Curbing fossil fuels: on the design of global reward payment funds to induce countries to reduce supply, reduce demand and expand substitutes

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Curbing coal

- Consider a global institution with a fixed budget to be split between:
  1) pay countries to reduce coal extraction (supply reduction)
  2) pay countries to reduce energy use (demand reduction)
  3) pay countries to expand renewables (substitute expansion)
- What is the optimal budget split under complete information?
- **Lemma**: Suppose the demand and supply elasticities are all finite. Then it is optimal to allocate a strictly positive amount to each of the three approaches.

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goods produced on previously forested land (palm oil, soy...)	same goods produced on non-forested land	REDD++		

The model

- I= set of countries of the world, all price takers
- country i chooses:
  x_i: coal extraction
  y_i: energy use
  z_i: renewable energy production
- global market for coal, price p
- $x_i - y_i + z_i$ = country i's net export of coal
- $U_i(x_i, y_i, z_i) = \underbrace{B_i(y_i)}_{\substack{B_i' > 0 \\ B_i'' < 0}} - \underbrace{G_i(z_i)}_{\substack{G_i' > 0 \\ G_i'' > 0}} - \underbrace{C_i(x_i)}_{\substack{C_i' > 0 \\ C_i'' > 0}} + p(x_i - y_i + z_i) + f_i(x_i, y_i, z_i)$

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The global institution's problem

- Global institution announces reward payment schemes: $f_{ix}(x_i), f_{iy}(y_i), f_{iz}(z_i) \geq 0$
- Countries choose their (x_i, y_i, z_i)

Definition

A **market equilibrium under a given set of reward payment scheme** $(f_{ix}, f_{iy}, f_{iz})_{i \in I}$ is a combination of an allocation $(x_i, y_i, z_i)_{i \in I}$ and a price p such that:

1) market clearing: $\sum_{i \in I} x_i - y_i + z_i = 0$

2) individual rationality:

$x_i = argmax_x px - C_i(x) + f_{ix}(x)$

$y_i = argmax_y - py + B_i(y) + f_{iy}(y)$

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Viewing the global institution as choosing the allocation and the price

market equilibrium

(surjective map)

$$(f_{xi}, f_{yi}, f_{zi})_{i \in I} \longrightarrow (p, (x_i, y_i, z_i)_{i \in I})$$

minimal required transfers

$$(F_{ix}, F_{iy}, F_{iz})$$

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- Objective: $\sum_{i \in I} B_i(y_i) - C_i(x_i) - G_i(z_i) - \eta(\sum_{j \in I} x_j)$
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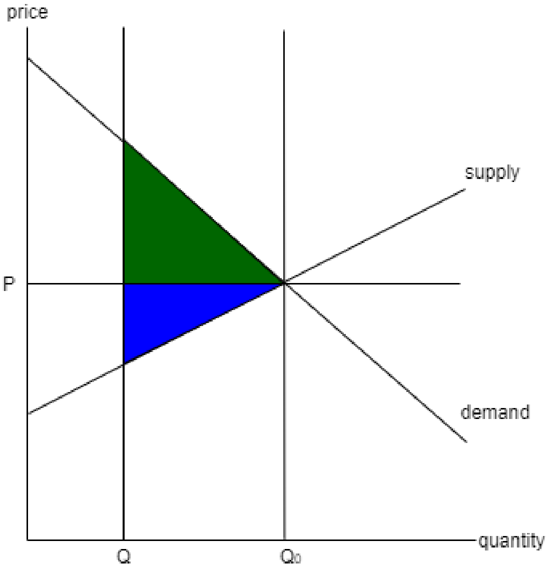
The Price Preservation Lemma

Lemma

At the optimal mechanism we have: The world market price p for coal ends up being the same as in the absence of any mechanism.

