

# The Optimal Design of Climate Agreements

## Inequality, Trade, and Incentives for Carbon Policy

*Thomas Bourany*

THE UNIVERSITY OF CHICAGO

*International Trade Working Group*

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- ▶ Proposals to fight climate inaction and the free-riding problem:
  - International cooperation through climate agreements, e.g. UN's COP
  - **Trade sanctions** needed to give incentives to countries to reduce emissions meaningfully
    - “**Climate club**”, Nordhaus (2015): trade sanctions on non-participations to sustain larger “clubs”
    - Carbon Border Adjustment mechanisms (CBAM), EU policy: carbon tariffs

# Introduction

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- Climate club setting – Nordhaus:  
The agreement boils down to a carbon tax, a tariff rate and a choice of countries
- Trade-off:  
*Intensive margin*: a “climate club” with few countries and large emission reductions  
vs. *Extensive margin*: a larger set of countries, at the cost of lowering the carbon tax



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► What I do:

- Build a rich Integrated-Assessment Model (IAM) with heterogeneous countries, energy markets, international trade and countries’ **strategic behaviors**
- Study the strategic implications of climate agreements and the **optimal club design**

## Preview of the results:

- Optimal climate agreement:
  - *Participation*: all the countries in the world except Russia
  - *Trade tariffs*: 50% on non-member to impose substantial retaliation
  - *Carbon tax*: \$100/ $tCO_2$ , lower than the policy benchmark without free-riding
- Impossibility result:
  - Because of free-riding, we can not achieve *both* a *high carbon tax* and *complete participation*, despite *arbitrary* trade tariffs
  - Some countries never join agreements with *high carbon taxes*
- *Participation choice*:
  - (i) the cost of distortionary carbon taxation, vs. (ii) the cost of tariffs ( $\sim$  gains from trade)
- The optimal agreement deters *free-riding* and solves the intensive-extensive margin tradeoff
  - Lower emissions by 30% compared to “Business as Usual”
  - Recover most of the welfare and climate gains of the policy benchmark absent free-riding

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# Literature

- ▶ Theoretical model of climate agreements: cooperation
  - *Climate clubs and cooperation*: Nordhaus (2015), Barrett (1994), Harstad (2012), Maggi (2016), Barrett (2003, 2013, 2022), Iverson (2024), Hagen and Schneider (2021), Chari, Nicolini, Teles (2023)
  - *Dynamics of coalition building*: Ray and Vohra (2015), Okada (2023), Nordhaus (2021), Harstad (2023), Maggi and Staiger (2022)
- ⇒ *Quantitative analysis of climate agreements and policy recommendation*

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## Model – Household & Firms

### ► Deterministic Neoclassical economy

- countries  $i \in \mathbb{I}$ , heterogeneous in many dimensions: income, temperature, energy production, etc.
- In each country, five agents:

#### 1. Representative household $\mathcal{U}_i = \max_{c_{ij}} u(c_i)$ , Trade, à la Armington

$$c_i = \left( \sum_j a_{ij}^{\frac{1}{\theta}} c_{ij}^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}} \quad \sum_{j \in \mathbb{I}} c_{ij} \underbrace{(1+t_{ij}^b)}_{\text{tariff}} \underbrace{\tau_{ij}}_{\text{iceberg cost}} p_j = \underbrace{w_i \ell_i}_{\text{labor income}} + \underbrace{\pi_i^f}_{\text{fossil firm profit}} + \underbrace{t_i^{ls}}_{\text{lump-sum transfers}}$$

$$\mathbb{P}_i = \left( \sum_j a_{ij} (\tau_{ij} (1+t_{ij}^b) p_j)^{1-\theta} \right)^{\frac{1}{1-\theta}}$$

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#### 2. Competitive final good firm:

$$\max_{\ell_i, e_i^f, e_i^c, e_i^r} p_i \mathcal{D}_i(\mathcal{E}) z_i F(\ell_i, e_i^f, e_i^c, e_i^r) - w_i \ell_i - (q^f + t_i^\varepsilon) e_i^f - (q_i^c + t_i^\varepsilon) e_i^c - q_i^r e_i^r$$

- Externality: Damage function  $\mathcal{D}_i(\mathcal{E})$ , Income inequality from  $z_i$ , Carbon tax:  $t_i^\varepsilon$

## Model – Energy markets & Emissions

### 3. Competitive fossil fuels (oil-gas) producer, extracting $e_i^x$

$$\pi_i^f = \max_{e_i^x} q^f e_i^x - \mathcal{C}_i^f(e_i^x) \mathbb{P}_i$$

- Energy traded in international markets, at price  $q^f$

$$E^f = \sum_{i \in \mathbb{I}} e_i^f = \sum_{i \in \mathbb{I}} e_i^x$$

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4. Coal energy firm, CRS  $e_i^c$ :  $\Rightarrow$  price  $q_i^c = z_i^c \mathbb{P}_i$

5. Renewable energy firm, CRS  $e_i^r$ :  $\Rightarrow$  price  $q_i^r = z_i^r \mathbb{P}_i$

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- Climate system: mapping from emission  $\mathcal{E} = \sum_{\mathbb{I}} e_i^f + e_i^c$  to damage  $\mathcal{D}_i(\mathcal{E})$



## Model – Equilibrium

- Given policies  $\{t_i^\varepsilon, t_{ij}^b, t_i^{ls}\}_i$ , a **competitive equilibrium** is a set of decisions  $\{c_{ij}, e_i^f, e_i^c, e_i^r, e_i^x\}_{ij}$ , emission  $\{\mathcal{E}\}_i$  changing climate and prices  $\{p_i, w_i, q_i^c, q_i^r\}_i, q^f$  such that:
  - Households choose  $\{c_{ij}\}_{ij}$  to max. utility s.t. budget constraint
  - Firm choose inputs  $\{e_i^f, e_i^c, e_i^r\}_i$  to max. profit
  - Oil-gas firms extract/produce  $\{e_i^x\}_i$  to max. profit. + Elastic renewable, coal supplies  $\{e_i^c, e_i^r\}$
  - Emissions  $\mathcal{E}$  affects climate and damages  $\mathcal{D}_i(\mathcal{E})$
  - Government budget clear  $\sum_i t_i^{ls} = \sum_i t_i^\varepsilon (e_i^f + e_i^c) + \sum_{i,j} t_{ij}^b c_{ij} \tau_{ij} p_j$
  - Prices  $\{p_i, w_i, q^f\}$  adjust to clear the markets for energy  $\sum_{\mathbb{I}} e_{it}^x = \sum_{\mathbb{I}} e_{it}^f$  and for each good

$$y_i := \mathcal{D}_i(\mathcal{E}) z_i F(\ell_i, e_i^f, e_i^r, e_i^r) = \sum_{k \in \mathbb{I}} \tau_{ki} c_{ki} + \sum_{k \in \mathbb{I}} \tau_{ki} (x_{ki}^f + x_{ki}^c + x_{ki}^r)$$

with  $x_{ki}^\ell$  export of good  $i$  as input in  $\ell$ -energy production in  $k$

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## Climate agreements and endogenous participation

- **Definition:** A climate agreement is a set  $\{\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b\}$  of  $\mathbb{J} \subseteq \mathbb{I}$  countries and a C.E. s.t.:
- Countries  $i \in \mathbb{J}$  pay carbon tax  $\mathbf{t}_i^\varepsilon = \mathbf{t}^\varepsilon$
  - If  $j$  exits agreement, club members  $i \in \mathbb{J}$  impose uniform tariffs  $\mathbf{t}_{ij}^b = \mathbf{t}^b$  on goods from  $j$   
They still trade with club members in oil-gas at price  $q^f$
  - Local, lump-sum rebate of taxes  $\mathbf{t}_i^{ls} = \mathbf{t}^\varepsilon (e_i^f + e_i^c) + \sum_{j \notin \mathbb{J}} \mathbf{t}^b \tau_{ij} c_{ij} p_j$
  - Indirect utility  $\mathcal{U}_i(\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b) \equiv u(c_i(\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b))$

## Climate agreements and endogenous participation

- **Definition:** A climate agreement is a set  $\{\mathbb{J}, \mathbf{t}^e, \mathbf{t}^b\}$  of  $\mathbb{J} \subseteq \mathbb{I}$  countries and a C.E. s.t.:
- Countries  $i \in \mathbb{J}$  pay carbon tax  $t_i^e = \mathbf{t}^e$
  - If  $j$  **exits** agreement, club members  $i \in \mathbb{J}$  impose uniform tariffs  $t_{ij}^b = \mathbf{t}^b$  on goods from  $j$   
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  - Indirect utility  $\mathcal{U}_i(\mathbb{J}, \mathbf{t}^e, \mathbf{t}^b) \equiv u(c_i(\mathbb{J}, \mathbf{t}^e, \mathbf{t}^b))$
- Equilibrium concepts:
- Exit from the agreement: unilateral deviation of  $i$ ,  $\mathbb{J} \setminus \{i\}$ ,  $\Rightarrow$  **Nash equilibrium**

