Optimal Climate Policy with Incomplete Markets

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Motivation

- Governments are doing little about climate change. Many are walking back climate commitments — but eventually, action will be unavoidable.
- **Carbon tax** is a textbook solution, but:
  - → may disproportionately burden low-income households
  - → risks exacerbating inequality
- Raises **two key policy dilemmas**:
  - → Should governments scale back climate ambitions because of inequality?
  - → Or should the broader tax system be adjusted to align climate action with distributional goals?

What we do

Introduction

- **Develop** a fiscal climate-economy model à la Barrage (2020), with inequality and idiosyncratic labor-income risk à la Aiyagari (1994)

- **Theoretically:**

  → **Characterize** the optimal carbon tax in an incomplete-market setting
  → Compare with the first-best Pigouvian benchmark

- **Quantitatively:**

  → Calibrate the model to match US macro data, inequality, and income risk
  → **Solve the Ramsey problem** to study:

    - Optimal climate policy
    - Its effects on the economy and welfare

What we find

Introduction

1. **Theory:**

   → Distortions of intra and intertemporal margins **introduce a wedge** between Piguovian rule and optimal carbon tax.

2. **Quantitative Model:**

   → Optimal carbon tax is essentially **equal to the Pigou one**.
   → Holds **regardless** of flexibility in other instruments.
   → True even when other tools have large economic effects.

3. **Link to policy:**

   → Relative to IPCC's business as usual scenario the optimal policy leads to **5% welfare gains**.
   → **Asymmetry** of welfare effects. Postponing has disproportionate welfare costs.

Where we fit

Introduction

We contribute to three strands of literature:

- Optimal climate policy with distortionary taxation (e.g., Bovenberg and de Mooij, 1994; Jacobs and de Mooij, 2015; Barrage, 2020; Douenne et al, 2023)
  - → **Our paper**: introduce incomplete markets
- Distributional effects of climate policy (e.g., Känzig, 2023; Fried et al, 2018 and 2023; Benmir and Roman, 2022)
  - → **Our paper**: study optimal policy, analyze the transition, and account for welfare benefits of mitigation
- Optimal fiscal policy with incomplete markets (e.g., Conesa et al, 2009; Dyrda and Pedroni, 2023)
  - → **Our paper**: introduce climate change and study climate policy

The Model

Environment

Model

- Time is discrete and indexed by t.
- Population at times t: N_t
- Ex ante heterogeneous households:
  - → type i is characterized by their initial productivity $e_{i0} \in E$ and their initial asset holdings $a_{i0} \in A_0$
  - → α_i: the fraction of type i households, with $\sum_i \alpha_i = 1$.
- Productivity evolves stochastically:
  - → household i draws a productivity level $e_{it} \in E$,
  - → $\pi_{it}(e_i^t)$: probability that household i experiences productivity realizations $e_i^t = \{e_{i0}, \ldots, e_{it}\}$

Preferences: consumption, labor, climate

Life-time, expected utility of type-i household:

$$\sum_t \beta^t N_t \sum_{e_i^t} \pi_{it}(e_i^t) u(c_{it}(e_i^t), h_{it}(e_i^t), Z_t),$$

- $\beta \in (0,1)$: the discount factor
- c : consumption
- h : labor
- Z_t: climate variable

Assumption

Climate and consumption-leisure composite are separable i.e. $u_{cZ} = u_{hZ} = 0$.

Budget constraint

Model

Household per-capita assets evolve according to

$$(1 + n_{t+1})a_{it+1}(e_i^t) = (1 + (1 - \tau_{K,t})(r_t - \delta))a_{it}(e_i^{t-1}) + T_t + w_t(1 - \tau_{H,t})e_{it}h_{it}(e_i^t) - c_{it}(e_i^t),$$

- $n_{t+1} = N_{t+1}/N_t - 1$: population growth rate
- w_t, r_t: before-tax wage and interest rate
- $\tau_{K,t}$: capital income tax
- $\tau_{H,t}$: labor income tax
- T_t: lump-sum transfer/tax

Production: Final Goods

Model

- Technology:

$$Y_t = (1 - D(Z_t))A_{1,t}F(K_{1,t}, H_{1,t}, E_t)$$

  → Y : output
  → K : capital
  → H : labor
  → E : energy
  → $D(Z_t)$: production damages from environmental degradation Z

- Firm rents capital and hires labor and energy at factor prices r_t, w_t, and $p_{E,t}$, respectively

Production: Energy Sector

Model

- Technology:

$$E_t = A_{2,t} G(K_{2,t}, H_{2,t}),$$

  → $G(\cdot)$: constant-returns-to-scale technology
  → $K_{2,t}$ and $H_{2,t}$: capital and labor inputs fully mobile across sectors.
  → $A_{2,t}$ denotes total factor productivity in the energy sector

- Energy production generates industrial CO_2 emissions,

$$E_t^M = (1 - \mu_t) E_t,$$

  → μ_t: share of energy generated using clean technologies

- Profits:

$$\mathcal{P}_t = p_{E,t} E_t - \tau_{E,t}(1 - \mu_t) E_t - w_t H_{2,t} - r_t K_{2,t} - \Theta(\mu_t, E_t),$$

  → $\Theta(\mu_t, E_t)$: abating emissions incurs a cost
  → $\tau_{E,t}$: a tax on carbon emissions

Government and Climate

Model

- Government budget:

$$G_t + N_t T_t + R_t B_t = \tau_{H,t} w_t H_t + \tau_{K,t}(r_t - \delta) K_t + \tau_{E,t} E_t^M + B_{t+1},$$

- The climate variable Z_t:

$$Z_t = J(S_0, E_0^M, \ldots, E_t^M, \eta_0, \ldots, \eta_t).$$

→ $\{E_t^M\}$: history of endogenous emissions
→ $\{\eta_t\}$: other exogenous drivers
→ S_0: initial conditions

Competitive Equilibrium

Definition

Given an initial stock of capital K_0 and government debt B_0, a distribution of types i over initial asset holdings a_{i0} and productivity levels e_{i0}, probabilities $\pi_{it}(e_i^t)$, population sizes $\{N_t\}_t$, and a tax policy $\mathcal{T} \equiv \{\tau_{H,t}, \tau_{K,t}, \tau_{I,t}, \tau_{E,t}, T_t\}_{t=0}^{\infty}$, a **competitive equilibrium** consists of individual- and history-specific variables $X_i \equiv \{a_{it+1}(e_i^t), c_{it}(e_i^t), h_{it}(e_i^t)\}_{i,t,e_i^t}$, aggregate variables $X \equiv \{C_t, H_t, H_{1,t}, H_{2,t}, K_{t+1}, K_{1,t}, K_{2,t}, E_t, \mu_t, Z_t, B_{t+1}\}_t$, and a price system $P \equiv \{R_t, w_t, r_t, p_{E,t}\}_t$, such that:

