \textit{consumption efficiency}$$

$$\frac{U^i_{x_{i2}}}{U^i_{x_{i1}}} - \frac{X^i_{e_{i1}}}{X^i_{e_{i2}}} = \frac{\bar{\lambda}\, p_x}{\lambda_e} \qquad i = A, B \qquad \textit{intertemporal distortion}$$

4 Unilateral carbon ceiling regulation

Assumption in the remainder of the paper:

- Government of country B abstains from emission taxation

- Government of country A meets the ceiling $\overline{e}_1$ unilaterally

- To reach informative results we need to reduce complexity:

  Production functions: $x_{it}^{s} = X^{i}\left(e_{it}\right) = ae_{it} - \frac{b}{2}e_{it}^{2}$, $i = A, B; t = 1, 2$

  Utility functions: $u_i = U^{i}\left(x_{i1}, x_{i2}\right) = x_{i1}^{\gamma} \cdot x_{i2}^{1-\gamma}$, $i = A, B$

4 Competitive equilibrium with unilateral ceiling regulation

$$X^A(e_{At}) + X^B(\overline{e}_t - e_{At}) = x_{At} + x_{Bt}, \qquad t = 1, 2,\ \overline{e}_2 := \overline{e} - \overline{e}_1$$

$$x_{i1} = \gamma y_i, \qquad x_{i2} = \frac{(1-\gamma) y_i}{p_x}, \qquad i = A, B$$

$$y_i := x_{i1}^s + p_x x_{i2}^s + p_e \underbrace{(\alpha_i \overline{e} - e_{i1} - e_{i2})}_{=: \vartriangle e_i}, \qquad i = A, B,\ t = 1, 2,\ \alpha_A = (1-\alpha_B) \in [0, 1]$$

$$e_{A1} = \frac{a}{b} - \frac{p_e}{b} - \boldsymbol{\pi_1}, \qquad e_{A2} = \frac{a}{b} - \frac{p_e}{bp_x} - \boldsymbol{\pi_2} \qquad \text{with } \boldsymbol{\pi_1 := \frac{\pi_{A1}}{b}} \text{ and } \boldsymbol{\pi_2 := \frac{\pi_{A2}}{bp_x}}$$

$$e_{B1} = \overline{e}_1 - e_{A1} = \frac{a}{b} - \frac{p_e}{b}, \qquad e_{B2} = \overline{e}_2 - e_{A2} = \frac{a}{b} - \frac{p_e}{bp_x}$$

12 equations and 12 variables: $e_{A1}, e_{A2}, p_e, p_x, x_{A1}, x_{A2}, x_{B1}, x_{B2}, y_A, y_B, \pi_1, \pi_2$.

4.1 Unilateral ceiling policies for alternative inputs $\boldsymbol{e_{A1}}$

- Drop the equilibrium condition $X^A(e_{A2}) + X^B(\bar{e}_2 - e_{A2}) = x_{A2} + x_{B2}$ and consider ceiling-policy equilibria for alternative fuel inputs e_{A1}

- *Notation:* - Given the ceiling $\bar{e}_1$, we denote by E the set of all $e_{A1} \geq 0$ for which a ceiling policy exists

  - $(\pi_1, \pi_2) = [\pi_1(e_{A1}), \pi_2(e_{A1})]$ is a unilateral ceiling policy of country A for $e_{A1} \in E$

- The set E is a subset of the interval $[0, \bar{e}_1]$

4.1 Two specific feasible unilateral (ceiling) policies

- Can ceiling policies be of the type $(\pi_1 = 0, \pi_2)$ or $(\pi_1, \pi_2 = 0)$?

- Answer in Eichner and Pethig (2010, IER forthcoming):

  $(\pi_1 > 0, \pi_2 = 0)$ and $(\pi_1 = 0, \pi_2 < 0)$ qualify as

  ceiling policies under mild restrictions

- *Assumption made in the present paper*: $e_{A1}(\pi_t = 0) \in E$ for t = 1, 2

  where $e_{A1}(\pi_t = 0)$ = value of e_{A1} that leads to the ceiling policy with $\pi_t = 0$