Coalition  $\mathbb{J}$  stable if  $\mathcal{U}_i(\mathbb{J}, \mathbf{t}^e, \mathbf{t}^b) \geq \mathcal{U}_i(\mathbb{J} \setminus \{i\}, \mathbf{t}^e, \mathbf{t}^b) \quad \forall i \in \mathbb{J}$

- Sub-coalitional deviation  $\Rightarrow$  **Coalitional Nash equilibrium**

# Optimal design with endogenous participation

- Objective: search for the optimal *and stable* climate agreement

$$\begin{aligned} \max_{\mathbb{J}, t^{\varepsilon}, t^b} \mathcal{W}(\mathbb{J}, t^{\varepsilon}, t^b) &= \max_{t^{\varepsilon}, t^b} \max_{\mathbb{J}} \sum_{i \in \mathbb{I}} \omega_i \mathcal{U}_i(\mathbb{J}, t^{\varepsilon}, t^b) \\ \text{s.t.} \quad &\mathcal{U}_i(\mathbb{J}, t^{\varepsilon}, t^b) \geq \mathcal{U}_i(\mathbb{J} \setminus \{i\}, t^{\varepsilon}, t^b) \end{aligned}$$

- Current design:

(i) choose taxes  $\{t^{\varepsilon}, t^b\}$  [outer problem]

(ii) choose the coalition  $\mathbb{J}$  s.t. participation constraints hold [inner problem]

$\Rightarrow$  *Combinatorial Discrete Choice Problem* for  $\mathbb{J} \in \mathcal{P}(\mathbb{I})$

Alternative approach [details](#)

Policy and deviation [details](#)

## Solution method

- ▶ Current design:  $\max_{\mathbf{t}} \max_{\mathbb{J}} \mathcal{W}(\mathbb{J}, \mathbf{t}) \text{ s.t. } \mathcal{U}_i(\mathcal{J}, \mathbf{t}) \geq \mathcal{U}_i(\mathcal{J} \setminus \{i\}, \mathbf{t})$
- ▶ Inner problem: CDCP Solution method
  - Use a “squeezing procedure”, as in Jia (2008), Arkolakis, Eckert, Shi (2023) extended to handle participation constraints

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    - Squeezing step:

$$\Phi(\mathcal{J}) \equiv \{j \in \mathbb{I} \mid \Delta_j \mathcal{W}(\mathcal{J}) > 0 \text{ \& \; } \Delta_j \mathcal{U}_j(\mathcal{J}, \mathbf{t}) > 0, \forall j \in \mathcal{J}\}$$

where marginal values of  $j \in \mathcal{J}$  for global  $\Delta_j \mathcal{W}(\mathcal{J}, \mathbf{t})$  and individual welfare  $\Delta_j \mathcal{U}_j(\mathcal{J}, \mathbf{t})$  are:

$$\Delta_j \mathcal{W}(\mathcal{J}, \mathbf{t}) \equiv \mathcal{W}(\mathcal{J} \cup \{j\}, \mathbf{t}) - \mathcal{W}(\mathcal{J} \setminus \{j\}, \mathbf{t}) \qquad \Delta_j \mathcal{U}_j(\mathcal{J}, \mathbf{t}) \equiv \mathcal{U}_j(\mathcal{J} \cup \{j\}, \mathbf{t}) - \mathcal{U}_j(\mathcal{J} \setminus \{j\}, \mathbf{t})$$

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- Iterative procedure build lower bound  $\underline{\mathcal{J}}$  and upper bound  $\overline{\mathcal{J}}$  by successive squeezing steps

$$\underline{\mathcal{J}}^{(k+1)} = \Phi(\underline{\mathcal{J}}^{(k)}) \qquad \overline{\mathcal{J}}^{(k+1)} = \Phi(\overline{\mathcal{J}}^{(k)})$$

- Squeezing procedure converges to the optimal set under *Complementarity* Assumption, Details



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## Quantification – Climate system and damage

### ► Static economic model:

decisions  $e_i^f + e_i^c$  taken “once and for all”,  $\mathcal{E} = \sum_i e_i^f + e_i^c$

- Climate system:

$$\dot{S}_t = \mathcal{E} - \delta_s S_t$$

$$T_{it} = \bar{T}_{i0} + \Delta_i S_t$$

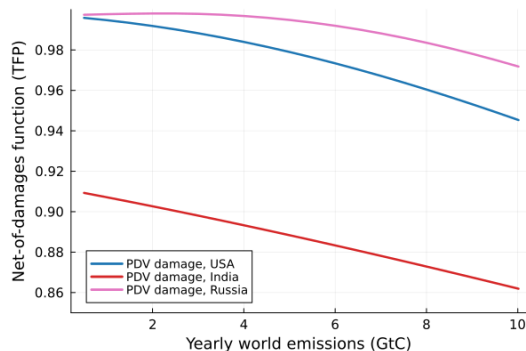
- Path damages heterogeneous across countries  
Quadratic, c.f. Nordhaus-DICE / IAM

$$\mathcal{D}(T_{it} - T_i^*) = e^{-\gamma(T_{it} - T_i^*)^2}$$

- Economic feedback in Present discounted value

$$\mathcal{D}_i(\mathcal{E}) = \bar{\rho}_i \int_0^\infty e^{-\overbrace{(\rho - n_i + \eta \bar{g}_i)}^{\equiv \bar{\rho}_i} t} \mathcal{D}(T_{it} - T_i^*) dt$$

- Similarly for  $LCC_i, SCC_i \dots$



# Quantification

- Pareto weights  $\omega_i$ : Imply no redistribution motive  
 $\bar{c}_i$  conso in initial equilibrium  $t = 2020$  w/o climate change

$$\omega_i = \frac{1}{u'(\bar{c}_i)} \quad \Leftrightarrow \quad C.E.(\bar{c}_i) \in \operatorname{argmax}_{\bar{c}_i} \sum_i \omega_i u(\bar{c}_i)$$

Details Pareto weights

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- Functional forms:
  - Utility: CRRA  $\eta$
  - Production function  $\bar{y} = zF(\ell_i, k_i, e_i^f, e_i^c, e_i^r)$ 
    - Nested CES energy  $e_i$  vs. labor-capital Cobb-Douglas bundle  $k_i^\alpha \ell_i^{1-\alpha}$ , elasticity  $\sigma_y < 1$
    - Energy: fossil/coal/renewable  $\sigma_e > 1$ ,  $CES(e_i^f, e_i^c, e_i^r)$ , elasticity  $\sigma^e$
  - Energy extraction of oil-gas: isoelastic  $\mathcal{C}^f(e^x) = \bar{\nu}_i (e_i^x / \mathcal{R}_i)^{1+\nu_i} \mathcal{R}_i$

## More details

# Calibration

- ▶ Parameters calibrated from the literature
- ▶ Parameters to match “world” moments from the data [Details calibration](#)
- ▶ Parameters to match (exactly) country-level variables [Details country-level moments](#)

# Calibration

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  - Damage parameter:  $\gamma$  from Krusell, Smith (2022) & Barrage, Nordhaus (2023)Target temperature:  $T_i^* = \alpha T^* + (1 - \alpha) T_{it_0}$  with  $T^* = 14.5$ ,  $\alpha = 0.5$ .
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  - CES shares in capital/labor/energy to match aggregate shares
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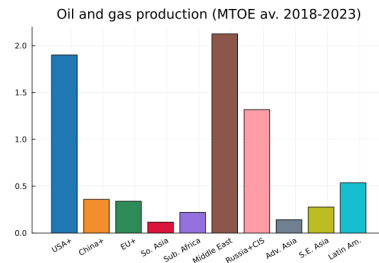
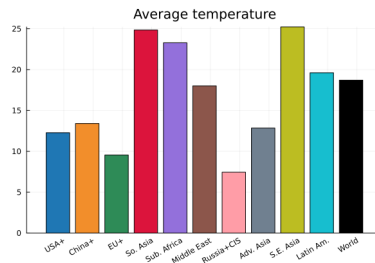
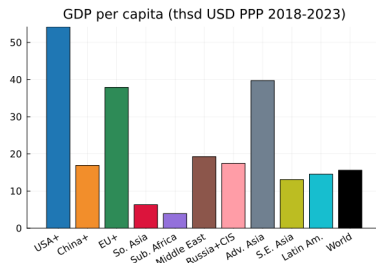
## ► Parameters to match (exactly) country-level variables Details country-level moments

- TFP  $z_i \Rightarrow$  GDP  $y_i$ , Population  $\mathcal{P}_i$ , Temperature  $T_{it_0}$ , Pattern scaling  $\Delta_i$
- Energy mix (Oil-gas  $e_i^f$ , Coal  $e_i^c$ , Non-carbon  $e_i^r$ ), energy share, oil-gas prod°, reserves, rents
- Trade: cost  $\tau_{ij}$  projected on distance, preferences  $a_{ij}$  to match import shares



## Quantitative application – Sample of 10 “regions”

- ▶ Sample of 10 “regions”: (i) US+Canada, (ii) China+HK, (iii) EU+UK+Schengen, (iv) South Asia, (v) Sub-saharian Africa, (vi) Middle-East+North Africa, (vii) Russia+CIS, (viii) Japan+Korea+Australia+Taiwan+Singap., (ix) South-East Asia (Asean), (x) Latin America **WIP: 25 countries + 7 regions**
- ▶ Data (Avg. 2018-2023)