The Price Preservation Lemma



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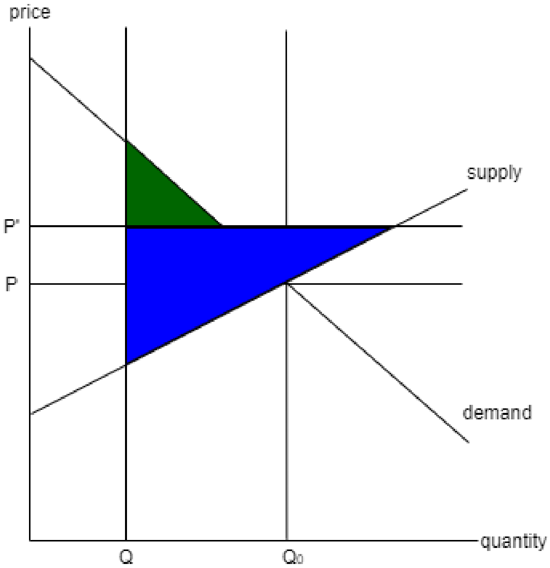

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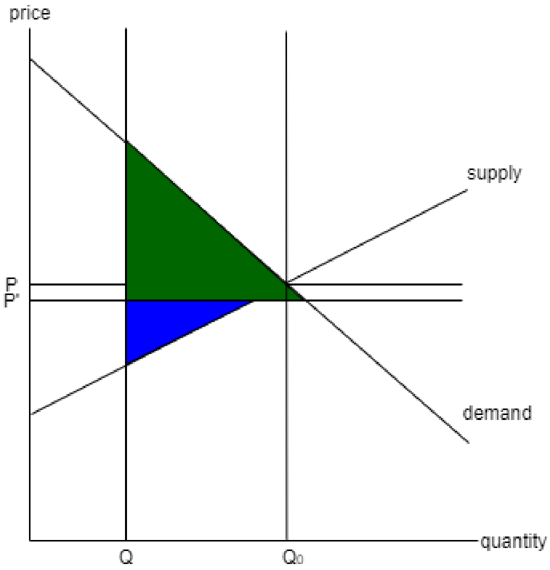
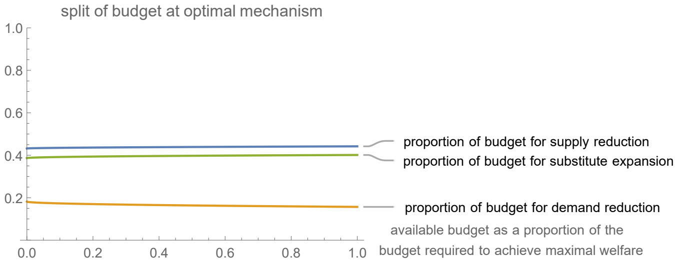


Numerical results for constant elasticity specifications

$$\varepsilon_x = 1.3, \varepsilon_y = 0.85, \varepsilon_z = 2.7, \eta = 1.27, \frac{X(0)}{Y(0)} = 0.6, \frac{Z(0)}{Y(0)} = 0.4$$



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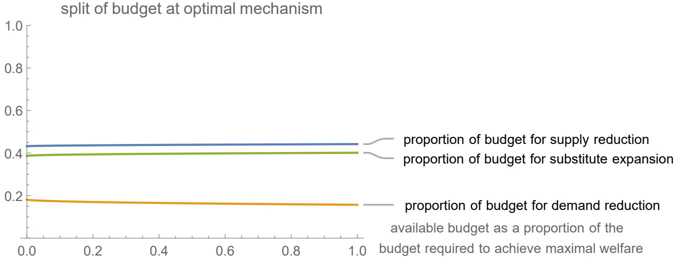

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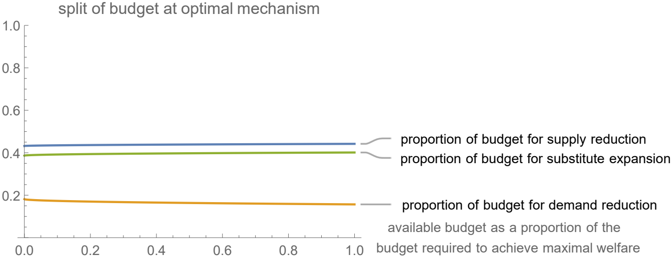