4.1 Unilateral ceiling policies for alternative inputs $\boldsymbol{e_{A1}}$

- Definition of subsets of the interval $\left[0, \bar{e}_1\right]$:

$$\underbrace{e_{A1}=0 \quad \overbrace{\qquad\qquad\qquad}^{E_\ell} \quad e_{A1}(\pi_2=0) \quad \overbrace{\qquad\qquad\qquad}^{E_m} \quad e_{A1}(\pi_1=0)=\tfrac{\bar{e}_1}{2} \quad \overbrace{\qquad\qquad\qquad\qquad\qquad}^{E_h} \quad e_{A1}=\bar{e}_1}_{\text{Interval } \left[0, \bar{e}_1\right]}$$

- Question: Is $e_{A1}(\pi_2=0) < e_{A1}(\pi_1=0)$ as drawn above? Is $E_m \neq \varnothing$?

4 Competitive equilibrium with unilateral ceiling regulation

$$X^A(e_{At}) + X^B(\overline{e}_t - e_{At}) = x_{At} + x_{Bt}, \qquad t = 1, 2,\ \overline{e}_2 := \overline{e} - \overline{e}_1$$

$$x_{i1} = \gamma y_i, \qquad x_{i2} = \frac{(1-\gamma) y_i}{p_x}, \qquad i = A, B$$

$$y_i := x_{i1}^s + p_x x_{i2}^s + p_e \underbrace{\left(\alpha_i \overline{e} - e_{i1} - e_{i2}\right)}_{=:\vartriangle e_i}, \qquad i = A, B,\ t = 1, 2,\ \alpha_A = (1-\alpha_B) \in [0,1]$$

$$e_{A1} = \frac{a}{b} - \frac{p_e}{b} - \boldsymbol{\pi_1}, \qquad e_{A2} = \frac{a}{b} - \frac{p_e}{bp_x} - \boldsymbol{\pi_2} \qquad \text{with } \boldsymbol{\pi_1 := \frac{\pi_{A1}}{b}} \text{ and } \boldsymbol{\pi_2 := \frac{\pi_{A2}}{bp_x}}$$

$$e_{B1} = \overline{e}_1 - e_{A1} = \frac{a}{b} - \frac{p_e}{b}, \qquad e_{B2} = \overline{e}_2 - e_{A2} = \frac{a}{b} - \frac{p_e}{bp_x}$$

12 equations and 12 variables: $e_{A1}, e_{A2}, p_e, p_x, x_{A1}, x_{A2}, x_{B1}, x_{B2}, y_A, y_B, \pi_1, \pi_2$.

4.1 Characterization of unilateral feasible ceiling policies

Result 3: $E_m \begin{Bmatrix} \neq \\ = \end{Bmatrix} \varnothing \iff e_{A1}(\pi_2 = 0) \begin{Bmatrix} < \\ = \end{Bmatrix} e_{A1}(\pi_1 = 0) = \dfrac{\bar{e}_1}{2} \iff \bar{e}_1 \begin{Bmatrix} < \\ = \end{Bmatrix} e_1^0$

Implication: The set $\left\{ \{0\}, E_\ell, \{e_{A1}(\pi_2 = 0)\}, E_m, \left\{\frac{\bar{e}_1}{2}\right\}, E_h, \{\bar{e}_1\} \right\}$ forms a partition of the interval $[0, \bar{e}_1]$

4.1 Characterization of unilateral feasible ceiling policies

Result 4: *Over the entire domain E of feasible ceiling policies, π_1 and π_2 are strictly decreasing in e_{A1}.*

The ceiling policy (π_1, π_2) satisfies

(a) $\pi_1 > 0, \pi_2 > 0,$ *if* $e_{A1} \in E_\ell$

(b) $\pi_1 > 0, \pi_2 = 0,$ *if* $e_{A1} = e_{A1}(\pi_2 = 0)$

(c) $\pi_1 > 0 > \pi_2,$ *if* $e_{A1} \in E_m$

(d) $\pi_1 = 0, \pi_2 < 0,$ *if* $e_{A1} = e_{A1}(\pi_1 = 0) = \overline{e}_1 / 2$