Details [Trade shares – details](#)

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5. **Policy Benchmarks:**  
**Optimal Policy without Free-riding Incentives**
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## Optimal policy : benchmarks

- ▶ Policy benchmarks, without free-riding incentives
  - ***First-Best***, Social planner maximizing global welfare with unlimited instruments
    - Pigouvian result: Carbon tax = Social Cost of Carbon
    - Relies heavily on cross-country transfers to offset redistributive effects

## Optimal policy : benchmarks

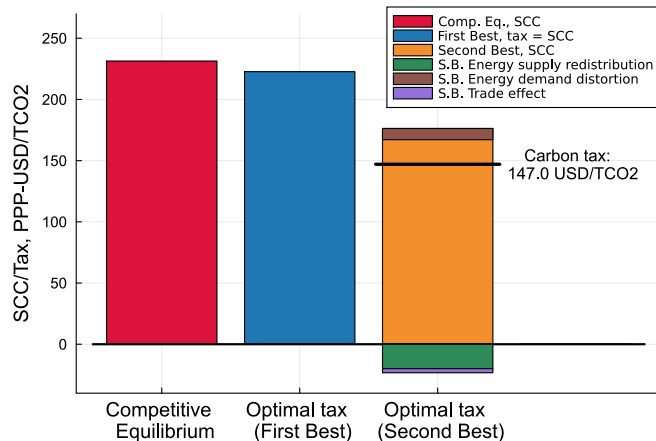
### ► Policy benchmarks, without free-riding incentives

- **First-Best**, Social planner maximizing global welfare with unlimited instruments
  - Pigouvian result: Carbon tax = Social Cost of Carbon
  - Relies heavily on cross-country transfers to offset redistributive effects
- **Second-Best**: Social planner, single carbon tax without transfers
  - Optimal carbon tax  $t^E$  correct climate externality, but also accounts for:
    - (i) Redistribution motives, and G.E. effects on (ii) energy markets and (iii) trade leakage

$$t^E = \underbrace{\sum_i \phi_i LCC_i}_{=SCC} + \sum_i \phi_i \text{Supply Redistrib}_i^o + \sum_i \phi_i \text{Demand Distort}_i^o - \sum_i \text{Trade Redistrib}_i^o \quad \phi_i \propto \omega_i u'(c_i)$$

- Details: **CE**, **First-Best**, **Second-Best**
- Companion paper: Bourany (2024), *Climate Change, Inequality, and Optimal Climate Policy*
- **Unilateral policy**: local planners choose their own optimal climate-trade policy,
  - see Farrokhi-Laksharipour (2024), Kortum, Weisbach (2022) **Nash-Unilateral Policies**

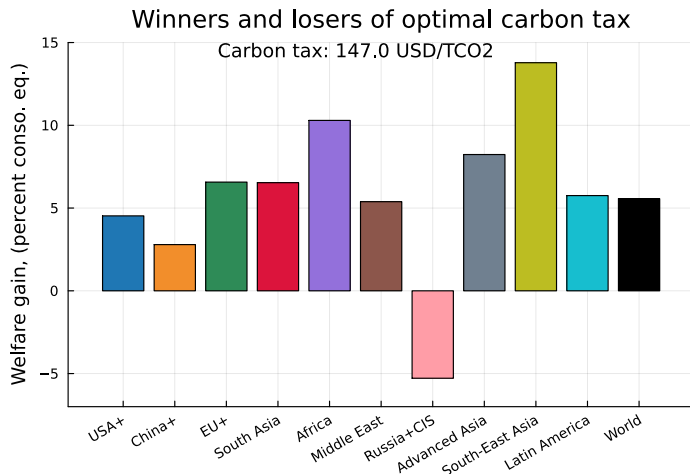
## Second-Best climate policy



- Accounting for redistribution and lack of transfers  
 ⇒ implies a carbon tax lower than the Social Cost of Carbon

## Gains from cooperation – World Optimal policy

- ▶ Optimal carbon tax  
Second Best:  $\sim \$147/tCO_2$
- ▶ Reduce fossil fuels /  $CO_2$  emissions by 42% compared to Competitive equilibrium (Business as Usual, BAU)
- ▶ Welfare difference between world optimal policy vs. Comp. Eq./BAU



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## Main result

► The optimal and stable climate agreement:

- **Participation:** all the countries in the world,  
with the exception of Russia, and former Soviet countries
- **Carbon tax:** need to reduce tax level from \$147 to \$98/ $tCO_2$
- **Trade tariffs:** impose substantial tariff 50% on the goods from non-members

► Impossibility result:

Because of free-riding, we can not achieve **both** a *high* carbon tax and *complete participation*, despite *arbitrary* trade tariffs



## Intuition

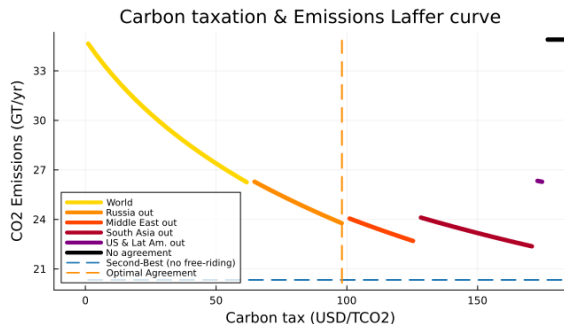
- ▶ The climate agreement needs to balance an **intensive** and **extensive** margin
  - *Intensive margin*: given a coalition: carbon tax decreases emissions
  - *Extensive margin*: carbon tax also deter participation  
individual countries free-ride, increasing emissions
  - And this, *despite complete discretion in the choice of tariffs*

## Intuition

- ▶ The climate agreement needs to balance an **intensive** and **extensive** margin
    - *Intensive margin*: given a coalition: carbon tax decreases emissions
    - *Extensive margin*: carbon tax also deter participation  
individual countries free-ride, increasing emissions
    - And this, *despite complete discretion in the choice of tariffs*
  - ▶ **Mechanism:**
    - Countries participate depending on  $\left\{ \begin{array}{l} \text{(i) the cost of distortionary carbon taxation} \\ \text{(ii) the cost of tariffs (= the gains from trade)} \end{array} \right.$
    - Russia/Middle East/South Asia do not join the club for high carbon tax  
*for any tariffs*, because cost of taxing fossil-fuels  $\gg$  cost of tariffs / autarky
- $\Rightarrow$  As a result, we need to decrease the carbon tax

## Laffer curve for carbon taxation

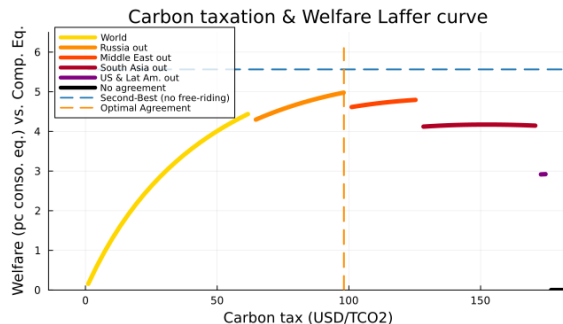
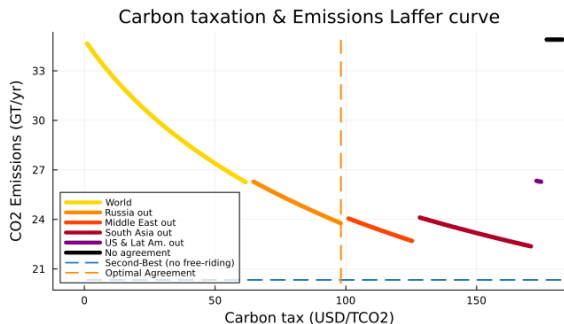
- Due to free-riding incentives, **cannot reach** globally optimal carbon tax  $t^{\varepsilon,*} = \$147$



Emissions  $\mathcal{E}$  (in  $GtCO_2/yr$ ) and welfare  $\mathcal{W}$  as a fct of carbon tax  $t^{\varepsilon}$  and tariff  $t^b = 50\%$ .

## Laffer curve for carbon taxation

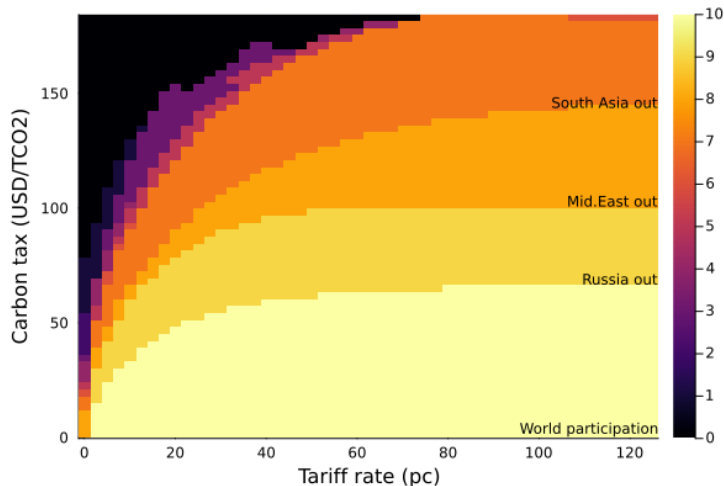
- Due to free-riding incentives, **cannot reach** globally optimal carbon tax  $t^{\epsilon,*} = \$147$
- Not optimal to **reduce participation**:  
 concentrates mitigation costs on remaining members  $\Rightarrow$  dampen welfare



Emissions  $\mathcal{E}$  (in  $GtCO_2/yr$ ) and welfare  $\mathcal{W}$  as a fct of carbon tax  $t^{\epsilon}$  and tariff  $t^b = 50\%$ .