1. households and firms optimize given prices and policies;
2. the government satisfies its intertemporal budget constraint, and debt remains bounded;
3. temperature evolves according to (10); and
4. markets clear, i.e., the following conditions are satisfied:

$$H_t = H_{1,t} + H_{2,t}, \tag{1}$$

$$K_t = K_{1,t} + K_{2,t}, \tag{2}$$

$$C_t + G_t + K_{t+1} + \Theta_t(\mu_t)E_t = \big(1 - D(Z_t)\big)A_{1,t}F(K_{1,t}, H_{1,t}, E_t) + (1-\delta)K_t, \tag{3}$$

$$K_t + B_t = N_t \sum_i \alpha_i \sum_{e_i^{t-1}} \pi_{it-1}(e_i^{t-1})a_{it}(e_i^{t-1}). \tag{4}$$

The economy is on a **balanced-growth path** if all aggregate variables, except temperature Z_t and abatement μ_t, grow at a constant rate and the competitive equilibrium conditions are satisfied.

Theory

Ramsey problem

Theory

We assume the planner has utilitarian preferences given by

$$\mathcal{W} = \sum_i \alpha_i \sum_t \beta^t N_t \sum_{e_i^t} \pi_{it}(e_i^t) u(c_{it}(e_i^t), h_{it}(e_i^t), Z_t)$$

and that it announces and commits to a sequence of policies at time zero.

Definition

Given K_0, B_0, and an initial distribution over asset holdings a_{i0} and productivity levels e_{i0}, for every policy $\mathcal{T}$, **equilibrium allocation rules** $(X_i(\mathcal{T}), X(\mathcal{T}))$ and **equilibrium price rules** $P(\mathcal{T})$ are such that $\{\mathcal{T}, X_i(\mathcal{T}), X(\mathcal{T}), P(\mathcal{T})\}$ constitute a competitive equilibrium. Given a welfare function $\mathcal{W}(\mathcal{T})$, the **Ramsey problem** is to $\max_{\mathcal{T}} \mathcal{W}(\mathcal{T})$ subject to $(X_i(\mathcal{T}), X(\mathcal{T}))$ and $P(\mathcal{T})$ being equilibrium allocation and price rules.

Pigouvian Tax

Theory

Definition

The **Pigouvian tax** is defined as

$$\tau_{E,t}^{Pigou} = \frac{1}{\mathcal{W}_{c,t}} \sum_{j=0}^{\infty} \beta^j \left(\mathcal{W}_{c,t+j} D'_{t+j} A_{1,t+j} F_{t+j} - N_{t+j} \mathcal{W}_{Z,t+j}\right) J_{E_t^M, t+j},$$

where

- $\mathcal{W}_{c,t} = \sum_i \alpha_i \sum_{e_i^t} \pi_{it} u_{cit}$: the marginal utility of consumption, averaged across household types i and histories e_i^t
- $\mathcal{W}_{Z,t} = \sum_i \alpha_i \sum_{e_i^t} \pi_{it} u_{Zit}$: the corresponding average marginal utility of a higher temperature.

Optimal Carbon Tax

Theory

Proposition

The second-best carbon tax satisfies a modified Pigouvian rule:

$$\tau_{E,t}^{SB} = \frac{1}{\nu_t} \sum_{j=0}^{\infty} \beta^j \left(\nu_{t+j} D'_{t+j} A_{1,t+j} F_{t+j} - N_{t+j} \mathcal{W}_{Z,t+j} \right) J_{E_t^M,t+j},$$

where ν_t *is the multiplier on the resource constraint for the final consumption good satisfying:*

$$\nu_t = \mathcal{W}_{c,t} + \sum_i \alpha_i \sum_{e_i^t} \pi_{it} (SD_{it} + LD_{it}),$$

with

$$SD_{i,t} \equiv u_{cc,it} \left(\kappa_{it}^s - \frac{R_t}{1+n_t} \kappa_{it-1}^s \right), \qquad LD_{i,t} \equiv \kappa_{it}^\ell \left(u_{cc,it} w_t (1-\tau_{H,t}) e_{it} + u_{ch,it} \right),$$

and where κ^s *and* κ^ℓ *are the multipliers associated with the household's modified Euler equation and first-order condition for labor supply.*

Optimal Carbon Tax - Intuition

Theory

- Assuming $\{\tau_{H,t}, \tau_{K,t}, T_t\}_{t=0}^{\infty}$ are optimized:

$$\nu_t = \mathcal{W}_{c,t} + \underbrace{\sum_i \alpha_i \sum_{e_i^t} \pi_{it}(SD_{it} + LD_{it})}_{\text{imapact of distortionary taxes}},$$

  where

$$SD_{it} \equiv u_{cc,it}(\lambda_{it}^{EE} - R_t \lambda_{it-1}^{EE}) \qquad \text{(Savings Distortions)}$$

$$LD_{it} \equiv (u_{cc,it} w_t (1 - \tau_{Ht}) e_{it} + u_{ch,it}) \lambda_{it}^{LS} \qquad \text{(Labor Distortions)}$$

  → $SD_{it} = 0$ if household is borrowing constrained
  → $LD_{it} = 0$ if there are no income effects on labor supply

- Constraints on $\{\tau_{H,t}, \tau_{K,t}, T_t\}_{t=0}^{\infty}$ imply additional terms
- To say more about $\tau_{E,t}^{SB}$, we use computational methods

Quantitative Analysis

Calibration strategy

Quantitative Analysis

- Climate model of the world
- Economic model of the US: scaled up to match global GDP and emissions
  - → Inequality and fiscal policy of the US
  - → GDP of the world, but GDP per capita of the US
- Optimal policy of the US if they assume rest of the world follows same climate policy

Climate model

Quantitative Analysis

- We use the model of Dietz and Venmans (2019) to capture two key climate facts: (i) temperature responds quickly and permanently to emissions, and (ii) temperature rises linearly with cumulative emissions