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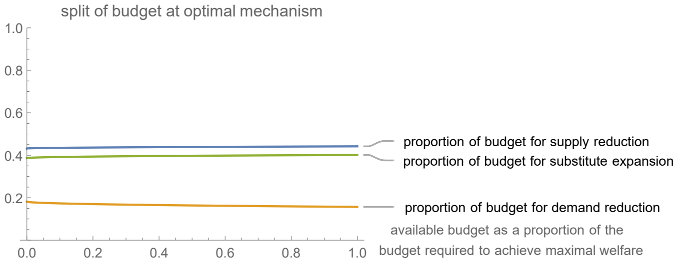
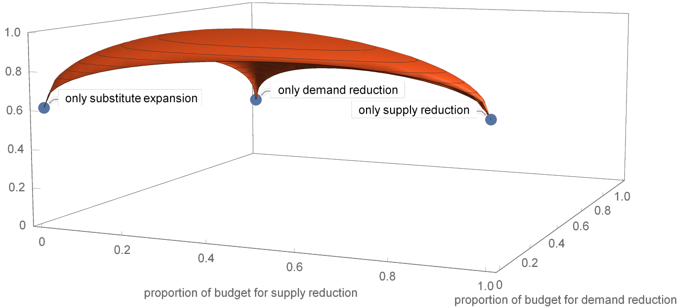


Global welfare as a function of budget split



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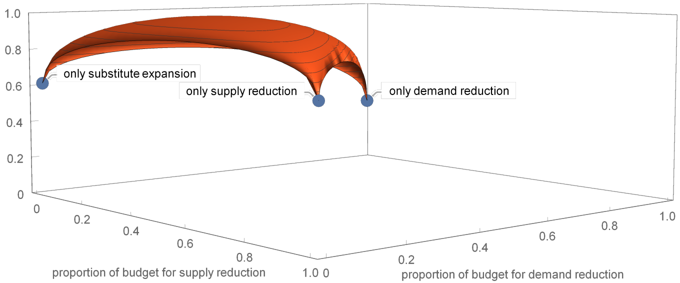

The dynamic model

- y_{it}: country i's energy use in period t
- z_{it}: country i's renewable energy production in period t
- x_{it}: country i's cumulative extraction of coal until the end of period t
- Country i's utility: $U_i = \sum_{t=1}^{T} \frac{1}{(1+r)^t} (b_{it}(y_{it}) - g_{it}(z_{it}) - (c_{it}(x_{it}) - c_{it}(x_{it-1})) + f_{it}(x_{it}, y_{it}, z_{it}) + p_t(x_{it} + z_{it} - y_{it}))$
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- x_{it}: country i's cumulative extraction of coal until the end of period t
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  $U_i = \sum_{t=1}^{T} \frac{1}{(1+r)^t}(b_{it}(y_{it}) - g_{it}(z_{it}) - (c_{it}(x_{it}) - c_{it}(x_{it-1})) + f_{it}(x_{it,} y_{it}, z_{it}) + p_t(x_{it} + z_{it} - y_{it}))$
- The global institution's objective:
  $\sum_{i \in I} U_i - \eta(\sum_{i \in I} x_{iT})$

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The global institution's problem under full commitment and without constraints on borrowing/saving

- Announce path of reward payment schemes $(f_{ixt}(x_{it}), f_{iyt}(y_{it}), f_{izt}(z_{it}))_{i \in I, t \in \{1,..,T\}}$ and fully commit to it
- Budget constraint: $\sum_{t=1}^{T} \sum_{i \in I} \frac{1}{(1+r)^t} (f_{ixt}(x_{it}) + f_{iyt}(y_{it}) + f_{izt}(z_{it})) \leq \sum_{t=1}^{T} \frac{1}{(1+r)^t} F_t$