## Climate Agreements: Intensive vs. Extensive Margin

- **Intensive margin:**  
higher tax, emissions ↓, welfare ↑
- **Extensive margin:**  
higher tax, participation ↓,  
free-riding and emissions ↑



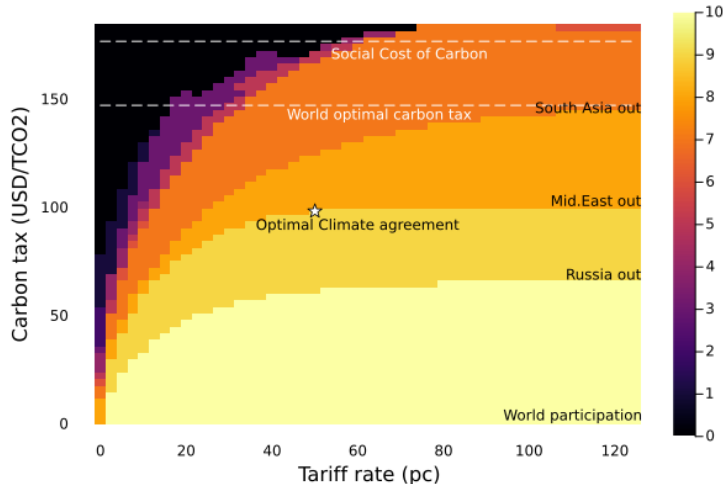
# Optimal Climate Agreement

► Despite full discretion of instruments ( $t^e, t^b$ ), we cannot sustain an agreement with Russia, Middle East & South-Asia

⇒ need to **reduce carbon tax** from \$147 to \$98

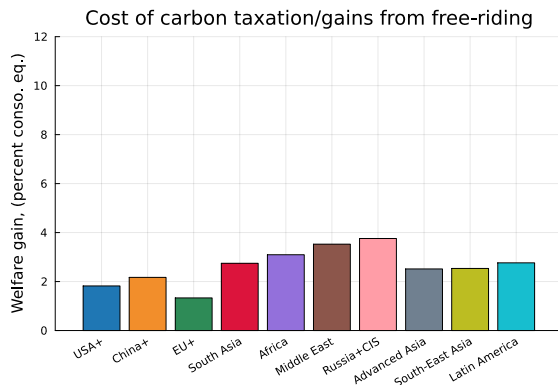
⇒ Beneficial to **leave Russia outside of agreement**  
no incentive to join: cold, closed to trade, and large fossil-fuel producer

Graph welfare



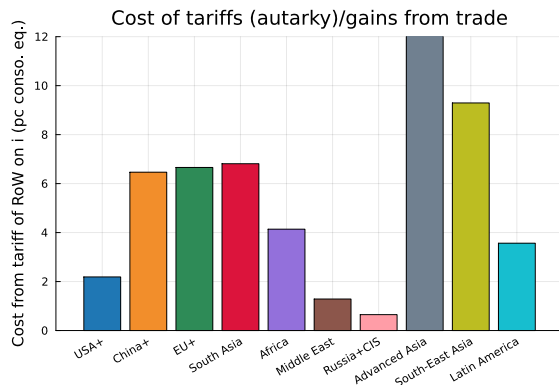
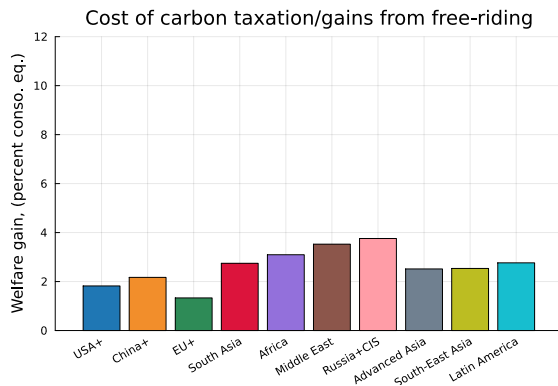
## Trade-off – Cost of Carbon Taxation vs. Gains from trade

Gains from **unilateral exit** from agreement vs. **Gains from trade**, i.e. loss from tariffs/autarky



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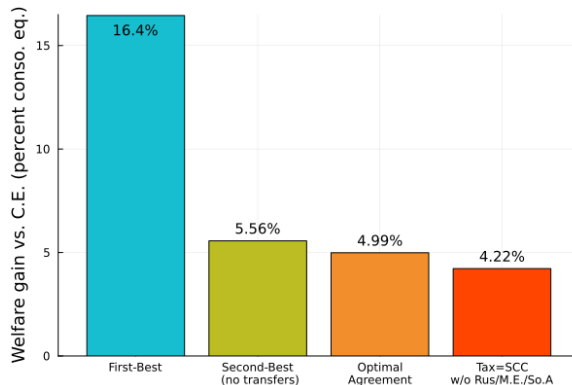
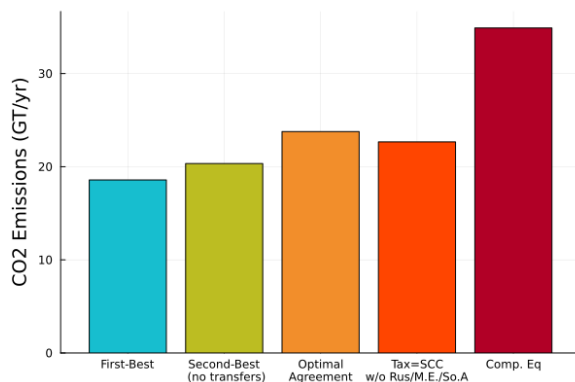


*Welfare decomposition* Linear decomposition



## Emission reduction vs. Welfare: Different metrics!

- Agreements with tariffs recover 91% of welfare gains from the Second-Best – optimal carbon tax without transfers – at a cost of increasing emissions by 13%
- First-best allocation relies heavily on transfers to be able to impose a higher carbon tax



## Coalition building

- ▶ How to build sequentially the climate coalition?
  - Which countries have the most interest in joining the club?

## Coalition building

### ► Sequence of "rounds" of the static equilibrium

- At each round  $(n)$ , countries decide to enter or not depending on the gain

$$\Delta_i \mathcal{U}_i(\mathbb{J}^{(n)}) = \mathcal{U}_i(\mathbb{J}^{(n)} \cup \{i\}, t^\varepsilon, t^b) - \mathcal{U}_i(\mathbb{J}^{(n)} \setminus \{i\}, t^\varepsilon, t^b)$$

- Construction evaluated at the optimal carbon tax  $t^\varepsilon = 98\%$ , and tariff  $t^b = 50\%$ .
- Sequential procedure – coming for free from our CDCP algorithm / squeezing procedure
- Idea analogous to Farrokhi, Lashkaripour (2024)

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### ► Result: sequence up to the optimal climate agreement

- Round 1: European Union
- Round 2: China, South-East Asia (Asean)
- Round 3: North America, South Asia, Africa, Advanced East Asia, Latin America
- Round 4: Middle-East
- ✱ Stay out of the agreement: Russia+CIS

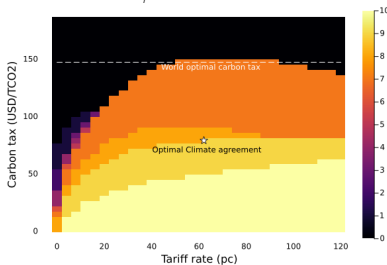
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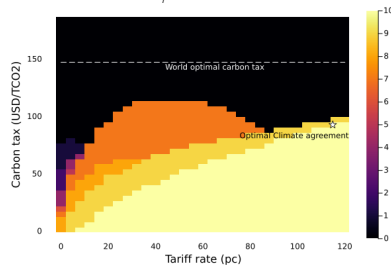
# Retaliation

- Trade policy retaliation:  
Suppose the regions outside the agreement impose retaliatory tariffs to club members
- Exercise:
  - Countries outside the club  $j \notin \mathbb{J}$  impose a tariffs  $t_{ji} = \beta t_{ij}$  on club members  $i$

