Pricing Externalities in the Presence of Adaptation

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Abstract

I study optimal taxation in general equilibrium settings where households compete against output producers for inputs that emit pollutants. For instance, as climate changes, households use more energy for air-conditioning. I show that increases in demand for such goods raise the marginal profit of polluting firms. Accordingly, these firms expand production, leading to higher pollution. To illustrate such equilibrium effects, I build a macroeconomic climate-economy model that uses heat-related discomfort and cooling as an example. Neglecting this negative feedback results in lower-than-optimal carbon prices, causing a 2.4% reduction in the welfare benefit of climate policies, measured by consumption equivalent variation.

Keywords: Climate Change, Optimal Taxes, Adaptation

JEL Classification Codes: E6, H21, H23, Q54, Q58

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1 Introduction

When people anticipate unfavorable changes in environmental conditions, they may engage in "*private adaptation*" by adjusting their behavior to reduce its negative impacts. Examples of private adaptation include using asphalt shingles to protect against wildfires, constructing houses on concrete stilts to prevent flooding, and installing air purifiers to reduce pollutant inhalation. Failing to consider such behaviors can overstate the social cost of externality-generating activities (Graff Zivin and Neidell, 2013; Kahn, 2016). Conventional wisdom in partial equilibrium analyses suggests that incorporating private adaptation in a cost-benefit analysis will lead to a lower pollution tax, as the focus is primarily on the role of adaptation in reducing negative externalities. However, when people adapt by using pollutant-intensive inputs, such as asphalt, cement, or energy, the market demand for these products increases. Accordingly, polluting industries expand their production to meet these new demands. An important question then arises: "How should policymakers consider the general equilibrium effects driven by adaptation when pricing externalities?"

In this paper, I examine the impact of pollutant-intensive adaptive behaviors on determining optimal pollution taxes. To this end, I compare outcomes in a general equilibrium setting incorporating endogenous adaptative responses to a benchmark without adaptation. The key element in this comparative statics is the rise in demand for pollutant-intensive intermediate products resulting from the competition between output producers and households. I theoretically show that endogenizing pollutant-intensive adaptation in utility and resource constraints not only reduces the external costs of pollution but also increases the profits of polluting firms, leading to higher pollution levels. Previous studies only account for adaptation by implicitly subtracting its net benefit from pollution damages, which overlooks the intersectoral linkages. Neglecting such general equilibrium interactions in a cost-benefit analysis will result in lower-than-optimal pollution prices. To illustrate this point, I employ a dynamic climate-economy model with heat-related discomfort and cooling energy use to quantify the impact of general equilibrium effects on the Pigovian mortality social cost of carbon.

This paper identifies a novel general equilibrium channel that explains how adaptation increases the "*marginal benefit of using pollutant-intensive inputs*" (or, equivalently, the marginal cost of pollution abatement). While some studies analyze the costs and benefits of investing in abatement technologies such as smokestack scrubbers, this paper focuses on the costs and benefits of emitting pollutants as a byproduct of producing intermediate products to highlight the mechanism in a simplified model. In the short run, the total production of a pollutant-intensive input in the economy is fixed. When environmental quality worsens, households demand more of this input for adaptive purposes, reducing its availability for output production due to a resource constraint. This scarcity drives up the price of pollutant-intensive inputs, as output producers are willing to pay more due to their diminishing marginal products. As a result, polluting intermediate firms experience higher marginal profits because they can now sell at a higher price. In response, forward-looking polluting industries hire more labor and capital to increase their production in the long run.

The magnitude of the general equilibrium effects relies on how much pollutant-intensive inputs households demand to adapt to endogenously changing pollution levels. This paper uses a dynamic climate-economy model à la Golosov et al. (2014) and Nordhaus (2017), which I augment with cooling energy use against heat-related discomfort. The crucial ingredient is the non-separability between temperature and energy use in utility, which is captured by the constant elasticity of substitution (CES) between emissions abatement and cooling. Since cooling is a substitute for carbon abatement in reducing damages, an increase in temperature caused by the elevated carbon stock will boost energy consumption for cooling. To pin down the magnitude of substitutability, I calibrate a quantitative climate-economy model based on recent empirical evidence from Carleton et al. (2022) and Rode et al. (2021), who study the global costs of climate change in terms of mortality and electricity consumption.

I study competitive equilibria with cooling in comparison to scenarios without adaptation to understand the response of dirty energy producers to changes in their marginal profits. In the absence of carbon taxes, households allocate about 3.4% of the total energy produced in the economy for cooling in 2100. The increased market demand for energy leads to a rise in the share of capital and labor in the dirty energy sector by around 0.17 and 0.06 percentage points, respectively, in 2100. Consequently, CO_2 emissions are projected to rise by about 4.5 Giga tonnes per year, which accounts for 3.2% of global carbon emissions in 2100. A sensitivity analysis with respect to key parameters affecting social discount rates provides general equilibrium effects of comparable magnitudes.

The mortality social cost of carbon in the first-best allocation that takes into account the general equilibrium effect amounts to \$7 per tCO_2 in 2010 USD for the year 2020. About 1.46 percent more consumption is needed in the absence of carbon taxes to maintain the same level of lifetime utility with this correct carbon tax. To assess the impact of general equilibrium effects on environmental policies, I compare optimal carbon taxes incorporating endogenous cooling with a scenario where a climate damage function implicitly reflects cooling benefits. In the latter case, general equilibrium effects are not present because the adaptive margin is implicitly incorporated into the damage function. I find that the mortality social costs of carbon in 2020 are understated by 2% when such feedback is neglected. The consumption equivalent variation required in a laissez-faire case to maintain the level of lifetime utility with this underestimated carbon tax now decreases to 1.42 percent, leading to a 2.4% welfare loss.

While I model adaptation as a flow decision, the use of energy for space cooling has intertemporal implications through households' saving decisions. In the social optima, households' saving in 2020 increases by 0.09% with endogenous cooling, in comparison to a scenario without adaptation. Consequently, the capital stock rises by 0.09% with cooling by the end of this century. As the globe warms over time, they derive significantly higher utility in converting the marginal unit of output to the first unit of cooling energy services in the next period compared to the current period. This is because avoided damages from cooling are higher when the climate is worse, providing higher incentives to save, all else equal.

I also investigate whether efficiency improvements in cooling technologies can substitute carbon abatement in the absence of carbon taxes. In my model, the elasticity of substitution between carbon abatement and adaptation measures the efficiency of cooling technologies in mitigating the negative impacts of climate change. With increased substitutability, households can maintain the same level of cooling services while consuming less energy, thereby reducing their energy expenditure. However, the additional disposable income resulting from energy savings may induce further energy use for cooling due to income effects, counteracting the direct savings. I find that a rise in substitutability—equivalent to a 10% increase in adaptation benefits—leads to a 20% increase in annual cooling energy use in 2100. Nevertheless, the mortality social costs of carbon decrease from \$12 per tCO_2 to \$9 per tCO_2 in 2010 USD for the year 2020 in the absence of climate policies. Thanks to the enhanced cooling, only 1.41 percent of the consumption equivalent variation is required in laissez faire to maintain households' welfare at the same level as with optimal carbon taxes, which is lower than that resulting from the benchmark case. This finding indicates that the concern regarding increased energy use due to efficiency improvements is not significant.

In this paper, I present a structural framework for reconciling the seemingly contradictory findings within the two strands of reduced-form studies on cooling energy use. One strand focuses on its role as self-protective mechanism in reducing mortality sensitivities to weather variations (Deschênes and Greenstone, 2011; Barreca et al., 2016; Heutel et al., 2021; Carleton et al., 2022). The other underscores the adverse effects of climate-driven cooling energy use by showing that electricity consumption responses to heat waves are more prominent in areas with higher levels of long-run average temperature (Davis and Gertler, 2015; De Cian et al., 2019; De Cian and Sue Wing, 2019; Van Ruijven et al., 2019; Biardeau et al., 2020; Rode et al., 2021; Auffhammer, 2022; Deschênes, 2022). Depending on the perspective, the welfare implication of cooling will vary. This paper addresses both the private benefits and social costs of cooling by specifying household preferences for adaptation.

This paper also conducts a consistent welfare analysis of climate change and adaptation by using a dynamic general equilibrium approach in line with other existing macroeconomic studies on endogenous climate including Acemoglu et al. (2012), Golosov et al. (2014), and Barrage (2020b). Extrapolating a dose-response relationship between economic outcomes and temperature fluctuations based on exogenously given emissions pathways, as commonly done in reduced-form studies (see Hsiang (2016) for a review), may not be innocuous. For example, as much as mortality sensitivities to temperature fluctuations decline due to cooling, an ensuing increase in emissions can feed back into the economy by heightening the risks of heat-related discomfort. This vicious cycle may further elevate the use of energy for cooling, leading to a different trajectory of carbon emissions. While such analysis is suitable when exogenously given scenarios closely align with implied emissions, it may not be ideal for simulating various policy counterfactuals that can endogenously change emissions pathways. The empirical literature has emphasized the importance of accounting for these feedback effects (Rode et al., 2021). In this paper, I adopt a general equilibrium framework that includes the interaction between the climate and economy to account for such feedback effects.