(e) $\pi_1 < 0, \pi_2 < 0,$ *if* $e_{A1} \in E_h$

4.1 Characterization of unilateral feasible ceiling policies

Illustration of Result 4:

$$\underset{\substack{\uparrow\\ e_{A1}=0\\ \uparrow}}{\bullet}\;\overbrace{\rule{3cm}{0.4pt}}^{\substack{\pi_1>0,\,\pi_2>0\\ E_\ell}}\;\underset{\substack{\uparrow\\ e_{A1}(\pi_2=0)\\ \uparrow\\ \pi_1>0,\ \pi_2=0}}{\bullet}\;\overbrace{\rule{3.5cm}{0.4pt}}^{\substack{\pi_1>0>\pi_2\\ E_m}}\;\underset{\substack{\uparrow\\ e_{A1}=\overline{e}_1/2\\ \uparrow\\ \pi_1=0,\ \pi_2<0}}{\bullet}\;\overbrace{\rule{6.5cm}{0.4pt}}^{\substack{\pi_1<0,\,\pi_2<0\\ E_h}}\;\underset{\substack{\uparrow\\ e_{A1}=\overline{e}\\ \uparrow}}{\bullet}$$

4.1 Characterization of unilateral feasible ceiling policies

Result 4: *Over the entire domain E of feasible ceiling policies, π_1 and π_2 are strictly decreasing in e_{A1}.*

The ceiling policy (π_1, π_2) satisfies

(a) $\pi_1 > 0, \pi_2 > 0,$ *if* $e_{A1} \in E_\ell$

$\boxed{\textbf{(b)}\ \boldsymbol{\pi_1 > 0, \pi_2 = 0,}\quad \textbf{if}\ \boldsymbol{e_{A1} = e_{A1}(\pi_2 = 0)}}$

(c) $\pi_1 > 0 > \pi_2,$ *if* $e_{A1} \in E_m$

(d) $\pi_1 = 0, \pi_2 < 0,$ *if* $e_{A1} = e_{A1}(\pi_1 = 0) = \overline{e}_1 / 2$

(e) $\pi_1 < 0, \pi_2 < 0,$ *if* $e_{A1} \in E_h$

4.1 Proof of Result 4(b)

We will show: "If $(\pi_1, \pi_2 = 0)$ is a ceiling policy for $\bar{e}_1 < e_1^0$, then $\pi_1 > 0$"

- **Claim I:** $\bar{e}_1 \begin{Bmatrix} < \\ = \end{Bmatrix} e_1^0 \;\Rightarrow\; \dfrac{x_1^{s*}}{x_2^{s*}} \begin{Bmatrix} < \\ = \end{Bmatrix} \dfrac{x_1^{s0}}{x_2^{s0}} = \bar{\gamma}\, p_x^0$

$$\textit{with } x_t^{s*} := a\bar{e}_t - \frac{b\bar{e}_t^2}{4} \;\textit{ and }\; x_t^s := x_{At}^s + x_{Bt}^s$$

$\dfrac{x_1^s}{x_2^s} = \bar{\gamma}\, p_x$ holds in laissez-faire as well as in case of ceiling regulation

$$x_t^s = a\bar{e}_t - \frac{b\bar{e}_t^2}{2} + be_{At}e_{Bt} = \underbrace{a\bar{e}_t - \frac{b\bar{e}_t^2}{4}}_{=:\,x_t^{s*}} + \frac{b\bar{e}_t^2}{4} - \frac{b\bar{e}_t^2}{2} + be_{At}e_{Bt} = x_t^{s*} - b\underbrace{\left(\frac{\bar{e}_t^2}{4} - e_{At}e_{Bt}\right)}_{\geq 0}$$

4.1 Proof of Result 4(b)

Claim II: $\left(\pi_1, \pi_2 = 0\right)$ *ceiling policy for* $\bar{e}_1 \begin{Bmatrix} < \\ = \end{Bmatrix} e_1^0 \quad \Rightarrow \quad \bar{\gamma}\, p_x^0 \begin{Bmatrix} > \\ = \end{Bmatrix} \dfrac{x_1^s}{x_2^s} = \bar{\gamma}\, p_x$

$$\Rightarrow \quad p_x^0 \begin{Bmatrix} > \\ = \end{Bmatrix} p_x$$

$$\frac{x_1^s}{x_2^s} = \frac{x_1^{s*} - b\overbrace{\left(\frac{\bar{e}_1}{4} - e_{A1}e_{B1}\right)}^{\geq 0}}{x_2^{s*} - b\underbrace{\left(\frac{\bar{e}_2}{4} - e_{A2}e_{B2}\right)}_{=0}} = \frac{x_1^s}{x_2^{s*}} \begin{Bmatrix} < \\ = \end{Bmatrix} \underbrace{\frac{x_1^{s*}}{x_2^{s*}} \begin{Bmatrix} < \\ = \end{Bmatrix} \frac{x_1^{s0}}{x_2^{s0}}}_{\text{Claim I}}, \text{ iff } \bar{e}_1 \begin{Bmatrix} < \\ = \end{Bmatrix} e_1^0$$