- Global mean temperature Z_t evolves as:

$$Z_{t+1} = Z_t + \epsilon\big(\zeta \mathcal{E}_t - Z_t\big)$$

  where $\zeta = 0.00045$°C/GtCO$_2$, and $\epsilon = 0.5$ governs adjustment speed

- Cumulative emissions $\mathcal{E}_t$ increase with industrial and land-use emissions:

$$\mathcal{E}_{t+1} = \mathcal{E}_t + E_t^M + E_t^{\text{ex}}$$

- Initial values from IPCC (2021) and Global Carbon Project (2022):

$$Z_{2020} = 1.1, \quad \mathcal{E}_{2020} = 2390, \quad E_{2020}^M = 36, \quad E_{2020}^{\text{ex}} = 4$$

Climate damages

Quantitative Analysis

- We model production damages following Dietz and Venmans (2019):

$$D(Z_t) = 1 - \exp\left(-\frac{\alpha_1}{2} Z_t^2\right)$$

- This form yields a damage curve similar to DICE 2023
- $\alpha_1 = 0.01$ implies damages of 2% of GDP at 2°C, and 7.7% at 4°C

Households

Quantitative Analysis

- Preferences over consumption, labor, and climate:

$$u(c,h,Z)=\frac{\left(c^{\gamma}(1-\varsigma h)^{1-\gamma}\right)^{1-\sigma}+\left(1+\alpha_z Z^2\right)^{\sigma-1}}{1-\sigma}$$

- $\{\beta,\gamma,\sigma,\varsigma\}$ calibrated to match:
  - → Capital-output ratio of 2.6 (NIPA, 2009–2019)
  - → Average hours worked = 0.24 (CPS)
  - → Intertemporal elasticity of substitution = $1/1.5$
  - → Average Frisch elasticity = 1.0
- α_z chosen so that 26% of damages directly affect utility (Barrage, 2019)

Calibration: Inequality

Quantitative Analysis

Cross-sectional distributions

	Bottom (%) 0–5	1st	2nd	Quintiles 3rd	4th	5th	Top (%) 95–100	Gini
				Wealth				
Data	−0.5	−0.5	0.8	3.4	8.9	87.4	65.0	0.85
Model	−0.2	0.1	1.7	3.6	6.7	88.1	70.0	0.85
				Earnings				
Data	−0.1	−0.1	3.5	10.8	20.6	65.2	35.3	0.65
Model	0.0	0.1	3.6	12.0	17.7	66.6	37.5	0.65
				Hours				
Data	0.0	2.7	13.8	19.2	27.9	36.4	11.1	0.34
Model	0.0	0.4	11.4	26.1	28.3	33.9	8.9	0.35

Calibration: Labor-Income Risk

Quantitative Analysis

Statistical properties of labor income		
	Target	**Model**
Variance of 1-year growth rate	2.33	2.32
Kelly skewness of 1-year growth rate	-0.12	-0.13
Moors kurtosis of 1-year growth rate	2.65	2.65

- Data for households from Pruitt and Turner (2020)

Production

Quantitative Analysis

- Cobb-Douglas technology for both sectors

$$F(K_{1,t}, H_{1,t}, E_t) = K_{1,t}^{\alpha} H_{1,t}^{1-\alpha-\nu} E_t^{\nu},$$

with $\alpha = 0.3$, and $\nu = 0.04$ (Golosov et al, 2014), and

$$G(K_{2,t}, H_{2,t}) = K_{2,t}^{\alpha_E} H_{2,t}^{1-\alpha_E},$$

with $\alpha_E = 0.6$ (Barrage, 2019)

- Abatement cost function adapted from DICE 2023:

$$\Theta(\mu_t, E_t) = P_t^{\text{back}} \frac{\mu_t^{c_2}}{c_2} E_t,$$

where P_t^{back} is the backstop price. ▸ Backstop Price

Computational method

Quantiative Analysis

- We want to find the time paths $\{\tau_{K,t}, \tau_{H,t}, \tau_{E,t}, T_t\}_{t=0}^{\infty}$ that maximize welfare
- If optimal paths are smooth over time, we can approximate them with polynomials as in Dyrda and Pedroni (2023) ▸ Details
- Polynomial parameters $\rightarrow$ path of fiscal instruments $\rightarrow$ transition to new balanced-growth path $\rightarrow$ welfare
- Optimize welfare by choosing polynomial parameters
- Bypasses the need to rewrite the Ramsey problem recursively

Policy experiments

Quantiative Analysis

We study a government that chooses a **time-varying carbon tax** under three fiscal regimes:

1. Fixed debt-to-GDP, fixed other taxes

   $\rightarrow$ Transfers adjust to balance the budget

2. Flexible debt-to-GDP, fixed other taxes

   $\rightarrow$ Transfers follow a flexible path: optimal to front-load transfers

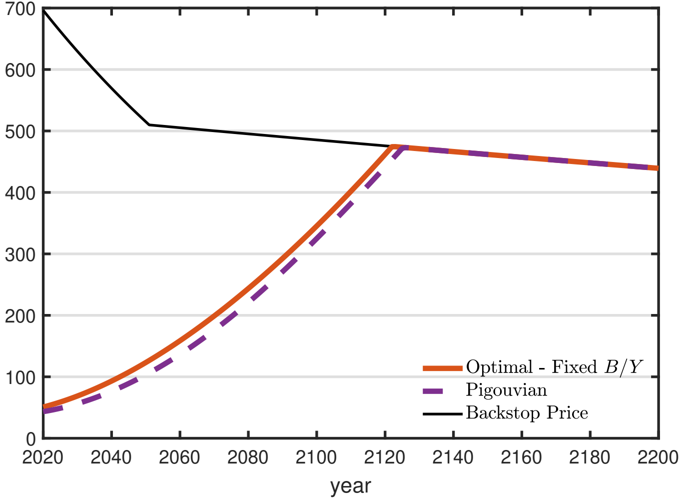
3. Flexible debt-to-GDP, optimal constant labor and capital taxes

   $\rightarrow$ Optimal to increase both taxes $\tau_H = 27.7\% \rightarrow 41.5\%$, and $\tau_K = 33.6\% \rightarrow 44.7\%$