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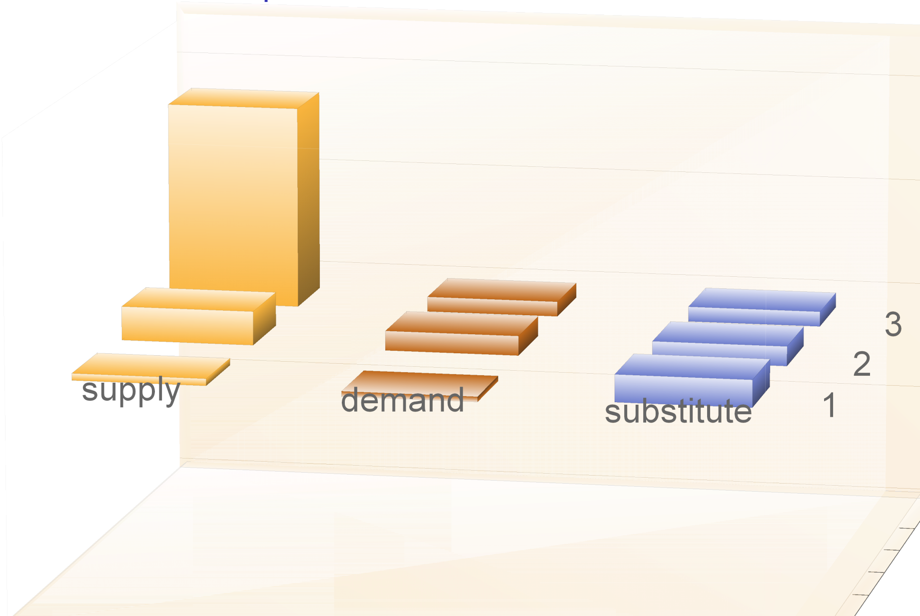
The Dynamic Price Preservation Lemma

Lemma

At the optimal mechanism we have:
The entire price path $(p_t)_{t \in \{1,\ldots,T\}}$ *is identical to when there is no mechanism.*

The global institution's spending path at the optimal mechanism in a 3-period model



Alternative implementation

- Demand/substitute side:
  Carbon pricing reward funds sufficient
- Supply side:
  Extraction based carbon pricing reward funds can cover first period
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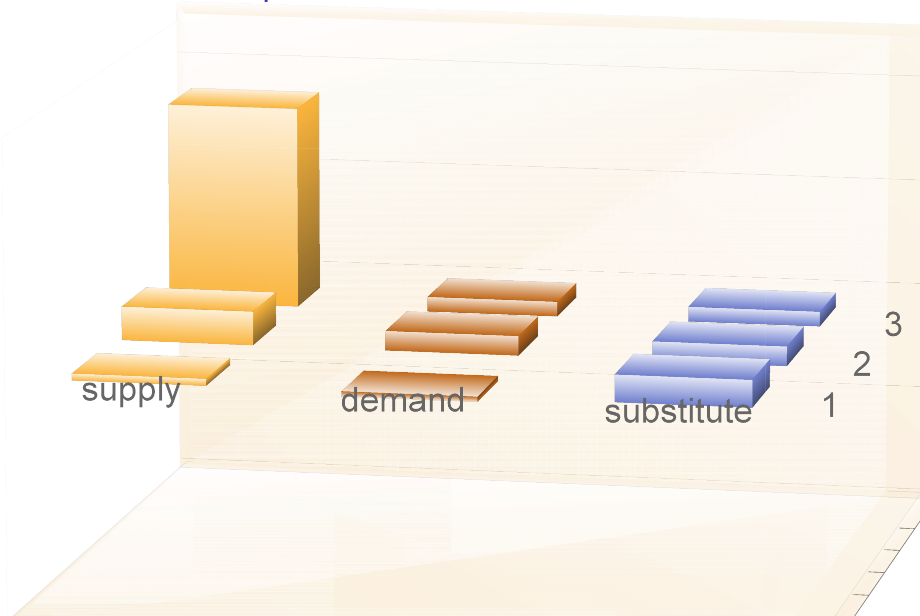