This paper contributes to the understanding of the interplay between private and public responses to climate externalities. In many structural cost-benefit studies of climate change, all the relevant welfare effects of adaptation are lumped into a stylized damage function; see Fankhauser (2017) for reviews. Specifically, each locus on this damage curve denotes the least-cost combination of adaptation costs and ceteris paribus temperature effects net of adaptation benefits. But there is an emerging literature that explicitly addresses adaptation. An earlier strand of the literature decomposes the climate damage in Nordhaus and Boyer (2000) on an ad-hoc basis to model adaptation as a decision variable (de Bruin et al., 2009).[1] More recently, several studies utilize micro-data to build an empirically-grounded damage function with adaptation in a quantitative macro model such as Fried (2021), Balboni (2021), Conte (2023), Cruz and Rossi-Hansberg (2023), Nath (2023), and Rudik et al. (2022). Notably, Barrage (2020a) builds a dynamic climate-economy model with distortionary taxes in which climate change affects public investments in adaptation, tax revenue, transfer payment, and government consumption requirements to investigate the interplay between optimal carbon taxes and the fiscal burden caused by climate change and public adaptation. But none of the previous studies delve into individuals' adaptive behavior using pollutant-intensive intermediate goods. Therefore, general equilibrium effects

[1] See also Settle et al. (2007), Bosello (2010), Bosello et al. (2010), Agrawala et al. (2011), and Millner and Dietz (2015) that use climate damages from Nordhaus and Yang (1996) or Nordhaus and Boyer (2000). Other integrated assessment models that account for adaptation are the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) by Tol (2007) and the Policy Analysis of the Greenhouse Effect (PAGE) by Hope (2011).

in factor markets do not arise in response to an endogenously evolving climate. Colelli et al. (2022), on the other hand, set out the multi-region optimal planning problem, focusing exclusively on the adjustment of the supply side of the energy sector to accommodate increased energy demands for climate-driven adaptation. Specifically, they address the negative feedback of carbon-intensive adaptation by introducing a technological retrogression in energy-augmenting productivities in output production, employing an ad-hoc approach that necessitates increased energy production to maintain a given output level. Moreover, their model lacks consideration for the health benefits associated with energy use in household preferences, thus overlooking the direct impact of adaptation.

The remainder of this paper proceeds as follows. In section 2, I illustrate how pollutant-intensive adaptation shifts up the marginal profit of polluting industries using a static model. Section 3 introduces a macroeconomic climate-economy model enriched with cooling against heat-related discomfort as an illustrative example, which is calibrated in section 4. Section 5 presents quantitative results, and I conclude with a discussion of the implication of this paper for reduced-form environmental studies in section 6.

2 A static model of externalities with adaptation

I construct a static model to show how adaptation shifts the marginal profit of polluters by altering factor prices. To highlight the mechanism, I focus on reducing the use of pollutant-intensive input as a means of emissions abatement without considering pollutant-free technologies. In section 3, I develop a dynamic climate-economy model that incorporates carbon cycles, capital accumulation, and carbon-free technologies to conduct quantitative analyses.

2.1 Environment

A representative household has preferences over non-durable consumption C, pollution T, and pollutant-intensive adaptation E^H. For simplicity, I assume quasi-linearity (to be relaxed in section 3). The literature has not reached a consensus on how the shape of utility functions changes based on health status (Finkelstein et al., 2009). I assume a state independence of consumption with respect to pollution externalities, and instead focus on the interdependence between private adaptation and pollution as follows

$$u(C, T, E^H) = C - h(T, E^H), \tag{1}$$

where $\frac{\partial h(T,E^H)}{\partial T} \geq 0$, $\frac{\partial^2 h(T,E^H)}{\partial (T)^2} \geq 0$, $\frac{\partial h(T,E^H)}{\partial E^H} \leq 0$, and $\frac{\partial^2 h(T,E^H)}{\partial (E^H)^2} \geq 0$. The household takes T as given and disregards the environmental impact of their consumption choices. Utility damages are determined by pollution level T and adaptation E^H. I consider heat-related discomfort from climate change T and cooling E^H as an illustrative example. But the framework is general enough to capture a broad set of pollutant-intensive goods for adaptation, such as cement stilts or asphalt shingles. Specifically, I model adaptation as a flow decision. I do not consider investments in durable goods—such as air conditioners—to focus on the pecuniary effects caused by cooling. Following the standard practice in the literature, I define T as a change in the global mean surface temperature relative to the pre-industrial level. The population size is normalized to one, and the household supplies one unit of labor inelastically.

Importantly, I assume that the sign of the cross-partial derivative of utility damages with respect to climate T and household energy consumption E^H is nonpositive; for any $(T, E^H) \in R_+^2$, $\partial^2 h / \partial E^h \partial T \leq 0$. This assumption implies that the marginal impact of a rise in temperature is less significant when people take an additional adaptive measure. It is consistent with the empirical observation that the dose-response relationship between extreme heat events and mortality rates becomes less sensitive as per capita income or long-run average temperature rises, which are important indicators of private adaptation (Barreca et al., 2016; Heutel et al., 2021; Carleton et al., 2022). As an extreme case, if the cross-partial derivative becomes zero, cooling will lessen damage to utility in level, but the slope of the marginal damage curve will remain unchanged. If the cross-partial derivative is negative, the marginal damage curve becomes flatter as households increase energy use for self-protection. Many empirical studies find a similar negative association between key determinants of adaptation and the marginal effect of environmental stresses such as heat events or hurricanes.[2]

Put differently, this assumption implies that the reduction in damage from adaptation is greater in magnitude with a more drastic change in climate.[3] It is consistent with empirical evidence that the dose-response relation between heat events and electricity consumption becomes more sensitive as either per capita income or long-run average temperature rises (Rode et al., 2021; Auffhammer, 2022). As reducing the use of fossil fuels curbs warming, this complementarity reflects the extent to which abatement can be substituted for cooling.

A representative firm in the final goods sector combines labor L^Y and energy E^Y to produce output Y. Its technology F^Y exhibits constant returns to scale with positive and diminishing marginal returns, satisfying the Inada condition

$$Y = F^Y(L^Y, E^Y). \tag{2}$$

A representative firm in the intermediate goods sector hires labor L^E to generate energy E. The production of energy is linear in labor L^E

$$E = A^E L^E \quad \text{where} \quad A^E > 0. \tag{3}$$

Both labor and energy are perfectly mobile across the sectors

$$L^Y + L^E = 1 \quad \text{and} \quad E^H + E^Y = E. \tag{4}$$

Producing energy yields carbon as its byproduct. I normalize E such that it can be expressed in the same unit of its carbon content. That is, one unit of energy produces one unit of carbon. I assume a linear model of warming with respect to cumulative carbon emissions, which will be discussed in section 3

$$T = \zeta E \quad \text{where} \quad \zeta > 0. \tag{5}$$

[2]See Sadowski and Sutter (2008), Keefer et al. (2011), Hsiang and Narita (2012), Deryugina and Hsiang (2017), Gourio and Fries (2020), Fried (2021), Cruz and Rossi-Hansberg (2023) and Nath (2023) for example.

[3]This assumption can be rewritten as $\frac{\partial}{\partial T}\left(-\frac{\partial h(T,E^H)}{\partial E^H}\right) \geq 0$.

2.2 Social planner's problem

The primary goal of this paper is to improve our understanding of the general equilibrium effects of pollutant-intensive adaptation on the marginal profit of polluting firms. I compare the two otherwise identical economies that differ in households' ability to adapt to uncover the role of pollutant-intensive adaptation on both the external marginal costs and private marginal benefit of pollution.

To provide comparative statics for the changes in the availability of energy as adaptation, I generate a damage function with a dummy parameter $\theta \in \{0,1\}$

$$d(T,E^H;\theta) = \theta\ h(T,E^H) + [1-\theta]\,g(T) = \begin{cases} h(T,E^H) & \text{if } \theta = 1 \\ g(T) & \text{otherwise} \end{cases}. \tag{6}$$

Here, g denotes the damage to utility caused by climate change without cooling, which is increasing and convex in T. I assume that marginal climate damages decrease when a household adapts; $dg/dT \geq \partial h/\partial T$ for all $(T,E^H) \in R_+^2$. This parameterization is along the lines of the monotone comparative statics analysis (Milgrom and Shannon, 1994), which allows for a discrete change in parameter space. If $\theta = 1$, households can use energy for space cooling. Otherwise, energy is unavailable as an adaptive measure (benchmark case).

Given $\theta \in \{0,1\}$, a benevolent planner solves the following welfare maximization problem: $\max_{\{C,T,E^H,L^Y,E^Y,L^E\}} C - d(T,E^H;\theta)$ subject to (2),(3),(4),(5), and $C = Y$, as well as nonnegativity constraints for choice variables. Substituting the constraints into the objective function, I transform the planner's problem into an unconstrained optimization with two choice variables and a dummy parameter θ

$$\max_{\{L^E,E^H\}} W\big(L^E,E^H;\theta\big) = F^Y\big(1-L^E, A^E L^E - E^H\big) - d\big(\zeta A^E L^E, E^H;\theta\big). \tag{7}$$

The planner decides the amount of emissions by adjusting labor in the energy sector L^E while protecting households from climate damages using energy E^H.