Results

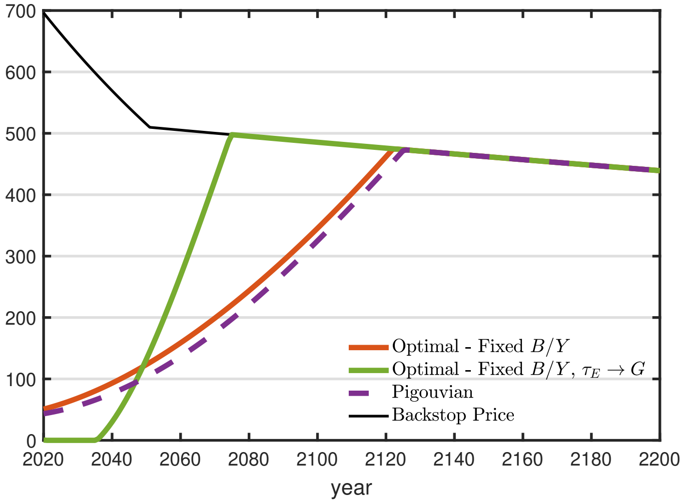
Optimal Carbon Taxes and Backstop Price (in $\$/tCO_2$)

Results



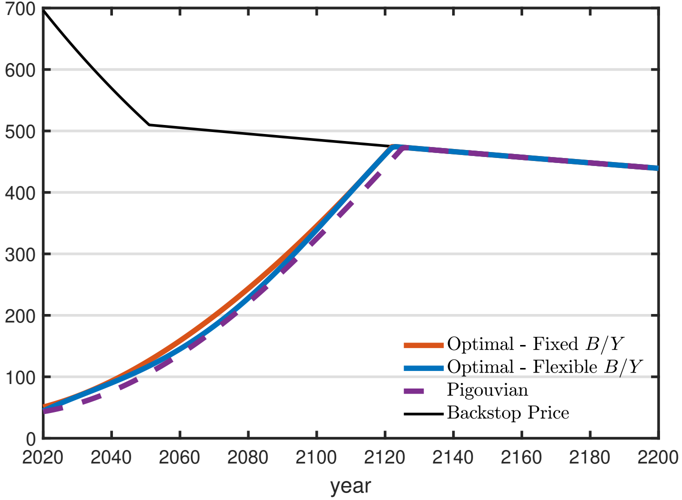
Optimal Carbon Taxes and Backstop Price (in \$/tCO_2)

Results



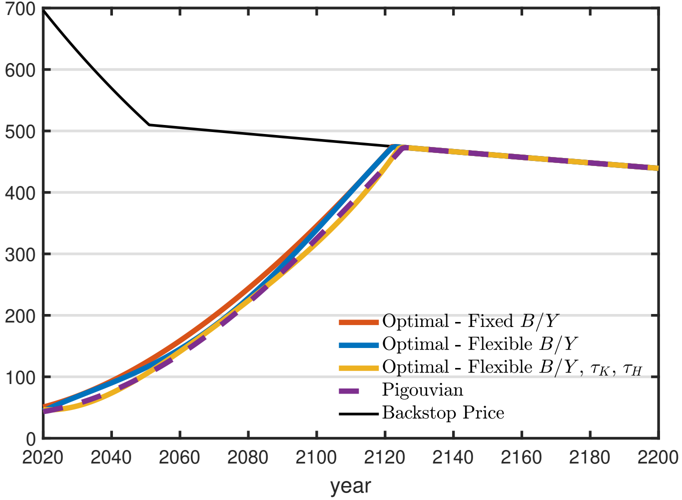
Optimal Carbon Taxes and Backstop Price (in $/tCO_2$)

Results



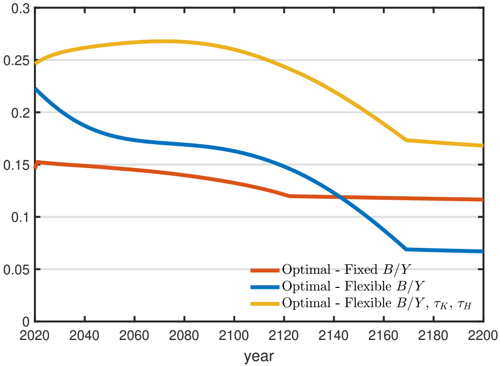
Optimal Carbon Taxes and Backstop Price (in $/tCO_2$) ▸ Decomposition