Conclusions

- Valuable to create global institutions rewarding countries for conserving fossil fuels
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Appendix slides

The Monotone Mitigation Lemma

Lemma

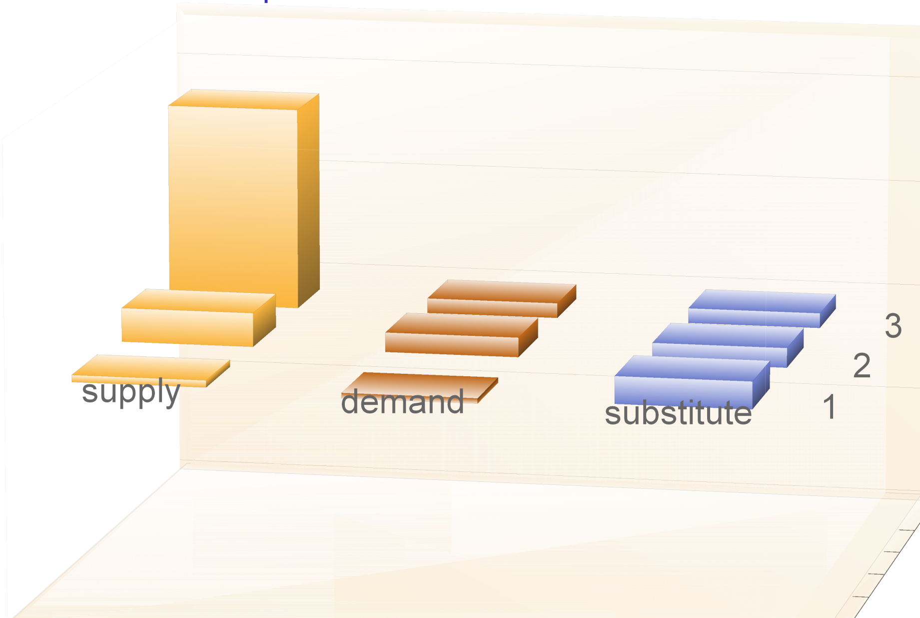
Suppose the global institution has an intertemporal budget of $F = \sum_{t=1}^{T} \frac{F_t}{(1+r)^t}$.
Denoting by $x_{it}(F)$ *the cumulative coal extraction of* i *by the end of period* t *at the optimal mechanism, we have:*
$0 > \frac{dx_{i1}}{dF} > ... > \frac{dx_{iT}}{dF} \forall i, t.$
In particular, increasing the budget F *reduces coal extraction (and use),* $\sum_i x_{it}(F) - x_{it-1}(F)$*, in all periods.*

The Monotone Optimal Spending Corollary

Corollary

Suppose the global institution has an intertemporal budget of $F = \sum_{t=1}^{T} \frac{F_t}{(1+r)^t}$.
Denoting by $F_{tx}(F), F_{ty}(F), F_{tz}(F)$ *the global institution's optimal spending on supply reduction, demand reduction and substitute expansion in period* t*, we have:*
$\frac{dF_{tx}}{dF} > 0, \frac{dF_{ty}}{dF} > 0, \frac{dF_{tz}}{dF} > 0 \forall t$

The global institution's spending path at the optimal mechanism in a 3-period model



2 architectures

- separated architecture:
  -separate funds for rewarding coal supply reduction and coal demand reduction
  -donors can earmark contributions
- unified architecture:
  -unified institution splitting its budget to maximize emissions reductions
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A model of the financing game

- player *im*: A group of coal importers:
  -internalizing s_{im} of global climate change damages
  -making up $2s_{im}$ of coal imports
- player *ex*: A group of coal exporters:
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- **Lemma:** Under both architectures there is a unique Nash Equilibrium.
- **Lemma:** Under the unified architecture, generically, exactly one player contributes.
- **Lemma:** Under the separated architecture both funds receive positive funding.
- **Proposition:** The emissions under the separated architecture are always lower or equal to those under the unified architecture

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Results under linear demand and supply functions