The first-order conditions are given by

$$\underbrace{-\theta\frac{\partial h(T,E^H)}{\partial E^H}}_{\text{Marginal benefit of adaptation}} = \underbrace{\frac{\partial F^Y(L^Y,E^Y)}{\partial E^Y}}_{\text{Marginal cost of adaptation}}, \text{ and} \tag{8}$$

$$\underbrace{\Big[\theta\frac{\partial h(T,E^H)}{\partial T}+[1-\theta]\frac{dg(T)}{dT}\Big]\zeta}_{\text{Marginal external cost from carbon}}=\underbrace{\Big[\underbrace{\frac{\partial F^Y(L^Y,E^Y)}{\partial E^Y}}_{\text{Gains from energy}}-\underbrace{\frac{\partial F^Y(L^Y,E^Y)}{\partial L^Y}\frac{1}{A^E}}_{\text{Losses from labor}}\Big]}_{\text{Marginal private profit from carbon}}. \tag{9}$$

The emissions inventory is one-to-one related to the energy production in the economy, which is determined by employment in the energy sector. Given any $L^E \in [0,1]$, the climate change T is determined according to (5). The planner then decides how much energy to allocate for households—$E^H(L^E)$—balancing damage reductions and losses from foregone consumption as in (8). While taking as given this contingent plan $E^H(L^E)$, the planner balances the external cost and private benefit from emissions as in (9). If $\theta = 0$, only the condition (9) becomes relevant, and the planner would not allocate any energy for households.

To study how efficient allocations change as adaptation becomes available ($\theta = 0 \to 1$), I use the monotone comparative statics by Milgrom and Shannon (1994).

Proposition 1 *The welfare function $W(L^E,E^H;\theta)$ has increasing differences in (L^E,θ), (E^H,θ), and (L^E,E^H).*

Proof. A function has increasing differences if an incremental return from one argument is larger when the other is higher. For any $(L^E,E^H)\in[0,1]\times R_+$,

$$\frac{\partial W(L^E,E^H;\theta=1)}{\partial E^H}-\frac{\partial W(L^E,E^H;\theta=0)}{\partial E^H}=-\frac{\partial h}{\partial E^H} \geq 0 \tag{10}$$

$$\frac{\partial W(L^E,E^H;\theta=1)}{\partial L^E}-\frac{\partial W(L^E,E^H;\theta=0)}{\partial L^E}=\left[\frac{dg}{dT}-\frac{\partial h}{\partial T}\right]\zeta A^E \geq 0 \tag{11}$$

$$\frac{\partial^2 W(L^E,E^H;\theta)}{\partial L^E \partial E^H}=\left[-\frac{\partial^2 F^Y}{\partial (E^Y)^2}+\frac{\partial^2 F^Y}{\partial L^H \partial E^Y}\frac{1}{A^E}\right]-\theta\,\frac{\partial^2 h}{\partial E^H \partial T}\,\zeta \geq 0 \tag{12}$$

Q.E.D.

Adaptation benefits are positive when it is available as in (10). The returns to fossil fuel use are higher with adaptation as the marginal damage curve becomes flatter with adaptation as in (11). Provided that the economy's total energy volume is fixed in the short run, transferring some from firms to households for cooling will crowd out energy that can be used to produce other consumption goods. This scarcity raises the marginal profit of carbon-emitting firms through general equilibrium effects on factor prices. Energy prices increase and wages go down. When a factor market is complete, the equilibrium factor price equals its marginal product because arbitrage opportunities do not exist. First, energy scarcity in the final goods sector increases energy prices because of the diminishing marginal product of energy. Second, the energy shortage in the final goods sector makes wages go down because the value of a marginal product of labor declines due to the complementarity between labor and energy. On the other hand, cooling energy modulates the marginal impacts of climate. In sum, adaptation and carbon emissions complement each other as in (12).

Proposition 1 provides sufficient conditions for monotone comparative statics.

Proposition 2 *It follows from monotone comparative statics analysis (Milgrom and Shannon, 1994) that*

$$E^H(\theta=1) \geq E^H(\theta=0)=0 \quad \textit{and} \quad L^E(\theta=1) \geq L^E(\theta=0).$$

When $\theta=0$, the planner does not allocate any energy for households due to the associated decrease in output without any adaptation benefits. Let $L_0^E := L^E(\theta=0)$ represent the optimal labor allocation in the absence of adaptation. Then, by construction, given any $l \in [0, L_0^E]$, the planner prefers L_0^E to l under $\theta=0$. That is, the incremental returns from choosing L_0^E over l are always positive under $\theta=0$; $W(L_0^E, E^H; \theta=0) - W(l, E^H; \theta=0) \geq 0$. It follows from Proposition 1 that these positive incremental returns persist under $\theta=1$. Therefore, even though self-protective measures directly contribute to negative externalities, the planner would never choose lower carbon emissions, which leads to a higher temperature rise.

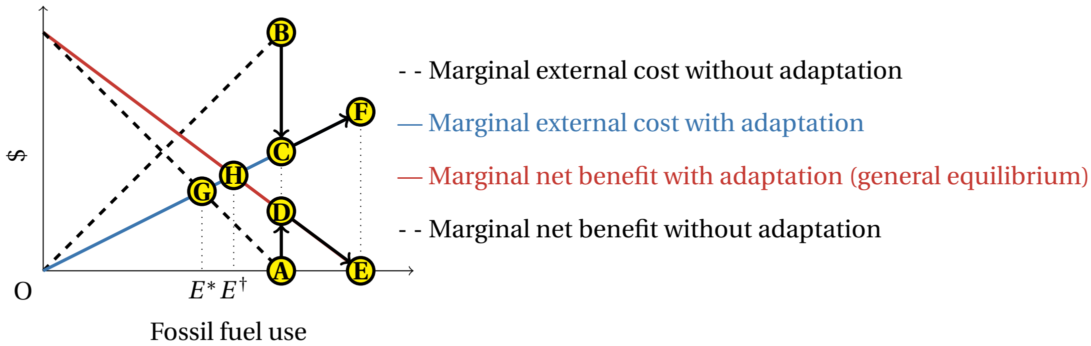

Figure 1: Graphical cost-benefit analysis

The optimal Pigouvian tax is determined where the marginal external cost and private profit from carbon emissions intersect according to the equation (9).

$$\text{Pigou Tax} = \begin{cases} \frac{dg(T)}{dT} & \text{if } \theta = 0 \\ \frac{\partial h(T,E^H)}{\partial T} & \text{if } \theta = 1 \end{cases} \tag{13}$$

While private adaptation reduces marginal climate impacts, leading to a decrease in optimal carbon taxes, an increase in emissions due to general equilibrium effects—$L^E(\theta = 1) \geq L^E(\theta = 0)$—counteracts the direct impact of adaptation, subsequently elevating the Pigouvian taxes.

2.3 General intuition and a comparison to existing IAMs

Figure 1 illustrates the model's general equilibrium effects using a graphical representation of a cost-benefit analysis. As a benchmark, consider an economy without cooling. In the absence of carbon taxes, energy producers will increase their production until they reach zero marginal profits (point A), resulting in external damages (point B). Now, suppose that energy is available for cooling. Private adaptation reduces the marginal impacts of climate change (point C). The crowding-out of industrial energy by residential energy increases energy prices but decreases wages. As a result, in the short run, carbon-emitting firms experience a profit increase (point D). With no carbon taxes, energy producers expand their production capacity in the long run (point E), leading to a higher external cost (point F) along the solid upward-slope curve, as forward-looking households adapt to the endogenously evolving climate.

In principle, climate externalities can be internalized by regulating the use of fossil fuel at the point where its private marginal net benefit equals its external marginal cost. However, such cost-benefit analyses may not be straightforward with endogenous adaptation because both curves shift. When it comes to optimal climate policies, failing to account for such effects may lead to inefficient levels of emissions. The existing literature has focused on the shift in the marginal damage curve. Notably, many Integrated Assessment Models (IAMs) implicitly incorporate the costs and benefits of adaptation into a single damage function by calibrating it to the least cost combination of residual damage and adaptation costs (Fankhauser, 2017)

$$\text{Damage}(T) := \min_{A} \left\{ \text{Residual Damage}(T, A) + \text{Adaptation Cost}(T, A) \right\}, \tag{14}$$

where T is a global mean surface temperature change relative to the pre-industrial level and A is adaptation. They lump all the relevant welfare effects of adaptive responses into one single stylized output damage function in a reduced manner

$$\text{Output} = \left[1 - \text{Damage}\,(T) \right] F(L, E), \tag{15}$$

where F is production, L is labor, and E is energy. As a result, prior research has overlooked the general equilibrium effects of pollutant-intensive adaptation on the relative factor price of energy to labor. This oversight arises from the cancellation of multiplicative damages during the derivation of relative prices. Furthermore, modeling individuals' adaptive behaviors using final goods cannot induce a shift in relative factor prices. The scarcity within the intermediate goods market influences factor prices by altering the value of their marginal products. The competition between households and final goods producers would not arise if households allocate output between non-durable consumption and adaptation.

This paper aims to address this research gap by specifying individual adaptive decisions using intermediate goods within preferences and resource constraints, thereby shedding light on the general equilibrium effects on factor prices. In section 3, I build a quantitative dynamic climate-economy model with private adaptation using the global mortality costs of climate change and electricity use for cooling as an example. I then recalibrate a damage function that implicitly incorporates the benefit of adaptation to quantify how much of the Pigou tax with endogenous cooling is attributable to its general equilibrium effects on factor markets (illustrated as the transition from point G to point H in Figure 1).