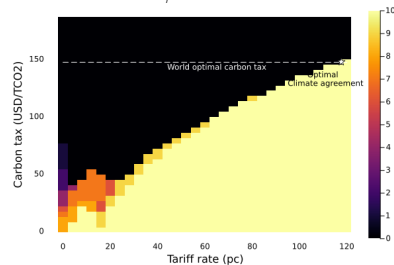
$\beta = 0.25$



$\beta = 0.5$



$\beta = 1.0$

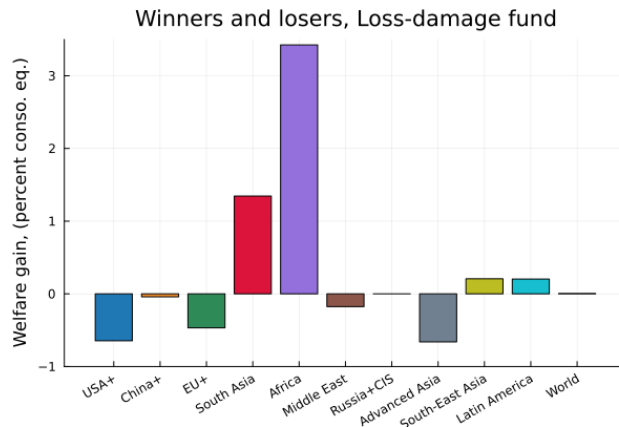


## Transfers – Loss and damage funds

- ▶ COP28 Major policy proposal:  
*Loss and damage funds* for countries vulnerable to the effects of climate change
- ▶ Simple implementation in our context: lump-sum receipts of carbon tax revenues:

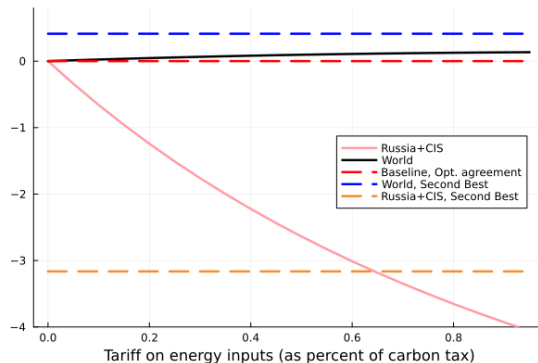
$$t_i^{ls} = (1-\alpha) t^\varepsilon \varepsilon_i + \alpha \frac{1}{P} \sum_j t^\varepsilon \varepsilon_j$$

- ▶ In practice: transfers from large emitters to low emitters



## Taxation of fossil fuels energy inputs

- ▶ Current climate club:  
only imposes penalty tariffs on final goods, not on energy imports
  - Empirically relevant, c.f. Shapiro (2021):  
inputs are more emission-intensives but trade policy is biased against final goods output
- ▶ Alternative: tax energy import from non-participants  $t_{ij}^{bf} = \beta t^b \mathbb{1}\{i \in \mathbb{J}, j \notin \mathbb{J}\}$





# Conclusion

- ▶ In this project, I solve for the optimal design of climate agreements
  - Correcting for inequality, redistribution effects through energy markets and trade leakage, as well as free-riding incentives
- ▶ Climate agreement design jointly solves for:
  - The optimal choice of countries participating
  - The carbon tax and tariff levels, accounting for both the climate externality, redistributive effects and the participation constraints
- ▶ Optimal coalition depends on the trade-off between
  - the gains from cooperation and free riding incentives
  - the gains from trade, i.e. the cost of retaliatory tariffs

⇒ Need a large coalition and a carbon tax at 65% of the world optimum
- ▶ Extensions:
  - Extend this to dynamic settings: coalition building and bargaining

# Conclusion

**Thank you!**

**[thomasbourany@uchicago.edu](mailto:thomasbourany@uchicago.edu)**

# Appendices

## Optimal design with endogenous participation

- ▶ Why uniform policy instruments  $t^\varepsilon$  and  $t^b$  for all club members:
  - Our social planner/designer solution represents the outcome of a “bargaining process” between countries (with bargaining weights  $\omega_i$ ).
  - Deviation from Coase theorem:
    - With transaction/bargaining cost: impossible to reach a consensual decision on  $I + I \times I$  instruments  $\{t_i^\varepsilon, t_{ij}^b\}_{ij}$
    - Such costs increase exponentially in the number of countries  $I$

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    - Such costs increase exponentially in the number of countries  $I$
- ▶ Optimal – country specific – carbon taxes:
  - Without free-riding / exogeneous participation

$$t_i^\varepsilon = \frac{1}{\phi_i} t^\varepsilon \propto \frac{1}{\omega_i u'(c_i)} [SCC + SCF - SCT]$$

- With participation constraints: multiplier  $\nu_i(\mathbb{J})$

$$t_i^\varepsilon \propto \frac{1}{(\omega_i + \nu_i(\mathbb{J})) u'(c_i)} [SCC + SCF - SCT]$$

# Optimal design with endogenous participation

## ► Equilibrium concepts and participation constraints:

- **Nash equilibrium**  $\Rightarrow$  unilateral deviation  $\mathbb{J} \setminus \{j\}$ ,  $\mathbb{J} \in \mathbb{S}(t^f, t^b)$  if:

$$\mathcal{U}_i(\mathbb{J}, t^e, t^b) \geq \mathcal{U}_i(\mathbb{J} \setminus \{i\}, t^e, t^b) \quad \forall i \in \mathbb{J}$$

- **Coalitional Nash-equilibrium**  $\mathbb{C}(t^f, t^b)$ : robust of sub-coalitions deviations:

$$\mathcal{U}_i(\mathbb{J}, t^f, t^b) \geq \mathcal{U}_i(\mathbb{J} \setminus \hat{\mathbb{J}}, t^f, t^b) \quad \forall i \in \hat{\mathbb{J}} \text{ \& \& } \forall \hat{\mathbb{J}} \subseteq \mathbb{J} \cup \{i\}$$

- Stability requires to check all potential coalitions  $\mathbb{J} \in \mathcal{P}(\mathbb{I})$  as all sub-coalitions  $\mathbb{J} \setminus \hat{\mathbb{J}}$  are considered as deviations in the equilibrium
- Requires to solve all the combination  $\mathbb{J}, t^f, t^b$ , by exhaustive enumeration.  
 $\Rightarrow$  becomes very computationally costly for  $I = \#(\mathbb{I}) > 10$

back

## Complementarity

- Application of *Squeezing procedure* as in Arkolakis, Eckert, Shi (2023)
- Condition: Single Crossing Differences in choice (SCD-C),  
that I extend to account for participation constraints (SCD-C,PC)
- In our setting, condition as follows:

IF the coalition  $\mathcal{J}$  makes (i) allocation outcomes better for welfare with  $\{j\}$ , if both  $\mathcal{J}$  and  $\mathcal{J} \cup \{j\}$  are stable, or (ii) the coalition  $\mathcal{J} \cup \{j\}$  is stable if  $\mathcal{J}$  is unstable  
THEN one of these conditions should also be respected for larger coalitions  $\mathcal{J}' \supseteq \mathcal{J}$ .

$$\left\{ \begin{array}{l} \Delta_i \mathcal{U}_i(\mathcal{J} \cup \{j\}) \geq 0 \\ \& \left[ \begin{array}{l} \left( \Delta_j \mathcal{W}(\mathcal{J} \cup \{j\}) \geq 0 \& \Delta_i \mathcal{U}_i(\mathcal{J}) \geq 0 \right) \\ \text{or } \Delta_i \mathcal{U}_i(\mathcal{J}) < 0 \end{array} \right] \end{array} \right. \Rightarrow \left\{ \begin{array}{l} \Delta_i \mathcal{U}_i(\mathcal{J}' \cup \{j\}) \geq 0 \\ \& \left[ \begin{array}{l} \left( \Delta_j \mathcal{W}(\mathcal{J}' \cup \{j\}) \geq 0 \& \Delta_i \mathcal{U}_i(\mathcal{J}') \geq 0 \right) \\ \text{or } \Delta_i \mathcal{U}_i(\mathcal{J}') < 0 \end{array} \right] \end{array} \right.$$

$\forall \mathcal{J} \subseteq \mathcal{J}' \quad \forall j \in \mathbb{I} \quad (\text{SCD-C, PC})$

back

## Welfare and Pareto weights

- Welfare:

$$\mathcal{W}(\mathbb{J}) = \sum_{i \in \mathbb{I}} \omega_i u(c_i)$$

- Pareto weights  $\omega_i$ :

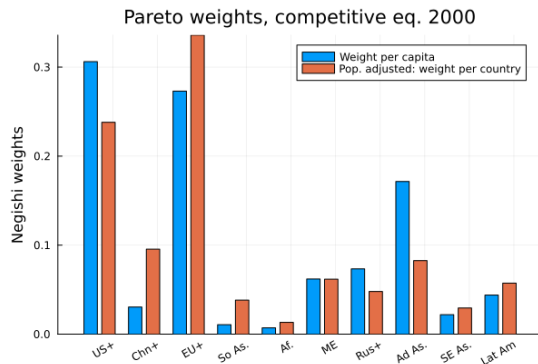
$$\omega_i = \frac{1}{u'(\bar{c}_i)}$$

for  $\bar{c}_i$  consumption in initial equilibrium  
“without climate change“, i.e. year = 2020