Results

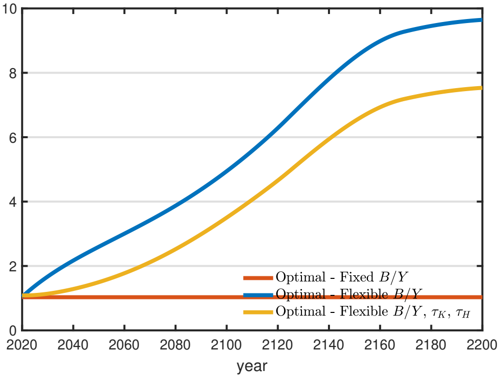


Aggregates

Results



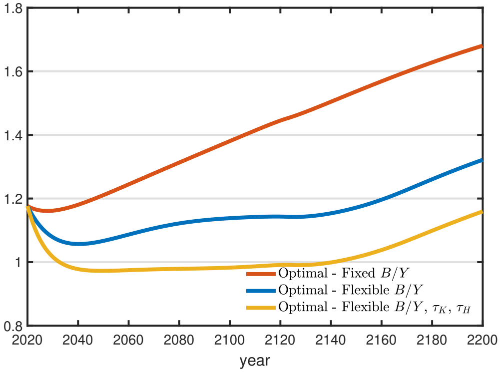
(a) Transfers to Output



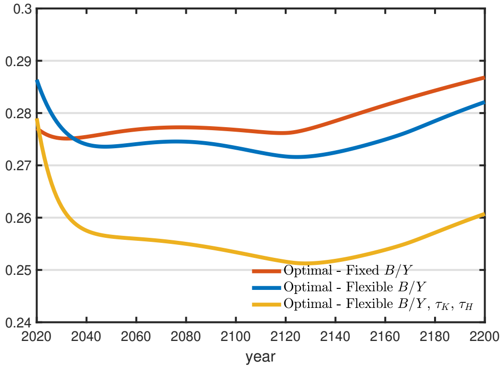
(b) Debt to Output

Aggregates

Results



(c) Capital



(d) Consumption

▸ Exogenous Growth Paths

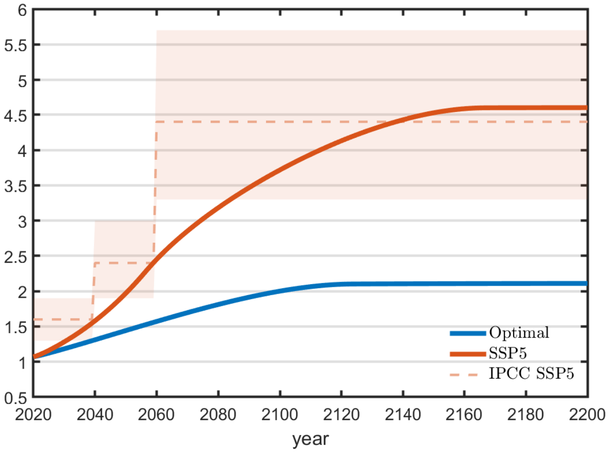
Welfare gains

Results

- We want to compute the welfare gains associated with implementing the optimal policy
- A commonly used benchmark is the **IPCC (2021)'s Shared Socioeconomic Pathway 5 (SSP5)** scenario
- It is supposed to capture a somewhat pessimistic business-as-usual (BAU) scenario

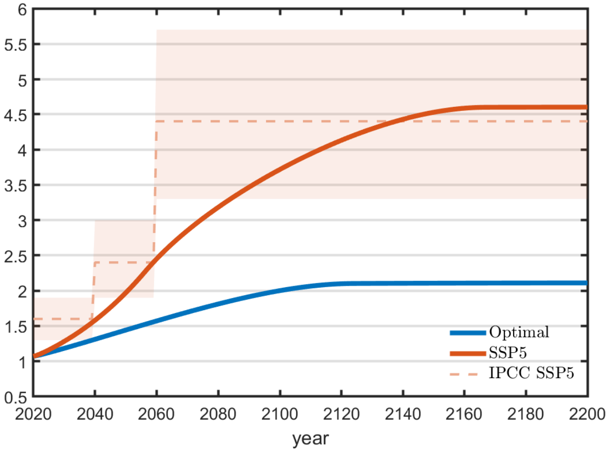
Temperature in BAU Scenario

Results



Temperature in BAU Scenario

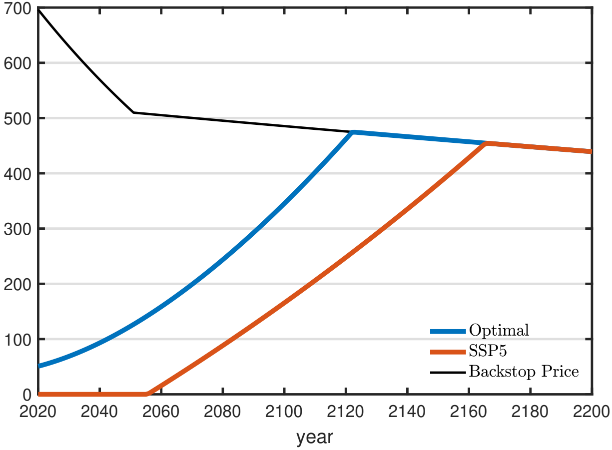
Results



Impose the BAU temepratures on the model by adjusting carbon taxes appropriately.

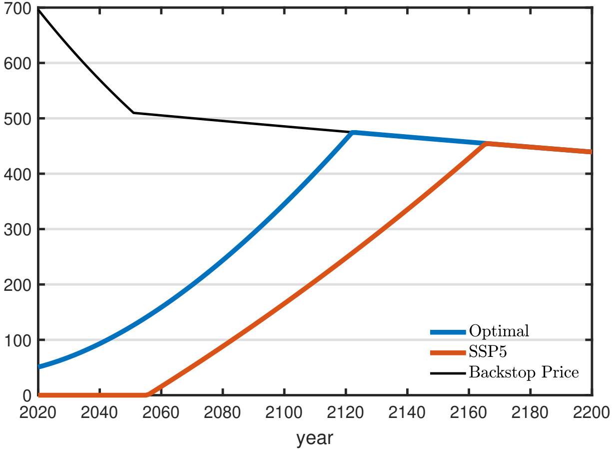
Corresponding Carbon Taxes (in \$/tCO_2)

Results



Corresponding Carbon Taxes (in \$/tCO_2)

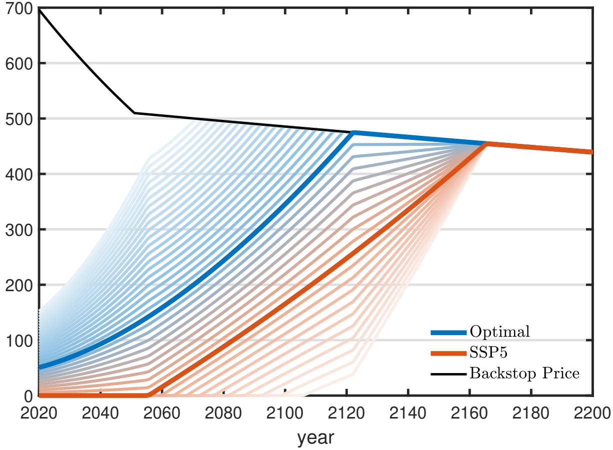
Results



Carbon taxes under SSP5 are postponed by two decades.

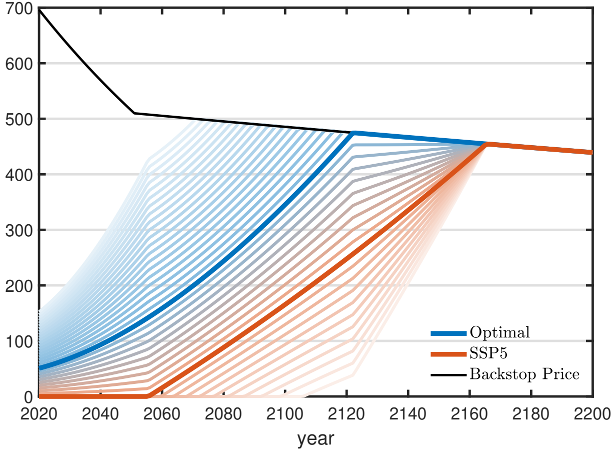
Varying Taxes From One to the Other

Results



Varying Taxes From One to the Other

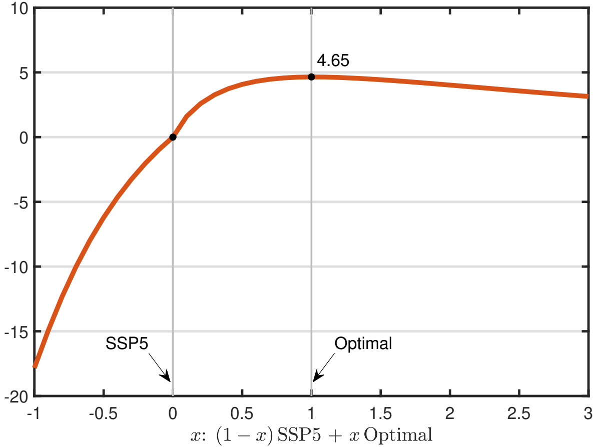
Results



Consider variation in the path of carbon tax according to: $(1 - x) \times \text{SSP5} + x \times \text{Optimal}$