3 Dynamic climate-economy model with adaptation

To evaluate the impact of adaptation on determining optimal carbon taxes, I extend the stylized framework to a much richer dynamic climate-economy model. First, I assume that climate damages are inversely proportional to environmental qualities, which is a constant elasticity of substitution aggregate of temperature and cooling energy. Second, I model the technology for producing an energy composite as a constant elasticity of substitution production function of carbon-free and fossil fuel-based energy. Third, I assume that the global mean surface temperature change is linear in the cumulative carbon dioxide emissions. I then characterize the optimal carbon taxes in a setting in which the government has access to lump-sum transfers.

The economy is populated by a representative household with the utility

$$\sum_{t=0}^{\infty} \beta^t \Big[v(C_t) - \big[\theta\, h(T_t, E_t^H) + [1-\theta]\, g(T_t)\big]\Big], \tag{16}$$

$$\begin{aligned}
\text{where} \quad v(C_t) &= \frac{C_t^{1-\eta_c}}{1-\eta_c}, \\
h(T_t, E_t^H) &= \frac{1}{\eta_h - 1}\left(\omega\left(\frac{1}{1+\gamma_h T_t^2}\right)^{1-\iota} + [1-\omega]\left(\epsilon E_t^H\right)^{1-\iota}\right)^{\frac{1-\eta_h}{1-\iota}}, \quad \text{and} \\
g(T_t) &= \frac{\omega}{\eta_h - 1}\left(\frac{1}{1+\gamma_h T_t^2}\right)^{1-\eta_h}.
\end{aligned}$$

Here, I use a power function characterized by a constant elasticity of marginal utility for both non-durable consumption and climate impacts, denoted by $\eta_c \geq 1$ and $\eta_h \geq 1$. The parameter $\gamma_h > 0$ scales gross impacts, representing ambient temperature effects that would occur with no cooling benefits. The parameter $\epsilon > 0$ denotes the efficiency of energy by augmenting its impact, which reduces the severity of climate impacts. The parameter $\beta \in (0,1)$ is the discount factor.

Climate impacts, after accounting for adaptation, decrease as environmental quality Q increases. I represent Q as a constant elasticity of substitution aggregate of gross impacts and cooling in line with Gerlagh and van der Zwaan (2002) and Hoel and Sterner (2007)

$$Q(T, E^H) = \left(\omega\left(\frac{1}{1+\gamma_h T^2}\right)^{1-\iota} + [1-\omega]\left(\epsilon E^H\right)^{1-\iota}\right)^{\frac{1}{1-\iota}} \text{ where } \iota \in [0, \eta_h]. \tag{17}$$

I restrict the parameter space for ι to ensure that the assumptions concerning h in section 2 hold (see the appendix A.1 for derivations). Emissions abatement improves ceteris paribus ambient temperature impacts by curbing climate change. Therefore, $\frac{1}{\iota}$ measures the ease with which the planner can switch between carbon mitigation and private adaptation along an indifference curve. This functional form is general enough to nest a wide range of climate damage functions used in the existing literature (see the appendix A.2 for comparison to other studies). Note that $g(T_t)$ is a special case of $h(T_t, E_t^H)$ when $\epsilon = 0$ and $\iota = \eta_h$.

Let $V_t(K_t)$ denote the value function of households in period t with capital K_t. Taking climate and prices as given, they decide $\{C_t, K_{t+1}, E_t^H\}$ to solve

$$V_t(K_t) = \max\left\{v(C_t) - \left[\theta\ h(T_t, E_t^H) + [1-\theta] g(T_t)\right] + \beta V_{t+1}(K_{t+1})\right\} \tag{18}$$
$$\text{subject to } C_t + p_t^E E_t^H + K_{t+1} = w_t L_t + [1+r_t]K_t + G_t,$$

where p_t^E is energy price, w_t is wage, r_t is capital rent, and G_t is government transfer.

Assuming complete markets for both final and intermediate goods, the economy comprises of four types of firms: output producers, energy aggregators, carbon-free energy producers, and fossil fuel-based energy producers. I assume that the final goods are produced à la Cobb-Douglas, with output being dependent on climate change à la Nordhaus (2017)

$$Y_t = \left[1 - D(T_t)\right] F_t(K_t^Y, L_t^Y, E_t^Y) = \frac{1}{1+\gamma_y T_t^2} A_t^Y \left(K_t^Y\right)^{\alpha} \left(L_t^Y\right)^{1-\alpha-\nu} \left(E_t^Y\right)^{\nu}. \tag{19}$$

A representative firm in the final goods sector solves

$$\max_{K_t^Y, L_t^Y, E_t^Y} Y_t - p_t^E E_t^Y - w_t L_t^Y - (r_t + \delta) K_t^Y, \tag{20}$$

subject to non-negativity constraints, where δ is the depreciation rate of capital.

There are two types of energy in the economy: dirty (D) and carbon-free (R). Carbon-free energy is not associated with climate externalities, while dirty energy releases carbon into the atmosphere. Energy from a source $i \in \{D, R\}$ is produced according to the Cobb-Douglas function

$$E_t^i = G_t^i(K_t^i, L_t^i) = A_t^i \left(K_t^i\right)^{\alpha_i} \left(L_t^i\right)^{1-\alpha_i}. \tag{21}$$

I assume that there is an unlimited supply of dirty energy and its producers do not collect the Hotelling rents à la Golosov et al. (2014), in which they demonstrate that when a non-fossil alternative becomes economically profitable in the distant future, coal is not depleted even in laissez-faire equilibria. Specifically, I calibrate the economy to justify this assumption in section 4. I normalize dirty energy production such that one unit of E^D generates one unit of carbon. Both renewable and dirty energy are expressed in the same unit.

A representative firm in the energy sector $i \in \{R, D\}$ solves

$$\max_{K_t^i, L_t^i} \left(p_t^i - \tau_t^i\right) E_t^i - w_t L_t^i - (r_t + \delta) K_t^i \tag{22}$$

subject to non-negativity constraints for choice variables, where p_t^i is the price of energy of type i and τ_t^i is its corresponding per-unit tax on its output.

Energy composites are made according to the constant elasticity of substitution production

$$E_t = \left[\kappa_R \left(E_t^R\right)^{\frac{\sigma_e - 1}{\sigma_e}} + \kappa_D \left(E_t^D\right)^{\frac{\sigma_e - 1}{\sigma_e}}\right]^{\frac{\sigma_e}{\sigma_e - 1}} \quad \text{where} \quad \sum_{i \in \{R, D\}} \kappa_i = 1. \tag{23}$$

Here, $\kappa_i \in (0,1)$ denotes the relative energy-efficiency of the source $i \in \{R, D\}$, and $\sigma_e > 0$ is the elasticity of substitution between carbon-free and dirty energy. An aggregator solves

$$\max_{E_t^R, E_t^E} p_t^E E_t - p_t^R E_t^R - p_t^D E_t^D. \tag{24}$$

I assume that the government redistributes revenues using lump-sum transfer

$$G_t = \sum_{i \in \{R,D\}} \tau_t^i E_t^i. \tag{25}$$

Most Earth System Models, which are used to calculate global and regional earth system responses under many environmental conditions, generate a near proportional relationship between cumulative carbon emissions and global mean surface temperature change over the pre-industrial level (MacDougall, 2017). But most existing climate models in economics research exhibit excessive delays in temperature responses to emissions, and they fail to account for carbon sinks' declining abilities to remove carbon from the atmosphere as it becomes more saturated (Dietz et al., 2021). They argue that unless cumulative emissions are too high, a linear mapping suffices to align climate dynamics with Earth System Models predictions. I specify climate change as a linear function of carbon stock

$$T_t = \zeta S_t \quad \text{and} \quad S_{t+1} = S_t + \vartheta_t E_t^D \tag{26}$$
$$\text{where} \quad \vartheta_t = 1 - \left(1 + \exp\left\{\left(\frac{t - n_{0.5}}{n_{0.01} - n_{0.5}}\right)\log\left(\frac{0.01}{0.99}\right)\right\}\right)^{-1}.$$

The parameter ζ captures the relation between cumulative emissions and warming, defined as the transient climate response to cumulative carbon emissions (TCRE) by Collins et al. (2013). Following Dietz and Venmans (2019), I assume a delay of 5 years for the temperature response to emissions. I also introduce a declining emissions intensity à la Krusell and Smith (2022). The parameter $\vartheta_t \in (0,1)$ denotes the fraction of carbon emitted. Here, $n_{0.01}$ is the period when $\vartheta_t = 0.01$ and $n_{0.5}$ is the period when $\vartheta_t = 0.5$. It is also consistent with Golosov et al. (2014) and

Nordhaus (2017), in which the economy becomes less carbon-intensive even without carbon taxes as abatement costs decline over time due to technological progress.

Let $W_t(K_t, S_t)$ represent the value function of a benevolent planner in period t with capital K_t and carbon stock S_t. The benevolent planner decides $\{C_t, K_{t+1}, L_t^Y, L_t^R, L_t^D, K_t^Y, K_t^R, K_t^D, E_t^H, E_t^Y\}$ to solve

$$W_t(K_t, S_t) = \max\left\{v(C_t) - \left[\theta\ h(T_t, E_t^H) + [1-\theta]g(T_t)\right] + \beta W_{t+1}(K_{t+1}, S_{t+1})\right\}$$

subject to (16), (19), (21), (23), (26), and

$$\begin{aligned} C_t + K_{t+1} &= Y_t + (1-\delta)K_t, \\ L_t^Y + L_t^R + L_t^D &= 1, \\ K_t^Y + K_t^R + K_t^D &= K_t, \\ E_t^H + E_t^Y &= E_t, \end{aligned} \tag{27}$$

as well as non-negativity constraints for each choice variable. The first-order conditions are fully characterized in the appendix A.3.