4.1 Proof of Result 4(b)

- **Claim III:** $(\pi_1, \pi_2 = 0)$ *ceiling policy for* $\bar{e}_1 < e_1^0 \;\Rightarrow\; \pi_1 > 0$

  Suppose, not. Then $(\pi_1 \le 0, \pi_2 = 0)$ is a ceiling policy.

  $$p_e = a - be_{B1} = \frac{p_x}{2}(2a - b\bar{e}_2)\ \&\ e_{B1} \le \frac{\bar{e}_1}{2} \;\Rightarrow\; p_x \ge \frac{2a - b\bar{e}_1}{2a - b\bar{e}_2}$$

  In laissez-faire: $p_x^0 = \dfrac{2a - be_1^0}{2a - be_2^0}$

  $\bar{e}_1 < e_1^0$ implies $p_x^0 = \dfrac{2a - be_1^0}{2a - be_2^0} < \dfrac{2a - b\bar{e}_1}{2a - b\bar{e}_2} \le p_x$ and hence $p_x^0 \le p_x$

  That contradicts Claim II

4.1 Characterization of unilateral feasible ceiling policies

- Implication of Result 4: $E_m \subset E$

- Rationale:

  Recall: Policies for $e_{A1} \in E_m$ satisfy $(\pi_1 > 0, \pi_2 < 0)$

  Decompose policy $(\pi_1 > 0, \pi_2 < 0)$ into two sub-policies

  of the type $(\pi_1 > 0, \pi_2 = 0)$ and $(\pi_1 = 0, \pi_2 < 0)$

$\Rightarrow$ $(\pi_1 > 0, \pi_2 < 0)$ is a kind of 'convex combination'
of $(\pi_1 > 0, \pi_2 = 0)$ and $(\pi_1 = 0, \pi_2 < 0)$

4.1 Characterization of unilateral feasible ceiling policies

Result 5: *(i)* *Over the entire domain E,* e_{A2} *and* p_e *are strictly increasing.*

(ii) *Over* $\left[e_{A1}\left(\pi_2 = 0\right), \overline{e}_1 / 2\right] \subset E$, p_x *is strictly increasing in* e_{A1}.

(iii) *The prices* p_e *and* p_x *are lower than their laissez-faire counter parts* p_e^0 *and* p_x^0 *over* $\left[\,0, e_{A1}\left(\pi_2 = 0\right)\right] \cap E$

(Side remark: $\dfrac{dp_x}{de_{A1}} \gtreqless 0 \quad \Leftrightarrow \quad \pi_1 \gtreqless \overline{\gamma}\pi_2$ where $\overline{\gamma} := \frac{\gamma}{1-\gamma}$)