- Imply no redistribution motive in  $t = 2020$

$$\omega_i u'(\bar{c}_i) = \omega_j u'(\bar{c}_j) \quad \forall i, j \in \mathbb{I}$$

- Climate change, taxation, and climate agreement (tax + tariffs) have redistributive effects  
 $\Rightarrow$  change distribution of  $c_i$



back

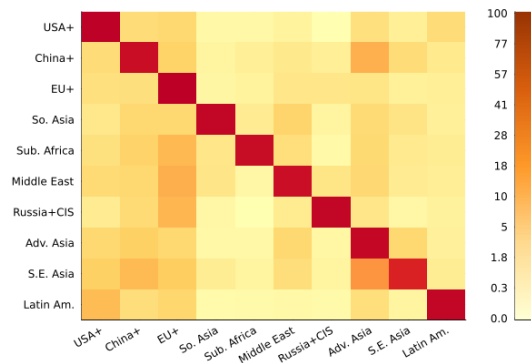


# Quantification – Trade model

- Armington Trade model:

$$s_{ij} \equiv \frac{c_{ij}p_{ij}}{c_i\mathbb{P}_i} = a_{ij} \frac{((1+t_{ij})\tau_{ij}p_j)^{1-\theta}}{\sum_k a_{ik}((1+t_{ik})\tau_{ik}p_k)^{1-\theta}}$$

- CES  $\theta = 5.63$  estimated from a gravity regression
- Iceberg cost  $\tau_{ij}$  as projection of distance  
 $\log \tau_{ij} = \beta \log d_{ij}$
- Preference parameters  $a_{ij}$  identified as remaining variation in the trade share  $s_{ij}$   
 $\Rightarrow$  policy invariant


[back](#)

## Step 0: Competitive equilibrium & Trade

- ▶ Each household in country  $i$  maximize utility and firms maximize profit
- ▶ Standard trade model results:
  - Consumption and trade:

$$s_{ij} = \frac{c_{ij}p_{ij}}{c_i p_i} = a_{ij} \frac{(\tau_{ij}(1+t_{ij}^b)p_j)^{1-\theta}}{\sum_k a_{ik}(\tau_{ik}(1+t_{ik}^b)p_k)^{1-\theta}} \quad \& \quad p_i = \left( \sum_j a_{ij}(\tau_{ij}p_j)^{1-\theta} \right)^{\frac{1}{1-\theta}}$$

- Energy consumption doesn't internalize climate damage:

$$p_i MPe_i = q^e$$

- Inequality, as measured in local welfare units:

$$\lambda_i = u'(c_i)$$

- “Local Social Cost of Carbon”, for region  $i$

$$LCC_i = \frac{\partial \mathcal{W}_i / \partial \mathcal{E}}{\partial \mathcal{W}_i / \partial c_i} = \frac{\psi_i^{\mathcal{E}}}{\lambda_i} = \Delta_i \gamma (T_i - T_i^*) p_i y_i \quad (> 0 \text{ for warm countries})$$

## Step 1: World First-best policy

- Maximizing welfare of the world Social Planner:

$$\mathcal{W} = \max_{\{\mathbf{t}, \mathbf{e}, \mathbf{q}\}_i} \sum_{i \in \mathbb{I}} \omega_i u(c_i) = \sum_{\mathbb{I}} \mathcal{W}_i$$

- Full array of instruments: cross-countries lump-sum transfers  $\mathbf{t}_i^{ls}$ , individual carbon taxes  $\mathbf{t}_i^f$  on energy  $e_i^f$ , unrestricted bilateral tariffs  $\mathbf{t}_{ij}^b$
  - Budget constraint:  $\sum_i \mathbf{t}_i^{ls} = \sum_i \mathbf{t}_i^f e_i^f + \sum_{i,j} \mathbf{t}_{ij}^b c_{ij} \tau_{ij} p_j$
- Maximize welfare subject to
- Market clearing for good  $[\mu_i]$ , market clearing for energy  $\mu^e$

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## Step 1: World First-best policy

### ► Social planner results:

- Consumption:

$$\omega_i u'(c_i) = \left[ \sum_j a_{ij} (\tau_{ij} \omega_j \mu_j)^{1-\theta} \right]^{\frac{1}{1-\theta}} = \mathbb{P}_i \qquad \omega_i \frac{u'(c_i)}{\mathbb{P}_i} = \bar{\lambda}$$

- Energy use:

$$\omega_i \mu_i MPe_i = \mu^e + SCC$$

- Social cost of carbon:

$$SCC = \sum_j \omega_j \Delta_j \gamma (T_i - T_i^*) y_j \mu_j$$

- Decentralization:

large transfers to equalize marg. utility + carbon tax =  $SCC$

$$t^e = SCC \qquad t_i^{lb} = c_i^* \mathbb{P}_i - w_i \ell_i + \pi_i^f \qquad s.t. \quad u'(c_i^*) = \bar{\lambda} \mathbb{P}_i / \omega_i$$

## Step 2: World optimal Ramsey policy

- Maximizing welfare of the world Social Planner:

$$\mathcal{W} = \max_{\{\mathbf{t}, \mathbf{e}, \mathbf{q}\}_i} \sum_{i \in \mathbb{I}} \omega_i u(c_i) = \sum_{\mathbb{I}} \mathcal{W}_i$$

- One single instrument: uniform carbon tax  $\mathbf{t}^f$  on energy  $e_i^f$
  - Rebate tax lump-sum to HHs  $\mathbf{t}_i^L = \mathbf{t}^e e_i^f + \mathbf{t}^e e_i^c$
- Ramsey policy: Primal approach, maximize welfare subject to
  - Budget constraint  $[\lambda_i]$ , Market clearing for good  $[\mu_i]$ , market clearing for energy
  - Optimality (FOC) conditions for good demands  $[\eta_{ij}]$ , energy demand  $[v_i]$  & supply  $[\theta_i]$ , etc.
  - Trade-off faced by the planner:
    - (i) Correcting climate externality, (ii) Redistributive effects, (iii) Distort energy demand and supply (iv) Distort good demand

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## Step 2: World optimal Ramsey policy

- The planner takes into account

- (i) the **marginal value of wealth**  $\lambda_i$
- (ii) the **shadow value of good  $i$** , from market clearing,  $\mu_i$ :
- (iii) the **shadow value of bilateral trade  $ij$** , from household FOC,  $\eta_{ij}$ :

w/ free trade  $u'(c_i) = \lambda_i$

vs. w/ Armington trade  $u'(c_i) = \lambda_i \left( \sum_{j \in \mathbb{I}} a_{ij} (\tau_{ij} p_j)^{1-\theta} \left[ 1 + \frac{\omega_j}{\omega_i} \frac{\mu_j}{\lambda_i} - \frac{\eta_{ij}}{\theta \lambda_i} (1 - s_{ij}) \right]^{1-\theta} \right)^{\frac{1}{1-\theta}}$

- Relative welfare weights, representing inequality

$$\hat{\lambda}_i = \frac{\omega_i \lambda_i}{\bar{\lambda}} = \frac{\omega_i u'(c_i)}{\frac{1}{I} \sum_{j \in \mathbb{I}} \omega_j u'(c_j)} \leq 1 \quad \Rightarrow \quad \text{ceteris paribus, poorer countries have higher } \hat{\lambda}_i$$

## Step 2: Optimal policy – Social Cost of Carbon

► Key objects: Local vs. Global Social Cost of Carbon:

- Marginal cost of carbon  $\psi_i^\mathcal{E}$  for country  $i$
- “Local social cost of carbon” (LCC) for region  $i$ :

$$LCC_i := \frac{\partial \mathcal{W}_i / \partial \mathcal{E}}{\partial \mathcal{W}_i / \partial w_i} = \frac{\psi_i^\mathcal{E}}{\lambda_i} = \Delta_i \gamma (T_i - T_i^*) y_i p_i$$

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- Social Cost of Carbon for the planner:

$$SCC := \frac{\partial \mathcal{W} / \partial \mathcal{E}}{\partial \mathcal{W} / \partial w} = \frac{\sum_{\mathbb{I}} \omega_i \psi_i^\mathcal{E}}{\frac{1}{I} \sum_{\mathbb{I}} \omega_i \lambda_i}$$

- Social Cost of Carbon integrates these inequalities:

$$SCC = \sum_{\mathbb{I}} \hat{\lambda}_i LCC_i = \sum_{\mathbb{I}} LCC_i + \mathbb{Cov}_i(\hat{\lambda}_i, LCC_i)$$



## Step 2: Optimal policy – Other motives

### ► Taxing fossil energy has additional redistributive effects:

1. Through energy markets: distort supply, lowers eq. fossil price, benefit net importers
2. Distort energy demand, of countries that need more or less energy
3. Reallocate goods production, which is then supplied internationally

$$\text{Supply Redistrib}^{\circ sb} + \text{Demand Distort}^{\circ sb} - \text{Trade effect}^{sb} = \underbrace{C_{EE}^f}_{\text{agg. supply inv. elast}^y} \underbrace{\text{Cov}_i(\hat{\lambda}_i, e_i^f - e_i^x)}_{\text{energy T-o-T redistrib}^{\circ}} - \underbrace{\text{Cov}_i\left(\hat{v}_i, \frac{q^f(1-s_i^e)}{\sigma_i e_i}\right)}_{\text{demand distortion}} - q^f \underbrace{\mathbb{E}_j[\hat{\mu}_j]}_{\text{good T-o-T redistrib}^{\circ}}$$