I define a recursive competitive equilibrium in this economy as follows.

Definition 1 *A recursive competitive equilibrium consists of prices* $\{p_t^E, w_t, r_t, p_t^R, p_t^D\}$*, climate change* $\{T_t\}$*, tax/transfer* $\{\tau_t^R, \tau_t^D, G_t\}$*, policy functions* $\{C_t, K_{t+1}, E_t^H, E_t^Y, L_t^Y, L_t^R, L_t^D, K_t^Y, K_t^R, K_t^D\}$*, and a value function* $\{V_t\}$ *such that in each period* $t = 0, 1, 2, \cdots$

1. *taking prices, climate change, and tax/transfer as given, the policy functions and the value function solve the maximization problems for households and producers,*

2. *the government budget is balanced as in* (25)*,*

3. *the climate change is consistent with the policy functions through* (26)*, and*

4. *the markets clear as in* (27)*.*

The first-order conditions in competitive equilibria are fully characterized in the appendix A.3.

Proposition 3 *Assuming the government aims to maximize economic efficiency through tax and transfer systems, the following tax on energy outputs decentralizes the first-best allocation derived from the planning problem*

$$\tau_t^R = 0 \; and \; \tau_t^D = \begin{cases} \frac{1}{v'(C_t)} \sum_{s=t+1}^{\infty} \beta^{s-t} \left(\frac{dg(T_s)}{dT_s} - v'(C_s) \frac{\partial Y_s}{\partial T_s} \right) \zeta \vartheta_t & \text{if } \theta = 0 \\ \frac{1}{v'(C_t)} \sum_{s=t+1}^{\infty} \beta^{s-t} \left(\frac{\partial h(T_s, E_s^H)}{\partial T_s} - v'(C_s) \frac{\partial Y_s}{\partial T_s} \right) \zeta \vartheta_t & \text{if } \theta = 1 \end{cases}$$

for every t where policy functions are the solutions for the planning problem.

See the appendix A.3 for the proof. According to the linear warming model, an extra unit of emissions in period t leads to a temperature rise by $\zeta\vartheta_t$ from period $t+1$ onwards. The optimal tax on dirty energy production is equal to the sum of the present values of all future climate impacts, divided by the marginal utility of non-durable consumption in period t. Adaptation flattens the marginal damage curve, leading to a decline in Pigouvian carbon taxes. On the other hand, an increase in temperature from general equilibrium effects elevates optimal carbon taxes due to the convexity of the damage function h with respect to T.

4 Calibration

I calibrate the model's laissez-faire equilibrium to match the projected impacts of climate change on heat-related mortality costs and electricity consumption under a high emissions scenario (Representative Concentration Pathway [RCP] 8.5) to justify the reduced-form evidence on the benefits and costs of the use of energy for cooling by Rode et al. (2021) and Carleton et al. (2022). For more details of this scenario, refer to Riahi et al. (2011). I choose this scenario because it does not include any emissions mitigation targets, which aligns with the model's competitive equilibrium without carbon taxes. I adopt other parameters from the existing literature. The time step is 5 years, with the base period being 2015 ($t=-1$), and simulations start in 2020 ($t=0$).

Using external parameters in Table 2, I relate my model to certain observables to initialize allocations. To compute the base-period consumption, I employ the 2015 world gross saving rate.[4] Similarly, for calculating the base-period household cooling energy, I use the 2016 world final energy consumption for space cooling, which accounts for about 3% of the world's total primary energy use (IEA, 2018a). For energy demand, the 2014 primary global fossil fuel-based energy demand was 11.1 Giga tonnes of oil equivalents of coal, oil, and gas. The 2014 primary global carbon-free energy demand amounted to 2.6 Giga tonnes of oil equivalents of nuclear, hydro, bioenergy, and other renewables (IEA, 2016). To express the energy demand in carbon units, I use the guidelines outlined in the national greenhouse gas inventories by IPCC (2006).

4.1 Internal parameters

According to Carleton et al. (2022), the ceteris paribus effects of climate change on global heat-related mortality in 2100 are projected to be 221 deaths per 100,000 people under the RCP8.5 scenario, which is approximately 8.3% of the global gross domestic product in 2100.[5] I calibrate the parameter γ_h such that the disutility caused by climate change from 2015 to 2100, without cooling, equals the utility loss resulting from an 8.3% reduction in consumption:

$$g\left(T_{2100}\right)-g\left(T_{2015}\right)=v\left(C_{2100}\right)-v\left([1-0.083]\,C_{2100}\right). \tag{28}$$

Carleton et al. (2022) also project that the mortality costs, after accounting for adaptation benefits, will amount to 73 deaths per 100,000 people, resulting in 148 lives saved per 100,000 people. To match the model-simulated adaptation benefits to the reduced-form evidence, I adjust the parameter ι such that

$$\frac{h^{\max}\left(T_{2100},E_{2100}^{H}\right)-h\left(T_{2100},E_{2100}^{H}\right)}{h^{\max}\left(T_{2100},E_{2100}^{H}\right)-h^{\min}\left(T_{2100},E_{2100}^{H}\right)}=\frac{148}{221}, \tag{29}$$

[4]World Bank national accounts data and OECD National Accounts data. "Gross savings (% of GDP)." World Bank, https://data.worldbank.org/indicator/NY.GNS.ICTR.ZS?end=2021&start=1960&view=chart (accessed December 12, 2023).

[5]Carleton et al. (2022) report climate damages as a percentage of global GDP only for the full mortality costs of climate change, which includes both the benefits and costs of adaptation. To calculate the ceteris paribus climate impacts as a percentage of global GDP, I assume that both the benefits and costs of adaptation occur proportionally across all age groups.

where $h^{\max}$ equals h when $1/\iota = 1/\eta_h$ and $h^{\min}$ equals h when $1/\iota \to \infty$. If cooling reduces deaths by 221 per 100,000 people, then the parameter $1/\iota$ becomes infinite. If no cooling benefits exist, the parameter $1/\iota$ equals its lower bound $1/\eta_h$.

The efficiency of carbon abatement, relative to cooling, is determined by the parameter ω, which in turn affects the environmental quality Q. Holding other factors constant, a rise in ω results in households needing to consume more energy for cooling to achieve the same level of well-being. Rode et al. (2021) project the global electricity consumption compared to the period of 2000 - 2010 under the RCP8.5 scenario. They adopt a standard two-way fixed effects model to identify a causal relation between weather fluctuations and electricity consumption. They also consider two key adaptation indicators, the long-run average temperature and income per capita, which affect the steepness of the dose-response function.

It is important to note that their projection does not account for secular trends in energy consumption, but rather only considers an increase in electricity use attributable to climate change.[6] Therefore, I calibrate the parameter ω to ensure that the changes in the model's simulated cooling energy, after netting out its secular trends, match the projected changes in electricity consumption in Rode et al. (2021), which amount to 1.21 Giga Joule per capita per year by the end of this century. I then multiply this estimate by the global population in 2015 to obtain the climate-driven cooling loads, which amounts to 3.32 Giga tonnes of CO_2 per five years. To derive the secular trends in household energy consumption, I simulate the competitive equilibrium without considering climate externalities.

$$\left[E^H_{2100} - E^H_{2015}\right] - \left[E^{H,\,\text{Secular}}_{2100} - E^H_{2015}\right] = 3.32 \tag{30}$$

Lastly, I calibrate the parameter ϵ such that the marginal rate of substitution between C and E^H equals its price ratio in the base year. It is worth noting that Carleton et al. (2022) identify the benefits of adaptation by estimating reduced mortalities to weather fluctuations, which result

[6]When projecting the impact of climate change on energy consumption, Rode et al. (2021) do not incorporate time fixed effects. This is because the standard two-way fixed effects model estimates time fixed effects in a non-parametric way, making it impossible to extrapolate them.

Table 1: Model's fit for targeted moments

Moment	Empirical	Model-simulated
Ceteris paribus mortality damages (% of the world GDP)	8.32	8.44
Mortality reduction due to cooling (% of the gross damage)	66.97	67.12
Climate-driven cooling demands ($GtCO_2$ per five years)	3.32	3.39
Asymptotic cumulative carbon emissions (GtC)	5,000	4,807

from all of the actions people take to alleviate their mortality costs. In this calibration, I assume that all the benefits result from using energy for cooling.

I introduce declining emissions intensities $\{\vartheta_t\}$ so that climate change can reach a steady state in the future. This assumption validates the linear warming model. At high cumulative emissions, the transient climate response to cumulative carbon emissions (TCRE) is no longer constant, and it starts to decline (MacDougall, 2017; Dietz et al., 2021). I set calibrate $n_{0.5}$ and $n_{0.01}$ such that the atmospheric carbon concentration in laissez faire converges to five trillion tonnes of carbon, which validates the TCRE parameter in Tokarska et al. (2016). Five trillion tonnes of carbon also corresponds to the lower end of the range of estimates of the total fossil fuel resource (IEA, 2013). Therefore, my calibration justifies the assumption of an unlimited supply of fossil fuel-based energy since the depletion of fossil fuels does not arise.