4.1 Illustration of unilateral feasible ceiling policies

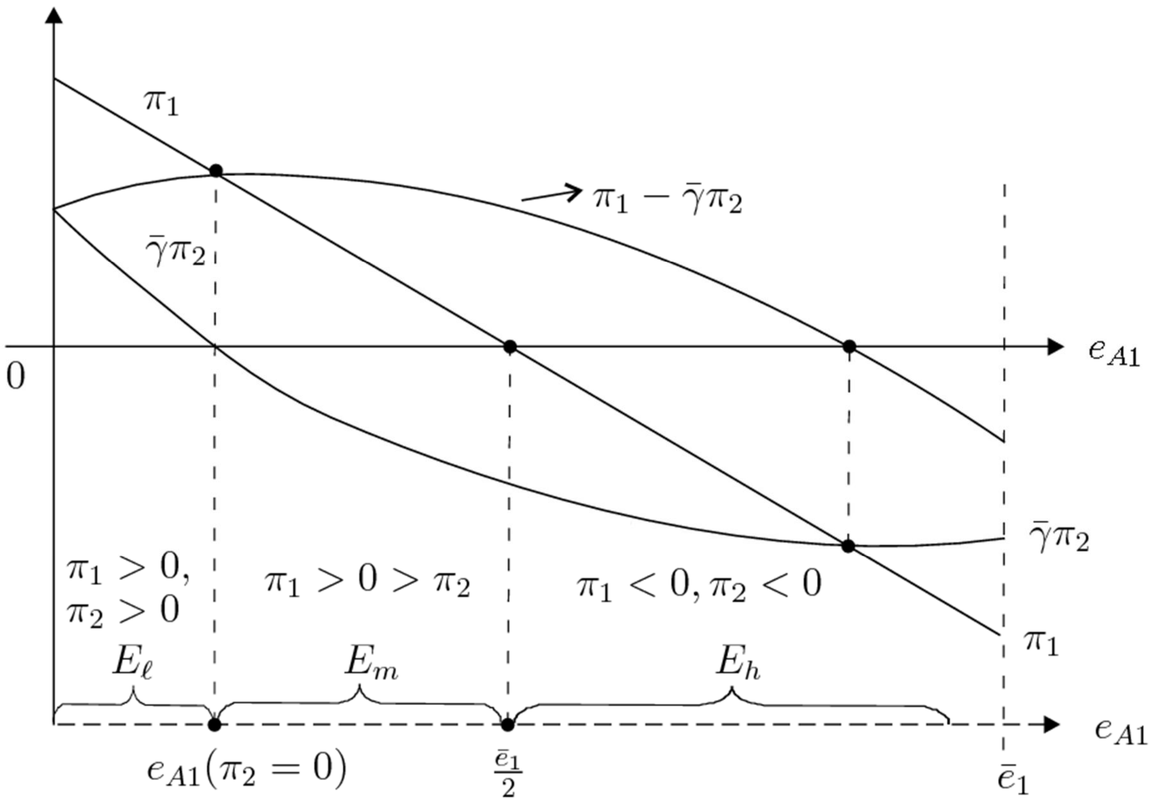


Figure 1: Classification of feasible unilateral ceiling policies

4.1 Some additional information from numerical examples

- With the help of numerical calculations (not detailed here) we found parameter constellations for which

  - there exist $e_{A1} \in E_\ell$ and $e_{A1} \in E_h$

  - $dp_x / de_{A1} > 0$ for all $e_{A1} \in E$ ($\Rightarrow$ p_x strictly increasing over E)

- Our conjecture is that the latter property holds more generally.
  In our view that would be of interest because
  $dp_x / de_{A1} > 0$ is equivalent to $\pi_1 > \bar{\gamma}\pi_2$ (where $\bar{\gamma} := \frac{\gamma}{1-\gamma}$)

4.2 Cost-effective unilateral ceiling policy

- The government of country A knows that country B refrains from climate policy and proceeds implementing a ceiling $\overline{e}_1 < e_1^0$ in unilateral action

- It knows
  - that it can meet the ceiling (if not too stringent) by a variety of unilateral ceiling policies (π_1, π_2) and
  - that those feasible policies differ in their impact on domestic welfare

- The government of country A aims to choose that particular ceiling policy which maximizes domestic welfare (and is thus cost-effective for country A)

4.2 Government A's optimization program

- Consider $e_{A1} \in E$ and denote by $x_{A1}(e_{A1})$, $x_{A2}(e_{A1})$, $\pi_1(e_{A1})$ etc. the values of x_{A1}, x_{A2}, π_1 etc. in the competitive equilibrium with ceiling $\overline{e}_1$
in which country A's first-period emissions are $e_{A1} \in E$

- The policy $\left[\pi_1\left(e_{A1}^*\right), \pi_2\left(e_{A2}^*\right)\right]$ is cost-effective, iff $e_{A1}^* = \arg\max\limits_{e_{A1} \in E} u_A\left(e_{A1}\right)$

where $u_A\left(e_{A1}\right) = \left[x_{A1}\left(e_{A1}\right)\right]^{\gamma} \cdot \left[x_{A2}\left(e_{A1}\right)\right]^{1-\gamma} \; = \; \gamma^{\gamma}\left(1-\gamma\right)^{1-\gamma} p_x\left(e_{A1}\right)^{\gamma-1} y_A\left(e_{A1}\right)$

[Assumption: $u_A\left(e_{A1}\right)$ is single-peaked on E]