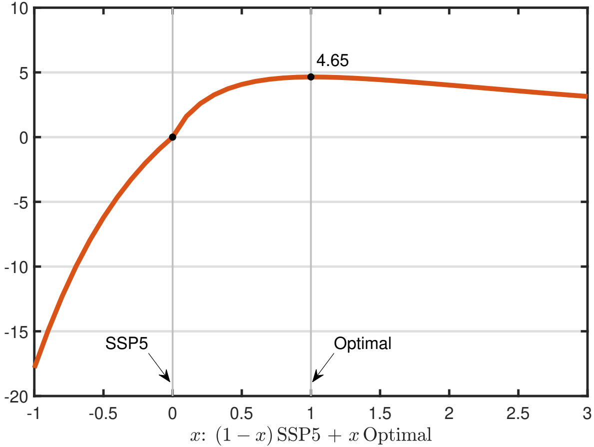
Welfare Gain

Results



Welfare Gain

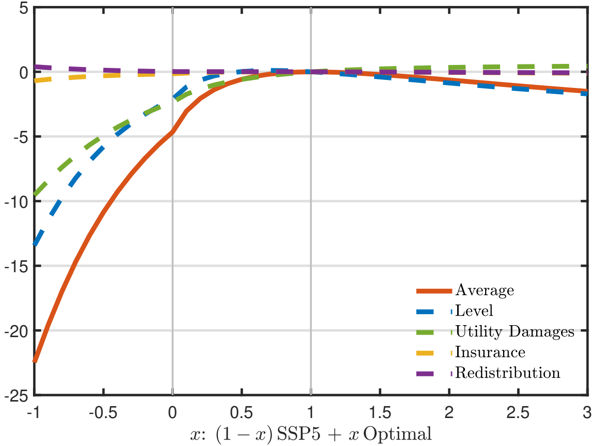
Results



Doing too much not so costly, doing too little could very well be.

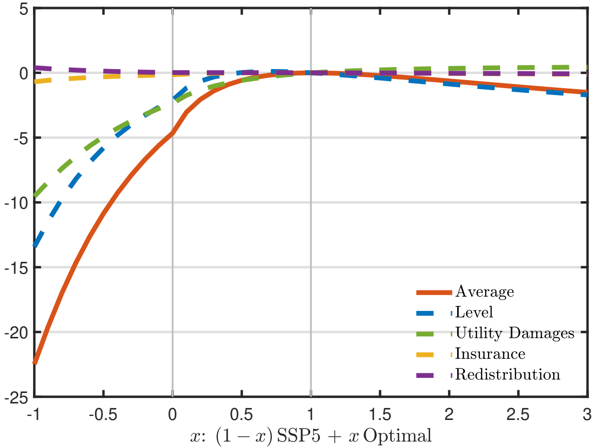
Welfare Decomposition

Results



Welfare Decomposition

Results



Welfare effects driven by efficiency (level) and utility damages. Insurance and redistribution not significantly affected.

Distribution of Gains

Results

Distribution of Gains

Results

Asset Quintile \ Labor Income Quintile	Q1	Q2	Q3	Q4	Q5
Q5	4.70	5.07	4.81	5.25	5.83
Q4	4.59	4.60	4.58	4.58	4.59
Q3	4.59	4.59	4.57	4.57	4.58
Q2	4.58	4.58	4.57	4.57	4.57
Q1	4.58	4.57	4.56	4.56	4.58

Gains shared broadly, but richest households benefited most.

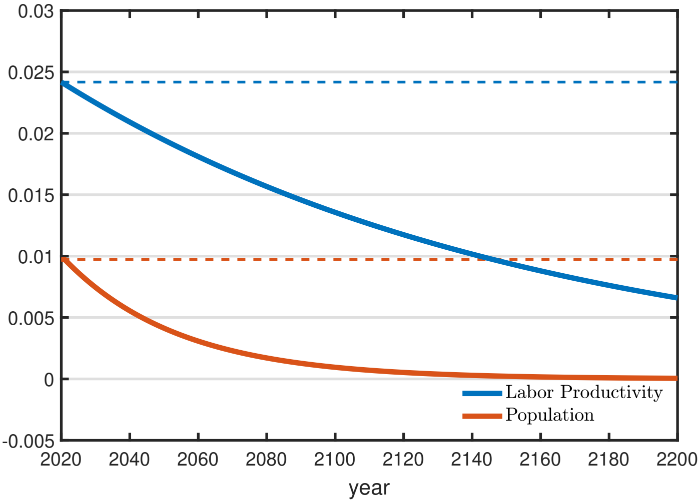
Conclusion

- The optimal carbon tax is quantitatively very close to the social cost of carbon (SCC), even in the presence of fiscal distortions and policy constraints
- This result is robust across fiscal regimes and holds even when other instruments have large economic effects
- Setting the carbon tax too low imposes significantly higher welfare costs than setting it too high
- In the paper, we extend the model to include energy goods that are necessary, results are very similar though welfare gains are even larger

Appendix

Productivity and population growth over transition

Results



Where we fit (2)

Other papers on optimal carbon taxes in an Aiyagari-type models:

- Bourany (2024): cross-country heterogeneity; no other fiscal instruments
- Kubler (2024): constrained-optimal policy à la Dávila et al. (2012); theory-focused, abstracts from redistribution
- Belfiori, Carroll, Hur (2024): constrained-optimal policy; combines theory and quantitative analysis
- Malafry and Brinca (2022): early attempt at full welfare maximization; stylized (2 periods, no other instruments)
- Wöhrmüller (2024): richer model and careful calibration, but fixes other instruments and focuses on steady-state