I numerically solve for the laissez-faire equilibrium of the model to match all the moments. The empirical moments are compared to the model-simulated moments in Table 1, and the resulting parameters are summarized in Table 2. In the baseline calibration, the 2020 mortality social cost of carbon with no carbon taxes is \$11.5 per tCO_2 in 2010 USD (\$13.8 per tCO_2 in 2019 USD), and the social discount rate according to Ramsey (1928) is 2.9% per year.[7] This SCC aligns with Carleton et al. (2022) in terms of order of magnitude.[8] Moreover, the median warming in 2100 relative to 2001-2010 under the RCP8.5 is 3.7°C across all the climate models considered in Carleton et al. (2022) and Rode et al. (2021). The simulated temperature change in 2100 relative

[7]A simple social discounting rule, commonly known as the Ramsey Rule, equals

$$\text{Pure rate of time preference} + \text{Elasticity of marginal utility of consumption} \times \text{Growth rate of consumption}$$

[8]According to Carleton et al. (2022), the mortality social cost of carbon is \$14.2 per tCO_2 in 2019 USD with a social discount rate of 3% under the high emissions scenario (RCP8.5).

Table 2: Calibration Summary

Parameter		Description	Sources and notes
Preferences			
η_c	1.5	Elasticity of marginal utility of consumption	
η_h	1.5	Elasticity of marginal utility of environmental quality	
β	$(0.985)^5$	Discount factor	
γ_h	0.0017	Utility damage	Internally calibrated
ϵ	0.810	Effectiveness of adaptation	Internally calibrated
$1/\iota$	0.734	Substitutability between abatement and adaptation	Internally calibrated
ω	0.053	Relative efficiency	Internally calibrated
Technology			
γ_y	0.0021	Production damage	Barrage (2020b)
α	0.3	Capital expenditure share in final good sector	Golosov et al. (2014)
ν	0.04	Energy expenditure share in final good sector	Golosov et al. (2014)
α_R	0.597	Capital expenditure share in renewable energy sector	Barrage (2020b)
α_D	0.597	Capital expenditure share in dirty energy sector	Barrage (2020b)
σ_e	1.949	Substitutability between dirty and renewable energy	Papageorgiou et al. (2017)
κ_R	0.442	Relative energy efficiency of renewable energy source	Papageorgiou et al. (2017)
κ_D	0.558	Relative energy efficiency of dirty energy source	$1-\kappa_R$
δ	0.4095	Capital depreciation rate	Nordhaus (2017)
gA_1^Y	0.076	Initial growth rate in output productivity	Nordhaus (2017)
δ_A	0.005	Decline rate in productivity growth	Nordhaus (2017)
gA_t^Y		$gA_1^Y \exp(-5\delta_A(t-1))$	Nordhaus (2017)
gA_t^R		Growth rate in clean energy sector productivity	$((1+gA_t^Y)^{\frac{1}{1-\alpha-\nu}})^{1-\alpha_R}-1$
gA_t^D		Growth rate in dirty energy sector productivity	$((1+gA_t^Y)^{\frac{1}{1-\alpha-\nu}})^{1-\alpha_D}-1$
Climate model			
S_{2015}	851	2015 atmospheric carbon concentration (GtC)	Nordhaus (2017)
ζ	1.63	TCRE (°C per Tera tonnes of carbon)	Tokarska et al. (2016)
$n_{0.5}$	95/5	Period when $\vartheta_t = 0.5$	Internally calibrated
$n_{0.01}$	185/5	Period when $\vartheta_t = 0.01$	Internally calibrated

to 2015 is approximately 3.44°C in laissez faire. The computational procedures are provided in the appendix A.4.

4.2 External parameters

The atmospheric carbon concentration in 2015 is from Nordhaus (2017). The transient climate response to cumulative carbon emissions (TCRE) is set to 1.63 °C per Tera tonnes of carbon from Tokarska et al. (2016). I assume that the elasticity of marginal utility equals 1.5 for both non-durable consumption goods and environmental qualities. The rate of pure time preference is set to be 0.015 per year, or $\beta = (0.985)^5$ in the quantitative model in line with Nordhaus (2017).

Following Golosov et al. (2014), I assume a capital expenditure share of 0.3 and an energy income share of 0.04 for the final goods sector. Based on Barrage (2020b), I assume a capital expenditure share of 0.597 in both fossil fuel-based and carbon-free energy sectors. Following Papageorgiou et al. (2017), I set the elasticity of substitution between renewable and dirty energy to be 1.949 and the relative efficiency of renewable energy to be 0.442. The capital depreciation rate is set to 0.1 per year, or $\delta = 0.4095$ in the quantitative model in line with Nordhaus (2017). The path of total factor productivity is also taken from Nordhaus (2017). The productivity in both dirty and renewable energy sectors is set such that the labor augmenting technological progress is the same across all sectors.

5 Quantitative results

Using the calibrated model, I evaluate the economic impacts of heat-related mortalities and cooling energy. First, I quantify the general equilibrium effects of pollutant-intensive adaptation on factor markets in competitive equilibria with no carbon taxes (laissez faire). Second, I calculate the impact of adaptation-driven general equilibrium effects on the Pigovian social costs of carbon dioxide related to mortality. Third, I conduct a comparative statics analysis of households' saving, examining scenarios with and without cooling in the first-best to quantify ex-ante adaptation to climate change. Finally, I investigate the welfare implications of exogenous advancements in cooling technology.

5.1 General equilibrium effects on factor markets with no carbon taxes

To disentangle the general equilibrium effects of household cooling energy use on the marginal profit of dirty energy producers, I compare competitive equilibrium allocations from two nearly identical economies that differ only in households' ability to adapt. When I do not incorporate adaptation in utility and resource constraints, changes in factor prices do not arise. Therefore, I can attribute the increase in factor shares between the two economies within the dirty energy sector to the general equilibrium effects of endogenous cooling.

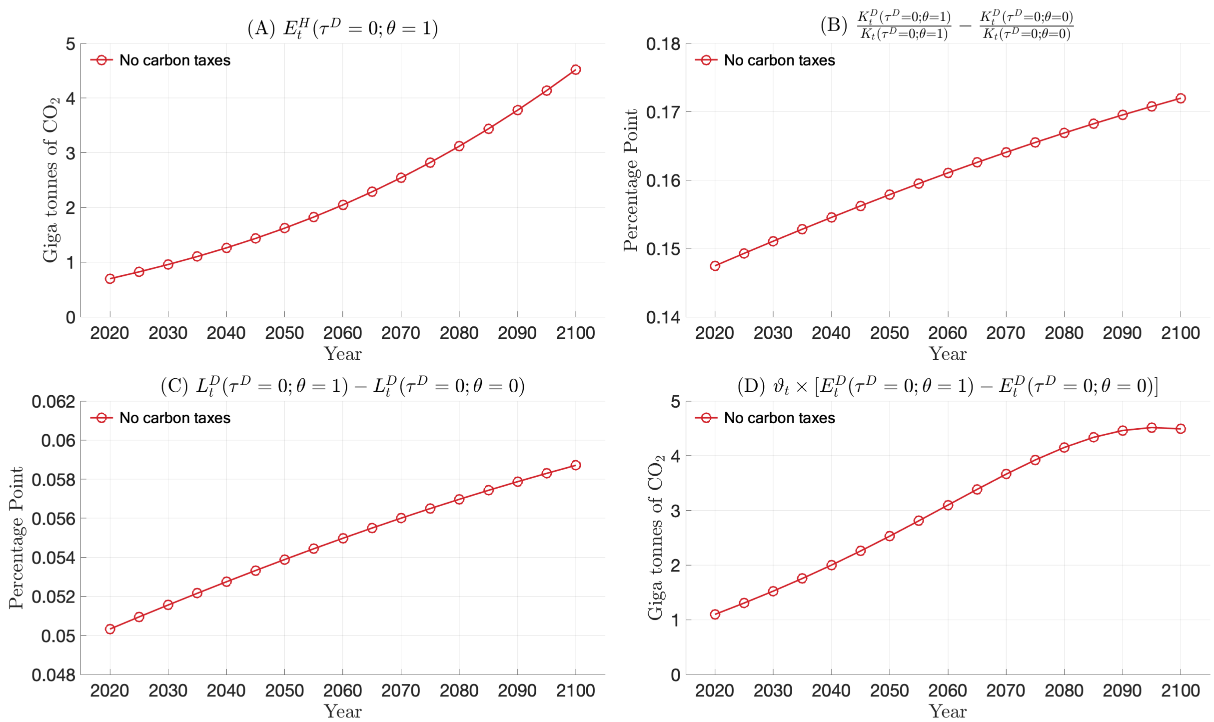

Figure 2: General equilibrium effects in competitive equilibria with no carbon taxes

Each panel presents the trajectories of competitive equilibrium allocations with and without cooling adaptation. Note that, for presentation purposes, I convert all energy sources to tonnes of oil equivalent and then convert them to CO_2. Additionally, each flow variable is adjusted from a per-five-year basis to a per-year basis. Panel (A): The use of energy for cooling per year. Panel (B): The difference in the capital share within the dirty energy sector. Panel (C): The difference in the labor share within the dirty energy sector. Panel (B): The difference in CO_2 emissions per year.

Figure 2 compares the trajectories of competitive equilibrium allocations with cooling against those without adaptation in the absence of carbon taxes. In Panel (A), the trajectory of cooling exhibits an upward trend under no climate policies. For example, in 2100, about 4.5 Giga tonnes of CO_2 per year—3.4% of the total energy supplied— will be allocated for cooling purposes. This trend results from the nonseparability between environmental quality and adaptation, where a higher temperature elevates marginal cooling benefits.