4.2 Government A's optimization program

F.o.c.: $$\frac{du_A}{de_{A1}} = \frac{u_A}{y_A} \cdot \frac{dy_A}{de_{A1}} - (1-\gamma)\frac{u_A}{p_x} \cdot \frac{dp_x}{de_{A1}} = 0$$

where $$\frac{dy_A}{de_{A1}} = \frac{b(\pi_1 + \gamma \vartriangle e_A)}{\gamma} - x_{B2}^s \frac{dp_x}{de_{A1}}$$ and $$\frac{dp_x}{de_{A1}} = \frac{bp_x(\pi_1 - \overline{\gamma}\pi_2)}{x_1^s - \overline{\gamma}\, p_e \pi_2}$$

After rearrangement of terms:

$$\frac{du_A}{de_{A1}} = \frac{u_A}{\gamma y_A}\left[(\pi_1 + \gamma \vartriangle e_A) - (\pi_1 - \overline{\gamma}\pi_2) \cdot G\right] = 0, \ \ where \ \ G := \frac{\gamma\, p_x\left(x_{A2} + x_{B2}^s\right)}{x_1^s - \overline{\gamma}\, p_e \pi_2} > 0$$

$$and \quad \vartriangle e_A := \alpha_A \overline{e} - e_{A1} - e_{A2}$$

4.2 Characterization of unilateral cost-effective ceiling policies

Result 6: *Suppose* $\bar{e}_1 = e_1^0$.

Country A's cost-effective ceiling policy belongs to the set

$$\left\{ \begin{matrix} E_\ell \\ \{\bar{e}_1 / 2\} \\ E_h \end{matrix} \right\} \text{ with tax rates } \left\{ \begin{matrix} (\pi_1 > 0, \pi_2 > 0) \\ (\pi_1 = \pi_2 = 0) \\ (\pi_1 < 0, \pi_2 < 0) \end{matrix} \right\} \text{ iff } \alpha_A \left\{ \begin{matrix} < \\ = \\ > \end{matrix} \right\} 1/2.$$

[Recall from Result 3 that $E_m = \varnothing$ iff $\bar{e}_1 = e_1^0$]

4.2 Characterization of unilateral cost-effective ceiling policies

Rationale of Result 6:

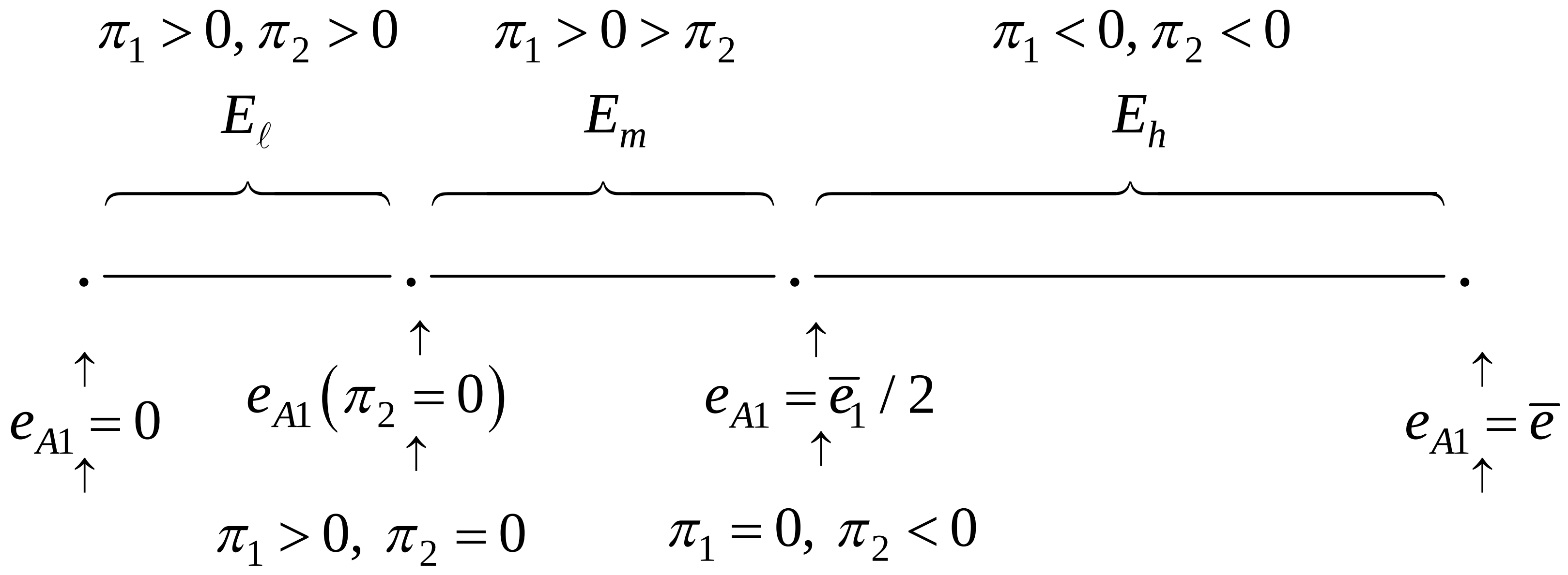
- Suppose, country A imports fuel $((\vartriangle e_A < 0))$ and levies tax $(\pi_1 > 0, \pi_2 > 0)$ on domestic fuel consumption (= emissions) e_{A1}, e_{A2}
- Tax covers imported fuel $\Rightarrow$ Tax is equivalent to an import tariff on fuel
- Tax diminishes world demand for fuel $\Rightarrow$ world fuel price declines ($p_e \downarrow$)
- Terms-of-trade effect ($p_e \downarrow$) reduces country A's fuel import bill