Our paper: solve for dynamic optimal fiscal policy to maximize social welfare, with a rich calibration and more flexibility over the instruments

Computational Method: Details

- Solving this problem involves searching on the space of sequences $\{\tau_{K,t}, \tau_{H,t}, \tau_{E,t}, T_t\}_{t=0}^{\infty}$
- To reduce the dimensionality of the problem, we follow Dyrda and Pedroni (2023) and parameterize the time paths of fiscal instruments:

$$x_t = \left(\sum_{j=0}^{m_{x0}} \alpha_j^x P_j(t) \right) \exp\left(-\lambda^x t\right) + \left(1 - \exp\left(-\lambda^x t\right)\right) \left(\sum_{j=0}^{m_{xF}} \beta_j^x P_j(t) \right)$$

→ x_t can be any of the fiscal instruments $\{\tau_{H,t}, \tau_{K,t}, \tau_{E,t}, T_t\}$
→ $\{P_j(t)\}_{j=0}^{m_{x0}}$ and $\{P_j(t)\}_{j=0}^{m_{xF}}$ are Chebyshev polynomials
→ $\{\alpha_j^x\}_{j=0}^{m_{x0}}$ and $\{\beta_j^x\}_{j=0}^{m_{xF}}$ are weights on the consecutive elements
→ λ^x controls the convergence rate of the fiscal instruments

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Temperature

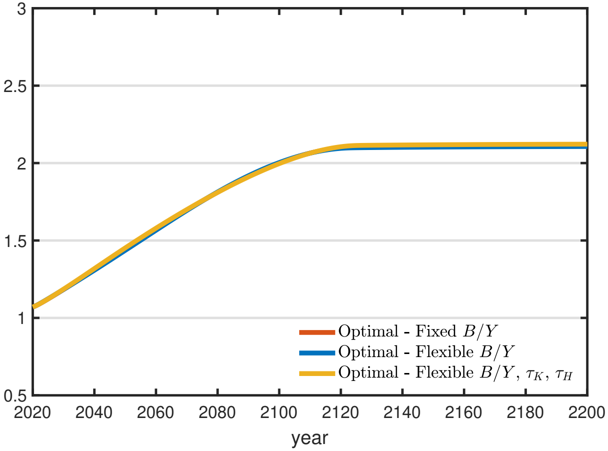

Figure: Temperature Change

Exogenously Imposed Parameters (1)

Parameter	Description	Value	Source
Production first sector			
a_1	Damage coefficient	0.0074	Dietz and Venmans, 2019 and Barrage, 2020
α	Return to scale on labor sector 1	0.3	DICE 2023
ν	Return to scale on energy sector 1	0.04	Golosov et al., 2014
δ	Depreciation rate on capital (per year)	0.1	DICE 2023
Y_{2020}	Initial output (in trillions 2023 USD)	83.476	World Bank (2016-2020)
Production second sector			
α_E	Return to scale on capital sector 2	0.597	Barrage, 2020
E_{2020}	Init. gross indus. emissions ($GtCO_2$ per year)	38.23	Friedlingstein et al., 2022
Climate			
S_{2020}	Initial cumulative carbon emissions (in GtCO2)	2390	IPCC, 2021
T_{2020}	Initial atmos. temp. change (C since 1900)	1.07	IPCC, 2021
ϵ	Initial pulse-adjustment timescale	0.5	Dietz and Venmans, 2019
ζ	Trans. clim. resp. to cum. emissions (TCRE)	0.00045	IPCC, 2021
E_{2020}^{land}	Init. gross CO_2 emis. land ($GtCO_2$ per year)	4.17	Friedlingstein et al., 2022
$g_{E^{\text{land}}}$	Ex. decline rate of gross land emissions (per period)	0.1	DICE 2023
Abatement costs			

Exogenously Imposed Parameters (2)

Parameter	Description	Value	Source
Exogenous growth parameters			
$g_{A_{1,2020}}$	Initial TFP growth rate sector 1 (per year)	0.0159	DICE 2023
$gg_{A_{1,t}}$	Decline rate TFP growth sector 1 (per year)	0.0072	DICE 2023
$g_{A_{2,2020}}$	Initial TFP growth rate sector 2 (per year)	0.0159	DICE 2023
$gg_{A_{2,t}}$	Decline rate TFP growth sector 2 (per year)	0.0072	DICE 2023
N_{2020}	Initial population (in millions)	1,368	World Bank US-adjusted
N_{max}	Asymptotic population (in millions)	1,910	DICE 2023 US-adjusted
g_N	Rate of convergence of population	0.145	DICE 2023
Fiscal Policy			
τ_K	Capital income tax (%)	33.6^*	Appendix **??**
τ_H	Labor income tax (%)	27.7^*	Appendix **??**
τ_C	Consumption tax (%)	4.2^*	Appendix **??**
$\tau_{I,t}$	Energy tax (%)	0.0	Appendix **??**
$\tau_{E,t}$	Initial carbon emission tax (%)	0.6	Appendix **??**

Calibration: Macroeconomic Variables

Macroeconomic aggregates		
	Target	**Model**
Intertemporal elasticity of substitution	0.66	0.66
Capital to output	2.57	2.54
Average Frisch elasticity (Ψ)	1.00	1.00
Average hours worked	0.24	0.25
Transfer to output (%)	14.7	14.7
Debt to output (%)	104.5	104.5
Fraction of hhs with negative net worth (%)	10.8	11.5
Correlation between earnings and wealth	0.51	0.43

Calibration: Population Partition

	Shares			
	Population	Earnings	Income	Wealth
	Workers			
Data	67.2	82.7	69.1	44.9
Model	70.9	86.3	78.7	47.0
	Business Owners			
Data	5.8	13.7	16.1	33.0
Model	6.6	13.7	14.8	31.2
	Inactive Households			
Data	27.0	3.6	14.8	22.2
Model	22.5	0.0	6.5	21.8

Notes: Data comes from 2019 wave of the SCF

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Labor Productivity Process

Quantitative Analysis

- Labor productivity has two components:
  - → Persistent component e_P: Markov process with 4 states
  - → Transitory component e_T: i.i.d. with 6 values
- Combined as: $e = e_P + e_T e_P^{\eta}$
  - → $\eta = 0$: additive shocks; $\eta = 1$: multiplicative
- 26 free parameters after normalizing average productivity to 1
- Parameters calibrated to match inequality, risk, and population structure