Lemma

Suppose the coal importer and the coal exporter are of equal size: $s_{im} = s_{ex} = s$. Switching from the unified architecture to the separated architecture multiplies the emissions reductions by the following factor:

$$1 + \frac{4\frac{\alpha}{(e_d+e_s)}}{\eta} \frac{1}{1 - \frac{s}{1-s}\alpha(\frac{e_d-e_s}{e_d+e_s})^2}$$

- *η = social cost of carbon of coal relative to its price*
- *α = global coal exports divided by global coal use*
- *e_d = current price elasticity of demand for coal*
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- η = *social cost of carbon of coal relative to its price* $= 1.27$
- α = *global coal exports divided by global coal use* $= 0.2$
- e_d = *current price elasticity of demand for coal* $= 0.7$
- e_s = *current price elasticity of supply of coal* $= 1.3$

Results under linear demand and supply functions

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$$1 + \frac{4\frac{\alpha}{(e_d+e_s)}}{\eta} \frac{1}{1-\frac{s}{1-s}\alpha(\frac{e_d-e_s}{e_d+e_s})^2} \approx 9.57$$

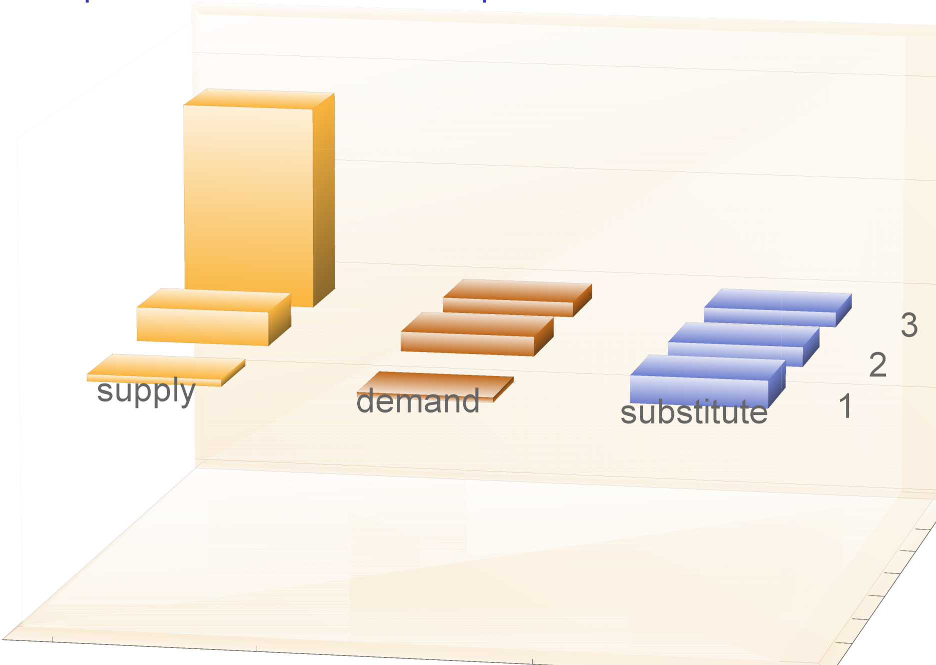
- η = *social cost of carbon of* ***oil*** *relative to its price* $= 0.24$
- α = *global* ***oil*** *exports divided by global* ***oil*** *use* $= 0.425$
- e_d = *current price elasticity of demand for* ***oil*** $= 0.5$
- e_s = *current price elasticity of supply of* ***oil*** $= 0.32$

Constrained Efficiency Lemma

Lemma

At the optimal mechanism we have:
The allocation $(x_{it}, y_{it}, z_{it})_{i \in I, t \in \{1,\ldots,T\}}$ *maximises global welfare amongst all allocations having the same value for climate change damages,* $\sum_{i \in I} \eta_i(\sum_{j \in I} x_{j1}, \ldots, \sum_{j \in I} x_{jT})$.