○ Params:  $C_{EE}^f$  agg. fossil inv. elasticity,  $s_i^e$  energy cost share and  $\sigma_i$  energy demand elasticity

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◦ Params:  $C_{EE}^f$  agg. fossil inv. elasticity,  $s_i^e$  energy cost share and  $\sigma_i$  energy demand elasticity

### ► Proposition 2: Optimal fossil energy tax:

$$\Rightarrow \quad \mathfrak{t}^f = \text{SCC}^{sb} + \text{Supply Redistribution}^{sb} + \text{Demand Distortion}^{sb} - \text{Trade effect}^{sb}$$

– Reexpressing demand terms:

$$\mathfrak{t}^e = \left(1 + \text{Cov}_i\left(\widehat{\lambda}_i^w, \frac{\sigma_i e_i}{1-s_i^e}\right)\right)^{-1} \left[ \sum_{\mathbb{I}} \text{LCC}_i + \text{Cov}_i(\widehat{\lambda}_i^w, \text{LCC}_i) + C_{EE}^f \text{Cov}_i(\widehat{\lambda}_i^w, e_i^f - e_i^x) - q^f \mathbb{E}_j[\widehat{\mu}_j] \right]$$

## Step 3: Ramsey Problem with participation constraints

- ▶ Consider that countries can “exit” climate agreement.
- ▶ For a climate “club” of  $\mathbb{J} \subset \mathbb{I}$  countries:
  - Countries  $i \in \mathbb{J}$  are subject to a carbon tax  $\tau^f$
  - Countries  $i \in \mathbb{J}$  can unilaterally leave, subject to retaliation tariff  $\tau^{b,r}$  on goods and get consumption  $\tilde{c}_i$
  - Countries  $i \notin \mathbb{J}$  trade in goods subject to tariff  $\tau^b$  with club members and countries outside the club. They still trade with the club members in energy at price  $q^f$

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  - Countries  $i \notin \mathbb{J}$  trade in goods subject to tariff  $t^b$  with club members and countries outside the club. They still trade with the club members in energy at price  $q^f$
- ▶ Participation constraints:

$$u(c_i) \geq u(\tilde{c}_i) \quad [\nu_i]$$

- ▶ Welfare:

$$\mathcal{W} = \max_{\{t, e, q\}_i} \sum_{\mathbb{J}} \omega_i u(c_i) + \sum_{\mathbb{J}^c} \alpha \omega_i u(c_i)$$

## Step 3: Ramsey Problem with participation constraints

### ► Participation constraints

$$u(c_i) \geq u(\tilde{c}_i) \quad [\nu_i]$$

### ► Proposition 3.1: Second-Best social valuation with participation constraints

- Participation incentives change our measure of inequality

$$\text{w/ trade:} \quad \omega_i(1+\nu_i)u'(c_i) = \left( \sum_{j \in \mathbb{I}} a_{ij}(\tau_{ij}p_j)^{1-\theta} \left[ \omega_i \tilde{\lambda}_i + \omega_j \tilde{\mu}_j + \tilde{\eta}_{ij}(1-s_{ij}) \right] \right)^{1-\theta} \frac{1}{1-\theta}$$

$$\Rightarrow \quad \hat{\tilde{\lambda}}_i = \frac{\omega_i(\tilde{\lambda}_i + \tilde{\mu}_i)}{\frac{1}{J} \sum_{j \in \mathbb{J}} \omega_i(\tilde{\lambda}_i + \tilde{\mu}_i)} \neq \hat{\lambda}_i$$

$$\text{vs. w/o trade} \quad \hat{\tilde{\lambda}}_i = \frac{\omega_i(1+\nu_i)u'(c_i)}{\frac{1}{J} \sum_{j \in \mathbb{J}} \omega_j(1+\nu_j)u'(c_j)} \neq \hat{\lambda}_i$$

- Similarly, the “effective Pareto weights” are  $\alpha\omega_i$  for countries outside the club  $i \notin \mathbb{J}$  and  $\omega_i(\alpha - \nu_i)$  for retaliation policy on  $i \in \mathbb{J}$

## Step 3: Participation constraints & Optimal policy

### ► Proposition 3.2: Second-Best taxes:

- Taxation with imperfect instruments:
  - Climate change & general equilibrium effects on fossil market affects all countries  $i \in \mathbb{I}$
  - Need to adjust for the "outside" countries  $i \notin \mathbb{J}$  not subject to the tax, which weight on the energy market as  $\vartheta_{\mathbb{J}^c} \approx \frac{E_{\mathbb{J}^c}}{E_{\mathbb{I}}} \frac{\nu \sigma}{q^f (1-s^f)}$   
with  $\nu$  fossil supply elasticity,  $\sigma$  energy demand elasticity and  $s^f$  energy cost share.
- Optimal fossil energy tax  $t^f(\mathbb{J})$ :

$$\Rightarrow t^f(\mathbb{J}) = \text{SCC} + \text{SVF}$$

$$= \frac{1}{1 - \vartheta_{\mathbb{J}^c}} \sum_{i \in \mathbb{I}} \tilde{\lambda}_i \text{LCC}_i + \frac{1}{1 - \vartheta_{\mathbb{J}^c}} C_{EE}^f \sum_{i \in \mathbb{I}} \tilde{\lambda}_i (e_i^f - e_i^x) - \sum_{i \in \mathbb{J}} \tilde{\lambda}_i \frac{q^f (1-s_i^f)}{\sigma}$$

- Optimal tariffs/export taxes  $t^{b,r}(\mathbb{J})$  and  $t^b(\mathbb{J})$ : In search for a closed-form expression  
As of now, only opaque system of equations (fixed point w/ demand/multipliers)

## Welfare decomposition

### ► Armington model of trade with energy:

- Linearized market clearing

$$\begin{aligned} \left( \frac{dp_i}{dp_i} + \frac{dy_i}{y_i} \right) = \sum_k t_{ik} \left[ \left( \frac{p_k y_k}{v_k} \right) (d \ln p_k + d \ln y_k) + \frac{q^f e_k^x}{v_k} d \ln e_k^x - \frac{q^f e_k^f}{v_k} d \ln e_k^f + \frac{q^f (e_k^x - e_k^f)}{v_k} d \ln q^f \right. \\ \left. + \theta \sum_h (s_{kh} d \ln t_{kh} - (1 + s_{ki}) d \ln t_{ki}) + (\theta - 1) \sum_h (s_{kh} d \ln p_h - d \ln p_i) \right] \end{aligned}$$

- Fixed point for price level  $d \ln p_i$

$$\begin{aligned} \left[ (\mathbf{I} - \mathbf{T} \odot \mathbf{v}^y) [\mathbf{I} - \alpha^{y,p} \odot \mathbf{I}] + \mathbf{T} (v^{e^x} \odot \frac{1}{v}) + \mathbf{T} v^{e^f} \frac{\sigma^y}{1 - s^e} - (\theta - 1) (\mathbf{TS} - \mathbf{T}') - \left( (\mathbf{I} - \mathbf{T} \odot \mathbf{v}^y) \alpha^{y,z} - \frac{\sigma^y}{1 - s^e} \right) \odot \bar{\gamma} \mathbf{I} \odot \left( \frac{\lambda^x}{v} \right)' \right] d \ln \mathbf{p} = \\ \left[ - (\mathbf{I} - \mathbf{T} \odot \mathbf{v}^y) \alpha^{y,qf} + \mathbf{T} (v^{e^x} \odot \frac{1}{v} + v^{e^f} \frac{\sigma^y}{1 - s^e} + v^{ne}) - \left( (\mathbf{I} - \mathbf{T} \odot \mathbf{v}^y) \alpha^{y,z} - \frac{\sigma^y}{1 - s^e} \right) \bar{\gamma} \frac{1}{v} \right] d \ln q^f \\ + \left[ - (\mathbf{I} - \mathbf{T} \odot \mathbf{v}^y) \alpha^{y,qf} + \mathbf{T} (v^{e^f} \odot \frac{\sigma^y}{1 - s^e}) \right] \odot \mathbf{J} d \ln \mathbf{t}^e + \theta (\mathbf{TS} \odot \mathbf{J} \odot d \ln \mathbf{t}^b - \mathbf{T} (\mathbf{1} + \mathbf{S}') \odot (\mathbf{J} \odot d \ln \mathbf{t}^b)') \end{aligned}$$