Cooling induces a rise in energy prices, accompanied by a decline in capital rents and wages, thereby pushing the marginal profit of the dirty energy sector upward. If there exist no changes in relative prices, factor shares between the two economies must remain constant. Panels (B) and (C) demonstrate adaptation-driven increases in factor shares within the dirty energy sector, providing indirect evidence of an upward shift in marginal profits. Moreover, the difference further intensifies as cooling demand rises over time. For example, when there are no carbon taxes, the capital and labor shares within the dirty energy sector are projected to increase by about 0.17 and 0.06 percentage points, respectively, in 2100. This is because a rise in cooling amplifies the general equilibrium effects.

As a consequence of the increase in factor shares within the dirty energy sector, carbon emissions increase over time, as illustrated in Panel (D). For example, in the absence of climate policies, carbon emissions per year are projected to increase by about 4.5 Giga tonnes of CO_2 per year by the end of this century, which accounts for about 3.2% of the global carbon emissions.

5.2 General equilibrium effects on Pigou taxes

To quantify the general equilibrium effects of cooling on optimal climate policies, I contrast the Pigou tax with cooling to a scenario in which a damage function is recalibrated to implicitly include adaptation benefits (G to H in Figure 1). In the case where adaptation is implicitly embedded in a damage function, general equilibrium effects are absent as household energy use does not appear in the resource constraint of a carbon-intensive intermediate input.

Figure 3 illustrates the global mean surface temperature change over the pre-industrial level and the mortality social costs of carbon in the first-best scenario. In social optima, the equilibrium temperature change is higher with cooling in Panel (A). It is a consequence of the upward shift in the marginal profit of dirty energy producers. The equilibrium temperature continues to rise over time in both cases. This is because the value of the marginal product of the initial unit of dirty energy is infinite due to the Inada condition, leading to a consistently positive utilization of fossil fuel in each period.

The social cost of carbon is defined as the present discounted sum of climate externalities arising from an additional tonne of carbon dioxide emissions. It follows from Proposition 3 that the optimal allocations can be fully decentralized by pricing carbon at its social cost in the first-best solution of the model. In the absence of carbon taxes, about 1.46 percent of compensation in consumption— defined as consumption equivalent variation (CEV)—is required to maintain the same level of lifetime utility from the efficient allocation.

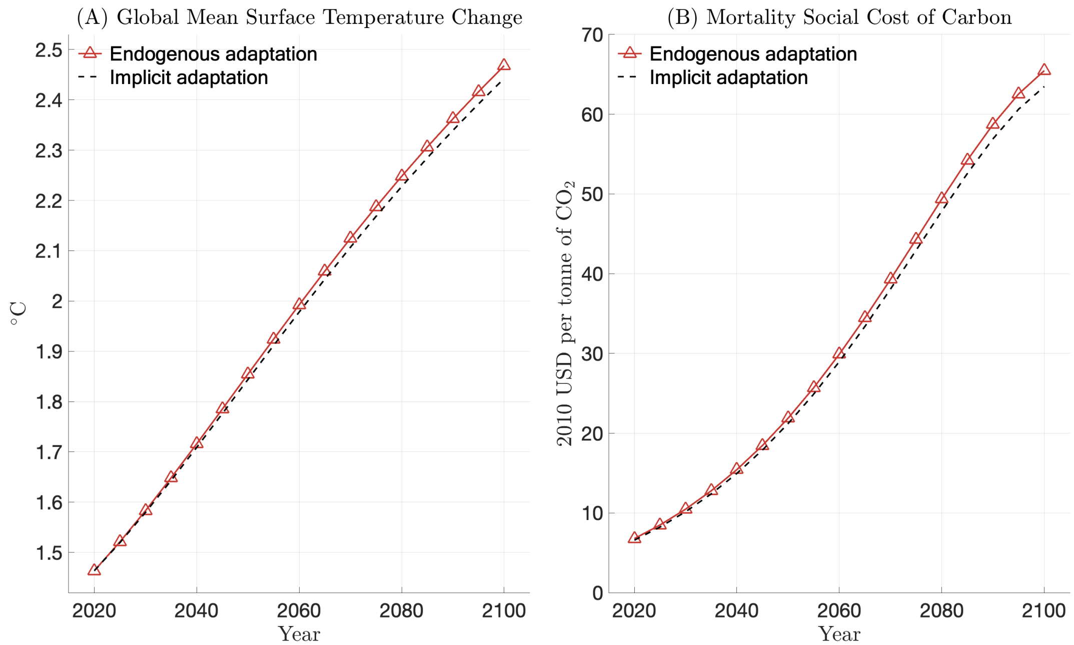

Figure 3: Simulated paths of optimal climate change and Pigou taxes

To highlight the general equilibrium effects, I isolate the mortality social costs of carbon from the social cost of carbon, which also includes production damages. In social optima, the mortality social cost of carbon in the base period, with endogenous cooling, is \$7 per tCO_2 in 2010 USD. This estimate is higher than those associated with implicit adaptation due to an upward shift in the marginal profit of dirty energy producers, as depicted in Panel (B). For instance, neglecting the negative feedback of cooling understates the social cost of carbon associated with mortality by 2% for the base period (2020). Such suboptimal climate policies lead to a reduced CEV of about 1.42 percent in laissez faire to maintain the level of lifetime utility with the underestimated carbon taxes, resulting in a 2.4% welfare loss.

5.3 Saving as ex-ante adaptation

Fankhauser et al. (1999) emphasize the importance of distinguishing between anticipatory (ex-ante) and reactive (ex-post) adaptation. In this paper, I model adaptation as an ex-post (reactive) flow decision, using cooling energy as an illustrative example. I do not explicitly consider investments in durable goods, such as air conditioners. Despite this modeling assumption about

Elasticity of substitution between carbon abatement and cooling $(1/\iota)$	0.734	0.744
Cooling energy use in 2100 (Giga tonnes of CO_2 per year)	4.5	5.4
Cumulative carbon dioxide emissions in 2100 (Giga tonnes of CO_2)	11,574	11,622
Mortality SCC[†] without carbon taxes in 2020 (2010 USD/tCO_2)	12	9
CEV	1.46	1.41

Table 3: The welfare impacts of advances in cooling technology

Each quantity is computed using the laissez-faire allocations under the two different calibration scenarios. The first column is calculated using the baseline parameters, as outlined in Table 2. The second column uses $(1/\iota)$ recalibrated to match a 10% increase in adaptation benefits, holding other parameters constant. The CEV, here, quantifies the compensation in non-durable consumption needed to maintain the same level of lifetime utility from the efficient allocation under each calibration.

adaptation, the use of energy for cooling has intertemporal implications through saving. In social optima, households' annual saving in 2020 rises by 0.09% with endogenous cooling. As a result, the capital stock increases by 0.09% with cooling by the end of this century. This observation suggests that household energy expenditures due to climate change do not divert resources from productive capital accumulation. The equilibrium temperature continues to rise over time since it is proportional to the cumulative carbon emissions. With cooling energy available as a self-protective mechanism, households derive higher utility from converting the marginal unit of final goods to the first unit of cooling energy services in the following period compared to the current period. This is because avoided damages from cooling are higher when the climate is worse, providing higher incentives to save.

5.4 The welfare impacts of advances in cooling technology

Energy efficiency improvements have received attention as one of the effective strategies to mitigate carbon (IEA, 2018c). However, they can additionally create income through energy savings and potentially result in increased energy use, known as "rebound" effects in the energy efficiency literature (Borenstein, 2015; Lemoine, 2020). I use a calibrated model to assess whether such rebound effects more than offset the welfare gains from technological advances. In this paper, I analyze competitive equilibria without carbon taxes, focusing on the role of energy efficiency improvements as a greenhouse gas mitigation strategy. In particular, I investigate an increase in the efficacy of cooling at reducing marginal damages through the elasticity of substitution between carbon abatement and cooling $(1/\iota)$.

Table 3 summarizes the welfare impact resulting from technological advances in cooling. In the baseline calibration, adaptation is projected to save 148 lives per 100,000 people in 2100. Holding other parameters constant, I recalibrate $(1/\iota)$ to match a 10% increase in adaptation benefits. The enhanced efficacy of cooling contributes to an approximately 20% increase in energy use by 2100, indicating that rebound effects reverse the initial energy savings. As a result, related general equilibrium effects also amplify, leading to higher carbon emissions.

However, the benefits derived from improved efficiency outweigh the unintended consequences, resulting in a decrease in mortality SCC from \$12 per tCO_2 to \$9 per tCO_2 in 2010 USD for the base period. To convert a decline in mortality social costs of carbon into more interpretable units, I compute the compensation of consumption in laissez faire necessary to maintain the same level of lifetime utility as the first-best allocation. With the increased cooling efficacy, only 1.41 percent of CEV in laissez faire is required to maintain the same level of lifetime utility from the efficient allocation. That is, despite rebound effects overturning the direct energy efficiency gains and contributing to a worsening climate, the enhanced cooling services more than offset these adverse effects, resulting in welfare gains.