The optimal mechanism in a 3 period model



A commitment problem

Corollary

Suppose the global institution announces at time 1 the optimal mechanism assuming it fully commits to it.
Suppose that at time $t > 1$ the global institution announces, to all countries' surprise, a new mechanism that it actually sticks to from then onwards.
Then the new mechanism involves less spending on rewarding supply reduction than the originally announced mechanism.

How severe is the commitment problem?

- From now on suppose that:
  - the global institution cannot commit at all
  - the global institution cannot save or borrow
  - T=3
- $x_t(F_1, F_2, F_3)$:=aggregate cumulative coal extraction in period t
- denote by y_t coal demand in period t

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Additional Funding will always decrease eventual emissions

Proposition

$\frac{\partial x_3}{\partial F_t}|_{(F_1,F_2,F_3)} < 0 \forall (F_1, F_2, F_3) \forall t \in \{1, 2, 3\}$

The Weak Green Paradox

Proposition

$\frac{\partial x_1}{\partial F_2}\big|_{(F_1,F_2,F_3)} > 0 \forall (F_1, F_2, F_3)$

Can climate change damages increase as a result of additional funding for the global institution?

Assumption

$\eta(x_1, x_2, x_3) = \tilde{\eta}(x_1 + \frac{1}{1+r}(x_2 - x_1) + \frac{1}{(1+r)^2}(x_3 - x_2))$

- By preceding propositions, increasing F_2 will:
  - increase x_1
  - decrease x_2 and x_3

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Necessary and Sufficient Conditions for the Strong Green Paradox to not arise for Small Budgets

Proposition

Denote $e_{xt} := \frac{dx_t^*}{dp_t}\frac{p_t}{x_t^*}$, $e_{yt} := -\frac{dy_t^*}{dp_t}\frac{p_t}{y_t^*}$ *and*

$$a := e_{y1}\frac{1}{(\frac{x_3-x_2}{x_1})((1+\frac{e_{y1}}{e_{x1}})(1+\frac{e_{y2}}{e_{x2}}(\frac{x_2-x_1}{x_2}))\frac{p_1(1+r)}{p_3}+\frac{e_{y1}}{e_{x2}}\frac{x_1}{x_2}\frac{p_2}{p_3})}$$

Then the following condition is sufficient for the Strong Green Paradox to not occur for small budgets:

$$e_{y3} \geq a$$

Moreover, if $e_{y3} < a$ *then the following condition is necessary and sufficient for the Strong Green Paradox to not occur for small budgets:*

$$e_{x3} \geq e_{y1}\frac{\frac{a-e_{y3}}{a}r}{\frac{x_3}{x_2}((1+\frac{e_{y1}}{e_{x1}})(\frac{x_2-x_1}{x_1}+\frac{x_2}{x_1}\frac{e_{y2}}{e_{x2}})\frac{p_1(1+r)^2}{p_3}+\frac{e_{y1}}{e_{x2}}\frac{p_2(1+r)}{p_3})}$$

Necessary and Sufficient Conditions for the Strong Green Paradox to not arise for Small Budgets

Proposition

Suppose that extraction costs do not change over time, so that we can denote them simply by $c(x)$.
Then the Strong Green Paradox occurs for small budgets in the three period model iff $h := g_1 g_2 + g_3 + g_4(g_5 + g_6) < 0$
with the following definitions:

$e_{yt} := -\frac{dy_t^*}{dp_t}\frac{p_t}{y_t^*}$

$g_1 := rc''(x_2)\left(e_{y3} r(x_3 - x_2)c''(x_3) + (1+r)c'(x_3)\right)$

$g_2 := (e_{y1}x_1 + e_{y2}(x_2 - x_1))\left(rc'(x_2) + c'(x_3)\right) - e_{y2} r(1+r)(x_1 - x_2)c'(x_1)$