▸ Population Partition ▸ Parameters

Labor Productivity Process: Parameters

Parameter	Value
Curvature η	1.12

Persistent shock

$$\Gamma_P = \begin{bmatrix} 0.994 & 0.002 & 0.004 & 3E{-}5 \\ 0.019 & 0.979 & 0.001 & 9E{-}5 \\ 0.023 & 0.000 & 0.977 & 5E{-}5 \\ 0.000 & 0.000 & 0.012 & 0.987 \end{bmatrix} e_P = \begin{bmatrix} 0.185 \\ 0.305 \\ 0.537 \\ 27.223 \end{bmatrix}$$

Transitory shock

$$P_T = \begin{bmatrix} 0.357 \\ 0.002 \\ 0.467 \\ 0.004 \\ 0.025 \\ 0.176 \end{bmatrix} e_T = \begin{bmatrix} 0.07 \\ 0.09 \\ 3.12 \\ 3.16 \\ 7.80 \\ 9.51 \end{bmatrix}$$

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Government

Quantitative Analysis

- We extend procedure of Trabandt and Uhlig (2012) up to 2019:
  - $\rightarrow$ labor income tax rate: $\tau_{H,0} = 27.7\%$
  - $\rightarrow$ capital income tax rate: $\tau_{K,0} = 33.6\%$
- Debt (2019): difference between total liabilities and financial assets from the US government's balance sheet: $B_0/Y_0 = 104.5\%$
- Transfers capture all personal transfers from NIPA: $T_0/Y_0 = 14.7\%$

Welfare decomposition

- The utilitarian welfare function can increase for four reasons:
  1. Reduction in distortions, if the utility of the average agent, $\sum_{t=0}^{\infty} \beta^t u(C_t, N_t)$, increases: **the level effect (Δ_L)**
  2. Lower utility damages from climate, $\sum_{t=0}^{\infty} \beta^t v(Z_t)$: **the utility-damages effect (Δ_{UD})**
  3. Transfers from ex-post rich to ex-post poor, if the risk of each individual path $\{c_t, n_t\}_{t=1}^{\infty}$ is reduced: **the insurance effect (Δ_I)**
  4. Transfers from ex-ante rich to ex-ante poor, if the inequality between certainty equivalents for $\{c_t, n_t\}_{t=1}^{\infty}$ is reduced: **the redistribution effect (Δ_R)**

Proposition

Let Δ be the utilitarian (average) welfare gain. The following decomposition holds:

$$(1 + \Delta) = (1 + \Delta_L)(1 + \Delta_{UD})(1 + \Delta_I)(1 + \Delta_R)$$

Decomposing the SCC

Decompose the Pigouvian tax (i.e., the SCC) as follows:

$$\tau_t^{e,Pigou} = \frac{1}{\lambda_t^A} \sum_{j=0}^{\infty} \beta^j \left(\lambda_{t+j}^A \lambda_{t+j}^B - \lambda_{t+j}^C \right) J_{E_t^M, t+j}, \tag{5}$$

with

$$\lambda_t^A = \widetilde{\mathcal{W}}_{c,t} \quad ; \quad \lambda_t^B = D_t' A_{1,t} F_t \quad ; \quad \lambda_t^C = \mathcal{W}_{Z,t}. \tag{6}$$

Components

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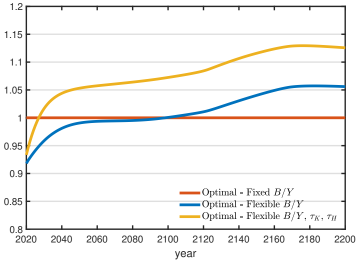
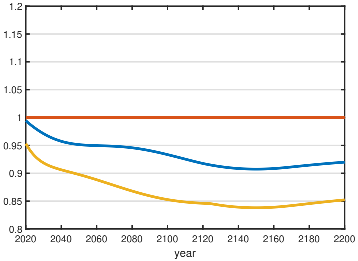
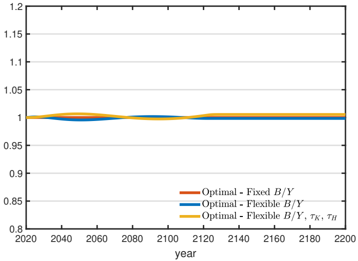


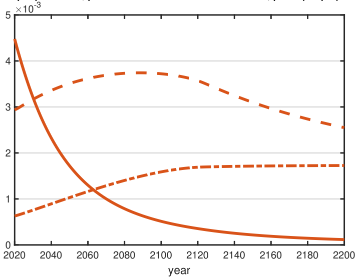
(a) Marginal Utility of Consumption



(b) Marginal Production Damages (λ_t^B)



(c) Marginal Utility from Climate (λ_t^C)



(d) Scale of Components

Backstop Price of Carbon Abatement ◂ Back

- The **backstop price** is the marginal cost of abating the last unit of CO_2.
- At this price, technology is available to:
  - → Fully capture all emitted carbon, or
  - → Produce carbon-free energy at scale to fully substitute fossil fuels.
- Key question: What is the **cost per ton of $\mathbf{CO_2}$** for the cheapest such technology?
- The DICE model uses an **exogenous path** for the backstop price.
- This path is taken from a synthesis of external studies.
- It is **independent of the model's internal calibration**.

Backstop Price

Barrage and Nordhaus 2024 (DICE 2023):
"The DICE model includes a backstop technology, which is a set of technologies that can replace all fossil fuels, albeit at a relatively high price. These technologies might be solar or wind power, safe nuclear power, or some as-yet-undiscovered source. Conceptually, at the cost of the backstop technology, the economy achieves zero net carbon emissions. Two revisions in the current version are noteworthy. Estimates of the cost of the backstop technology are controversial, with the DICE model having a high backstop cost relative to some estimates of the cost of renewables or carbon capture. The cost function is derived from highly detailed process models. Examining estimates of the marginal cost of scenarios with zero net emissions, we can estimate the marginal cost of the backstop technology. A statistical analysis from the results of the ENGAGE study (18, 19) indicates a median backstop price of $\$15/tCO_2$ in 2019 in 2050, which is the earliest year that most models can reach zero net emissions. Models assume improvements over time in the technologies needed to attain zero emissions. The decline rate of the cost of the backstop technology is assumed to be 1%/year from 2020 to 2050, and then 0.1% year after that."

Optimal Carbon Taxes and Backstop Price (in $\$/tCO_2$)

Results