## Quantification – Firms

- Production function  $y_i = \mathcal{D}_i^y(T_i) z_i F(k, \varepsilon(e^f, e^r))$

$$F_i(\varepsilon(e^f, e^c, e^r), \ell) = \left[ (1 - \epsilon)^{\frac{1}{\sigma_y}} (\bar{k}^\alpha \ell^{1-\alpha})^{\frac{\sigma_y-1}{\sigma_y}} + \epsilon^{\frac{1}{\sigma_y}} \left( z_i^e \varepsilon_i(e^f, e^c, e^r) \right)^{\frac{\sigma_y-1}{\sigma_y}} \right]^{\frac{\sigma_y}{\sigma_y-1}}$$

$$\varepsilon_i(e^f, e^c, e^r) = \left[ (\omega^f)^{\frac{1}{\sigma_e}} (e^f)^{\frac{\sigma_e-1}{\sigma_e}} + (\omega^c)^{\frac{1}{\sigma_e}} (e^c)^{\frac{\sigma_e-1}{\sigma_e}} + (\omega^r)^{\frac{1}{\sigma_e}} (e^r)^{\frac{\sigma_e-1}{\sigma_e}} \right]^{\frac{\sigma_e}{\sigma_e-1}}$$

- Calibrate TFP  $z_i$  to match  $y_i = GDP_i$  per capita in 2019-23 (avg. PPP).
- Technology:  $\omega^f = 56\%$ ,  $\omega^c = 27\%$ ,  $\omega^r = 17\%$ ,  $\epsilon = 12\%$  for all  $i$
- Calibrate  $(z_i^e)$  to match Energy/GDP  $q^e e_i / p_i y_i$

- Damage functions in production function  $y$ :

$$\mathcal{D}_i^y(T) = e^{-\gamma_i^{\pm, y} (T - T_i^*)^2}$$

- Asymmetry in damage to match empirics with  $\gamma^y = \gamma^{+, y} \mathbb{1}_{\{T > T_i^*\}} + \gamma^{-, y} \mathbb{1}_{\{T < T_i^*\}}$
- Today  $\gamma_i^{\pm, y} = \bar{\gamma}^{\pm, y}$  &  $T_i^* = \bar{\alpha} T_{it_0} + (1 - \bar{\alpha}) T^*$



## Quantification – Energy markets

- ▶ Fossil production  $e_{it}^x$  and reserve  $\mathcal{R}_{it}$ 
  - Cost  $\mathcal{C}_i(e^x, \mathcal{R}) = \frac{\bar{\nu}_i}{1+\nu_i} \left(\frac{e^x}{\mathcal{R}}\right)^{1+\nu_i} \mathcal{R}$
  - Now:  $\bar{\nu}_i$  to match extraction data  $e_i^x$ ,  $\mathcal{R}_{it}$  calibrated to *proven reserves* data from BP.  $\nu_i$  extraction cost curvature to match profit  $\pi_i^f = \frac{\bar{\nu}_i \nu_i}{1+\nu_i} \left(\frac{e_i^x}{\mathcal{R}_i}\right)^{\nu_i} \mathcal{R}_i \mathbb{P}_i$
  - Future: Choose  $(\bar{\nu}_i, \nu_i, \mathcal{R}_i)$  to match marginal cost  $\mathcal{C}_e$  & extraction data  $e_i^x$  (BP, IEA)
- ▶ Coal and Renewable: Production  $\bar{e}_i^r, \bar{e}_i^x$  and price  $q_i^c, q_i^r$ 
  - Calibrate  $q_i^c = z^c \mathbb{P}_i, q_i^r = z^r \mathbb{P}_i$   
Choose  $z_i^c, z_i^r$  to match the energy mix  $(e_i^f, e_i^c, e_i^r)$
- ▶ Population dynamics
  - Match UN forecast for growth rate / fertility

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# Calibration

**Table:** Baseline calibration (\* = subject to future changes) [back](#)

<i>Technology &amp; Energy markets</i>			
$\alpha$	0.35	Capital share in $F(\cdot)$	Capital/Output ratio
$\epsilon$	0.12	Energy share in $F(\cdot)$	Energy cost share (8.5%)
$\sigma$	0.3	Elasticity capital-labor vs. energy	Complementarity in production (c.f. Bourany 2022)
$\omega^f$	0.56	Fossil energy share in $e(\cdot)$	Oil-gas/Energy ratio
$\omega^c$	0.27	Coal energy share in $e(\cdot)$	Coal/Energy ratio
$\omega^r$	0.17	Non-carbon energy share in $e(\cdot)$	Non-carbon/Energy ratio
$\sigma_e$	2.0	Elasticity fossil-renewable	Slight substitutability & Study by Stern
$\delta$	0.06	Depreciation rate	Investment/Output ratio
$\bar{g}$	0.01*	Long run TFP growth	Conservative estimate for growth
<i>Preferences &amp; Time horizon</i>			
$\rho$	0.015	HH Discount factor	Long term interest rate & usual calib. in IAMs
$\eta$	1.5	Risk aversion	Standard Calibration
$n$	0.0035	Long run population growth	Average world population growth
<i>Climate parameters</i>			
$\xi^f, \xi^c$	2.761 & 3.961	Emission factor – Oil+nat. gas vs. Coal	Conversion 1 MTOE $\Rightarrow$ 1 MT CO <sub>2</sub>
$\chi$	2.3/1e6	Climate sensitivity	Pulse experiment: 100 GtC $\equiv$ 0.23° C medium-term warming
$\delta_s$	0.0004	Carbon exit from atmosphere	Pulse experiment: 100 GtC $\equiv$ 0.15° C long-term warming
$\gamma^\oplus$	0.003406	Damage sensitivity	Nordhaus, Barrage (2023)
$\alpha^T$	0.5	Weight historical climate for optimal temp.	Marginal damage correlated with initial temp.
$T^*$	14.5	Optimal yearly temperature	Average yearly temperature/Developed economies

## Matching country-level moments

**Table:** Heterogeneity across countries

Dimension of heterogeneity	Model parameter	Matched variable from the data	Source
Population	Country size $\mathcal{P}_i$	Population	UN
TFP/technology/institutions	Firm productivity $z_i$	<b>GDP per capita (2019-PPP)</b>	WDI
Productivity in energy	Energy-augmenting productivity $z_i^e$	Energy cost share	SRE
Cost of coal energy	Cost of coal production $C_i^c$	Energy mix/coal share $e_i^c/e_i$	SRE
Cost of non-carbon energy	Cost of non-carbon production $C_i^r$	Energy mix/coal share $e_i^r/e_i$	SRE
Local temperature	Initial temperature $T_{it_0}$	<b>Pop-weighted yearly temperature</b>	Burke et al
Pattern scaling	Pattern scaling $\Delta_i$	Sensitivity of $T_{it}$ to world $\bar{T}_t$	Burke et al
Oil-gas reserves	Reserves $\mathcal{R}_i$	Proved Oil-gas reserves	SRE
Cost of oil-gas extraction	Slope of extraction cost $\bar{\nu}_i$	<b>Oil-gas extracted/produced <math>e_i^x</math></b>	SRE
Cost of oil-gas extraction	Curvature of extraction cost $\nu_i$	Profit $\pi_i^f$ / energy rent	WDI
Trade costs	Distance iceberg costs $\tau_{ij}$	Geographical distance $\tau_{ij} = d_{ij}^\beta$	CEPII
Armington preferences	CES preferences $a_{ij}$	Trade flows	CEPII

## Theoretical investigation: decomposing the welfare effects

### ► Experiment:

- Start from the equilibrium where carbon tax  $t_j^\varepsilon = 0$ ,  $t_{jk}^b = 0$ ,  $\forall j$ ,
- Change in welfare: Linear approximation around that point  $\Rightarrow$  small changes in carbon tax  $dt_j^\varepsilon$ ,  $\forall j$  and tariffs  $dt_{j,k}^b$ ,  $\forall j, k$  for a club  $J_i$

$$\frac{d\mathcal{U}_i}{u'(c_i)} = \eta_i^c d \ln p_i + \left[ -\eta_i^c \tilde{\gamma}_i \frac{1}{\bar{\nu}} - \eta_i^c s_i^e s_i^f + \eta_i^\pi \left(1 + \frac{1}{\bar{\nu}}\right) \right] d \ln q^f - \left[ \eta_i^c s_i^e (s_i^c + s_i^r) + \eta_i^\pi \frac{1}{\bar{\nu}} + 1 \right] d \ln \mathbb{P}_i$$

- GE effect on energy markets  $d \ln q^f \approx \bar{\nu} d \ln E^f + \dots$ , due to taxation

$$d \ln q^f = - \frac{\bar{\nu}}{1 + \bar{\gamma} + \text{Cov}_i(\tilde{\lambda}_i^f, \tilde{\gamma}_i) + \bar{\nu} \bar{\lambda}^{\sigma f}} \sum_i \tilde{\lambda}_i^f J_i dt^\varepsilon + \sum_i \beta_i d \ln p_i$$

- Climate damage  $\tilde{\gamma}_i = \gamma(T_i - T_i^*) T_i s^{E/S}$
- Trade and leakage effect: GE impact of  $t_j^\varepsilon$  and  $t_{jk}^b$  on  $y_i$  and  $p_i$

◦ Params:  $\sigma$  energy demand elast<sup>y</sup>,  $s^e$  energy cost share,  $\bar{\nu}$  energy supply inverse elas<sup>y</sup>

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## Climate agreement and welfare

Recover 90% of welfare gains, i.e. 5% out of 5.5% conso equivalent. [back](#)