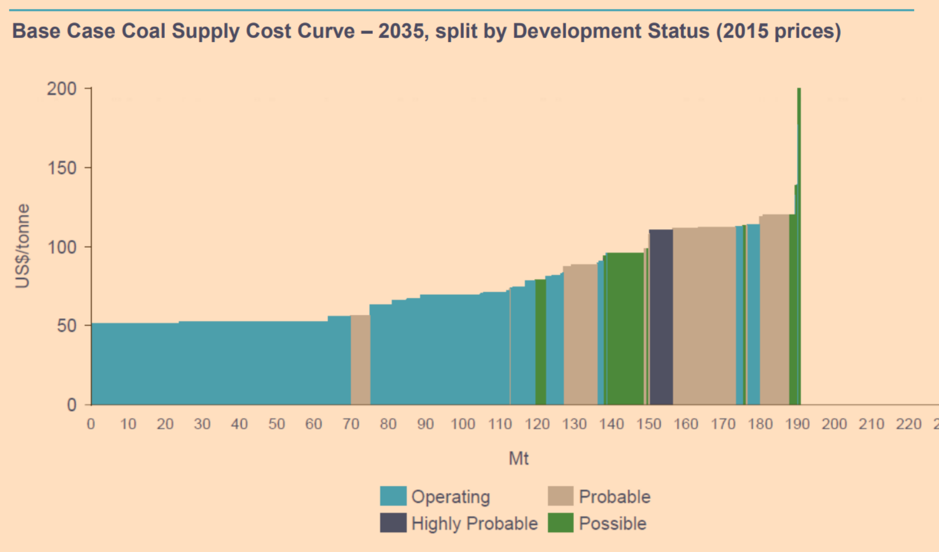
$g_3 := e_{y1} r(1+r)x_1 c''(x_1)\left(e_{y3} r(x_3 - x_2)c''(x_3) + (r+1)c'(x_3)\right)\left(e_{y2} r(x_2 - x_1)c''(x_2) + rc'(x_2) + c'(x_3)\right)$

$g_4 := rc'(x_2) + c'(x_3)$

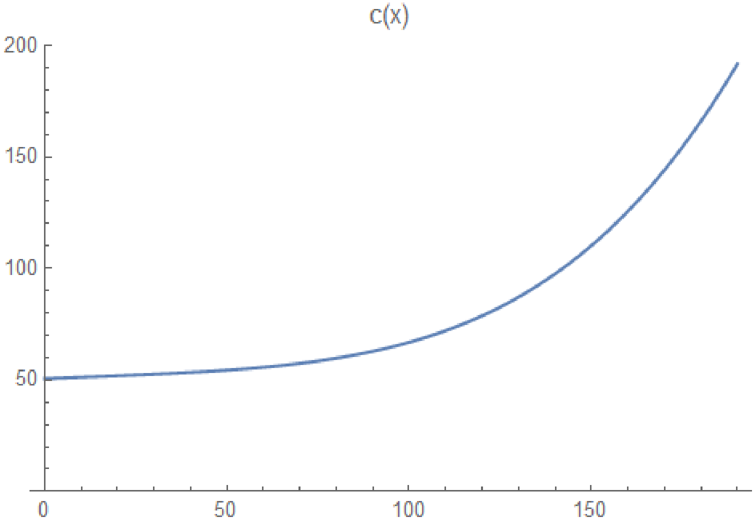
$g_5 := (1+r)c'(x_3)\left(r(1+r)c'(x_1) + rc'(x_2) + c'(x_3)\right)$

$g_6 := rc''(x_3)\left(e_{y3}(x_3 - x_2)\left(r(1+r)c'(x_1) + rc'(x_2) + c'(x_3)\right) - e_{y1}(1+r)x_1 c'(x_3)\right)$

Empirical estimate of $c(x)$



Cubic approximation of the empirical estimate of $c(x)$



Corollary

Suppose that the third period extraction is not more than the second period extraction. Then the Strong Green Paradox can only occur for small budgets if $\frac{e_{y1}}{e_{y2}} > 15.55$ *or* $\frac{e_{y1}}{e_{y3}} > 15.55$.

2 architectures

- separated architecture:
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  -unified institution **committing to the ex ante optimal way of splitting its available funding flow**
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Global welfare as a function of budget split