4.2 Characterization of unilateral cost-effective ceiling policies

Result 7: *Suppose* $\overline{e}_1 < e_1^0$.

(a) If $\alpha_A \leq \frac{1}{2}$, *country A's cost-effective ceiling policy belongs to the set* $E_\ell \cup \left\{ e_{A1}\left(\pi_2 = 0\right) \right\} \cup E_m$ *and exhibits* $\pi_1 > 0$. *The sign of* π_2 *is unclear.*

(b) If $\alpha_A \geq \frac{1}{2}$ *and* $\gamma \geq \frac{1}{2}$, *country A's cost-effective ceiling policy belongs to the set* $E_m \cup \left\{ \frac{\overline{e}_1}{2} \right\} \cup E_h$ *and exhibits* $\pi_2 < 0$. *The sign of* π_1 *is unclear.*


$\pi_1 > 0, \pi_2 > 0$
E_ℓ
$\pi_1 > 0 > \pi_2$
E_m
$\pi_1 < 0, \pi_2 < 0$
E_h
$e_{A1} = 0$
$e_{A1}(\pi_2 = 0)$
$\pi_1 > 0,\ \pi_2 = 0$
$e_{A1} = \overline{e}_1 / 2$
$\pi_1 = 0,\ \pi_2 < 0$
$e_{A1} = \overline{e}$

4.2 Characterization of unilateral cost-effective ceiling policies

$$\frac{du_A}{de_{A1}} = \frac{u_A}{\gamma y_A}\left[\underbrace{\left(\pi_1 + \gamma \vartriangle e_A\right)}_{=:F\left(e_{A1};\alpha_A\right)} - \underbrace{\left(\pi_1 - \bar{\gamma}\pi_2\right)\cdot G}_{=:H\left(e_{A1}\right)}\right] = 0$$

where $F\left(e_{A1};\alpha_A\right) := \pi_1\left(e_{A1}\right) + \gamma \overbrace{\left[\alpha_A \bar{e} - e_{A1} - e_{A2}\left(e_{A1}\right)\right]}^{=:\vartriangle e_A}$

and $H\left(e_{A1}\right) := \left[\pi_1\left(e_{A1}\right) - \bar{\gamma}\pi_2\left(e_{A1}\right)\right]\cdot G\left(e_{A1}\right).$

$$\frac{du_A}{de_{A1}} = 0 \quad \Leftrightarrow \quad F\left(e_{A1};\alpha_A\right) = H\left(e_{A1}\right)$$

4.2 Illustration of unilateral cost-effective ceiling policies

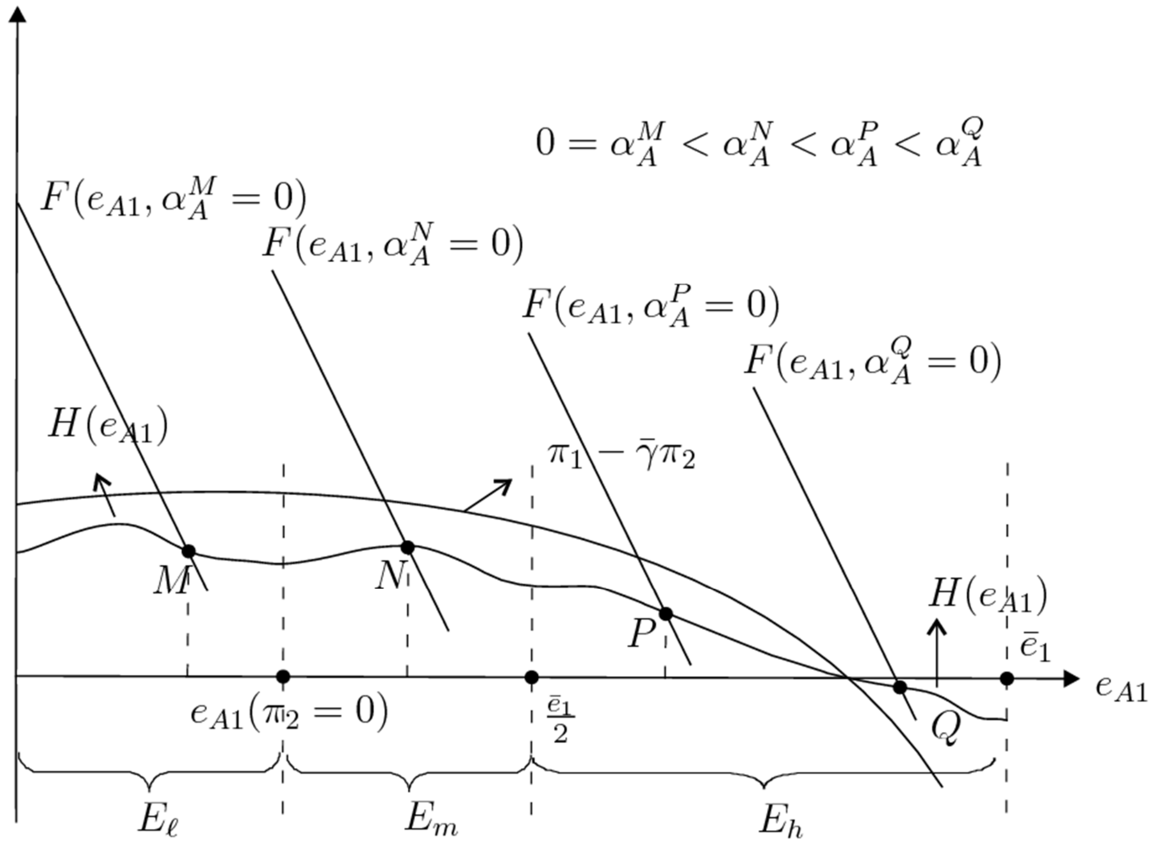


Figure 2: Cost-effective unilateral ceiling policies depending on country A's fossil-energy endowment

4.2 Illustration of unilateral cost-effective ceiling policies

Insight from Figure 2:

The larger is country A's share α_A *of the world stock of fossil fuel* ($\overline{e}$),
the higher is the level of $e_{A1} \in E$
which determines the cost-effective ceiling-policy equilibrium for α_A

4.2 Comparison of unilateral and fully cooperative cost-effective ceiling policies

- *The fully cooperative cost-effective ceiling policy* can be attained via multiple ceiling policies

  But different combinations of taxes and subsidies have distributional con sequences only while leaving unchanged the (unique) cost-effective world allocation of resources

- The *unilateral cost-effective ceiling policy* needs to be chosen from a large set of feasible ceiling policies which differ with respect to the costs to be borne by the sub-global climate coalition

  Through strategic taxation, the coalition can shift part of the burden on the rest of the world that abstains from climate policy

6 Concluding remarks

- Driving forces of results: Hotelling rule - requirement of clearing all markets in all periods - strategic taxation on the part of country A

- Price for informative *analytical* results is very simple modeling: Countries identical up to their stock of fossil energy resources - two periods only – no capital accumulation – no stock-dependent extraction costs – no insecure property rights – no (backstop) renewable energy - no, no, no…etc.

- Some restrictive assumptions can be relaxed (Eichner and Pethig 2010). But: Adding more complexity requires resorting to CGE modeling

Thank you for your attention