5.5 Sensitivity analysis

The calculation of the social cost of carbon (SCC) generally involves converting the future consequences of current emissions using social discount rates (SDRs). As SDRs quantify the value of changes in future environmental quality, the SCC is connected to the intertemporal marginal rates of substitution. But considerable disagreement exists among experts within the economics profession, particularly concerning their perspectives on the pure rate of time preferences (Drupp et al., 2018). In this context, I examine whether the model-simulated SCC matches the reduced-form estimate derived from various levels of SDRs. Table 4 shows that an increase (decrease) in SDRs leads to a lower (higher) SCC in both laissez faire and social optimum, which is consistent with the recent evidence in terms of order of magnitude.[9] But the general equilibrium effects,

[9]According to Carleton et al. (2022), the mortality SCC is \$14.2 per tCO_2 in 2019 USD (\$11.8 per tCO_2 in 2010 USD) with a SDR of 3% and \$3.7 per tCO_2 in 2019 USD (\$3.1 per tCO_2 in 2010 USD) with a SDR of 5% under the RCP8.5.

	Benchmark	Alternative 1	Alternative 2	Alternative 3
Discount factor (β)	$(0.985)^5$	$(0.985)^5$	$(0.99)^5$	$(0.99)^5$
Elasticity of marginal utility ($\eta_c = \eta_h$)	1.5	2	1.5	2
Laissez faire (No climate policies)				
Ramsey SDR per year (%)	2.9	3.3	2.4	2.8
Mortality SCC with cooling (2010 USD/tCO_2)	12	5	19	9
Social optimum				
Ramsey social discount rate per year (%)	2.9	3.4	2.4	2.9
Mortality SCC with cooling (2010 USD/tCO_2)	7	3	9	4
General equilibrium effects in laissez faire				
A rise in capital share in dirty sector in 2100 (percentage point)	0.17	0.17	0.17	0.16
A rise in labor share in dirty sector in 2100 (percentage point)	0.06	0.06	0.06	0.06
Cooling-driven annual carbon emissions in 2100 (% of global emissions)	3.2	3.1	3.1	3.0

Table 4: Sensitivity analysis

I employ a simple social discounting rule according to Ramsey (1928) to calculate SDRs; Rate of pure time preference + Elasticity of marginal utility of consumption × Growth rate of consumption. A discount factor is equal to $(1/(1+\text{Pure rate of time preference}))^5$. Each quantity is derived using the recalibrated parameters listed in Table 5.

measured by a rise in factor shares arising from a change in relative prices, are robust to different assumptions about the pure rate of time preference and the elasticity of marginal utility.

6 Summary and concluding remarks

In this paper, I develop a theory of how pollutant-intensive adaptation affects optimal pollution taxes. The most apparent effect, previously highlighted in the literature, is that adaptation reduces the external marginal costs of pollution; this effect always decreases Pigouvian taxes. However, I show that adaptation using pollutant-intensive intermediate inputs comes with unintended consequences on factor prices. A rise in demand for pollutant-intensive inputs raises the marginal profit of polluting firms. This second effect works in the opposite direction and increases optimal pollution prices. To illustrate these general equilibrium effects, I employ a macroeconomic climate-economy model that incorporates heat-related discomfort and cooling energy as a stylized example. I find that about 2% of the Pigouvian tax for correcting heat-related mortality is due to the inadvertent warming induced by the use of energy for cooling.

They also find that the mortality SCC is \$7.9 per tCO_2 in 2019 USD (\$6.6 per tCO_2 in 2010 USD) with a SDR of 3% and \$2.9 per tCO_2 in 2019 USD (\$2.4 per tCO_2 in 2010 USD) with a SDR of 5% under the RCP4.5.

The theoretical insight presented in this paper provides a guiding principle for interpreting the policy implications of reduced-form studies on adaptation. It is becoming more popular, in econometric analyses, to incorporate adaptation by allowing the dose-response relation between economic outcomes and temperature fluctuations to depend on long-run average temperature and per capita income, which are indicators of adaptation (see Kolstad and Moore (2020) for a review). Policymakers should be concerned about general equilibrium effects when the mechanisms explaining adaptive benefits involve pollutant-intensive intermediate products. IPCC (2022) calls for best practices to prevent maladaptive behaviors that may increase carbon emissions. In this case, a SCC calculation based on partial equilibrium could prescribe a lower-than-optimal carbon tax rate.

Lastly, I conclude with a discussion of potential extensions of my model for future research. First, while a multi-sector growth model with various energy sources as intermediate goods elucidates the general equilibrium effects of private adaptation, additional efforts need to be undertaken to generalize the framework to a multi-sector model with input-output linkages. Adaptive behaviors that can lead to increased greenhouse gas emissions include, but are not limited to, cooling energy. For example, in 2014, the cement industry accounted for the second-largest share, emitting 2.2 $GtCO_2$ per year, representing 27% of the total direct industrial CO_2 emissions (IEA, 2018b). The macroeconomic literature on production networks can provide a useful framework to study the transmission of such risks over the input-output networks. Second, future research should probe the distributional effects of climate-driven adaptation. In this paper, I focus on the wedge between potential and realized exposures to climate change, driven by a representative household's adaptive behaviors. But economically disadvantaged people may not enjoy the same benefits because of their lack of resources to adapt to even worse climate conditions caused by rich households' adjustments to climate change. The heterogeneous agent macro model with idiosyncratic income shocks can be a helpful framework for designing climate policies that reduce both carbon emissions and inequality among households.

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A Appendix

A.1 Regularity conditions on h

Given any $(T,E^H)\in R^2_+$, if $\eta_h \geq 1$, $\iota \in [0,\eta_h]$, and γ_h is small enough,

$$\frac{\partial h(T,E^H)}{\partial T} = \omega\frac{2\gamma_h T}{(1+\gamma_h T^2)^{2-\iota}}\left(\omega\left(\frac{1}{1+\gamma_h T^2}\right)^{1-\iota}+[1-\omega]\left(\epsilon E^H\right)^{1-\iota}\right)^{\frac{1-\eta_h}{1-\iota}-1} > 0 \tag{31}$$

$$\begin{aligned}\frac{\partial^2 h(T,E^H)}{\partial (T)^2} &= 2\omega\gamma_h\left(\omega\left(\frac{1}{1+\gamma_h T^2}\right)^{1-\iota}+[1-\omega]\left(\epsilon E^H\right)^{1-\iota}\right)^{\frac{1-\eta_h}{1-\iota}-2} \\ &\times\left[\frac{1+\omega\gamma_h T^2\left(2\eta_h-3\right)}{(1+\gamma_h T^2)^{4-2\iota}}+[1-\omega]\frac{1+\gamma_h T^2(2\iota-3)}{(1+\gamma_h T^2)^{1+\iota}}(\epsilon E^H)^{1-\iota}\right] > 0\end{aligned} \tag{32}$$

$$\frac{\partial h(T,E^H)}{\partial E^H} = -[1-\omega]\frac{\epsilon}{(\epsilon E^H)^{\iota}}\left(\omega\left(\frac{1}{1+\gamma_h T^2}\right)^{1-\iota}+[1-\omega]\left(\epsilon E^H\right)^{1-\iota}\right)^{\frac{1-\eta_h}{1-\iota}-1} < 0 \tag{33}$$

$$\begin{aligned}\frac{\partial^2 h(T,E^H)}{\partial (E^H)^2} &= [1-\omega]\frac{\epsilon^2}{(\epsilon E^H)^{1+\iota}}\left(\omega\left(\frac{1}{1+\gamma_h T^2}\right)^{1-\iota}+[1-\omega]\left(\epsilon E^H\right)^{1-\iota}\right)^{\frac{1-\eta_h}{1-\iota}-2} \\ &\times\left[\iota\omega\left(\frac{1}{1+\gamma_h T^2}\right)^{1-\iota}+\eta_s[1-\omega]\left(\epsilon E^H\right)^{1-\iota}\right] > 0\end{aligned} \tag{34}$$

$$\begin{aligned}\frac{\partial^2 h(T,E^H)}{\partial T\partial E^H} &= -\left[\eta_h-\iota\right]\omega[1-\omega]\frac{2\gamma_h T}{(1+\gamma_h T^2)^{2-\iota}}\frac{\epsilon}{(\epsilon E^H)^{\iota}} \\ &\times\left(\omega\left(\frac{1}{1+\gamma_h T^2}\right)^{1-\iota}+[1-\omega]\left(\epsilon E^H\right)^{1-\iota}\right)^{\frac{1-\eta_h}{1-\iota}-2} < 0\end{aligned} \tag{35}$$

A.2 Climate damage functions in the literature

The specification in section 3 nests a wide range of damage functions used in the existing literature to investigate the impact of climate adaptation.

1. When $\iota \to 1$, the environmental quality Q becomes multiplicative (de Bruin et al., 2009; Bosello, 2010; Bosello et al., 2010; Bréchet et al., 2013; Millner and Dietz, 2015; Barrage, 2020a; Fried, 2021);

$$h(T,E^H) = \frac{1}{\eta_h-1}\left(\left(\frac{1}{1+\gamma_h T^2}\right)^{\omega}\left(\epsilon E^H\right)^{1-\omega}\right)^{1-\eta_h}. \tag{36}$$

2. When $\iota \downarrow 0$, the environmental quality Q becomes additive (Bretschger and Valente, 2011; Zemel, 2015):

$$h(T, E^H) = \frac{1}{\eta_h - 1}\left(\omega\left(\frac{1}{1+\gamma_h T^2}\right) + [1-\omega]\left(\epsilon E^H\right)\right)^{1-\eta_h}. \tag{37}$$

3. When $\iota \uparrow \eta_h$, the climate impacts h become separable in T and E^H;

$$h(T, E^H) = \frac{\omega}{\eta_h - 1}\left(\frac{1}{1+\gamma_h T^2}\right)^{1-\eta_h} + \frac{1-\omega}{\eta_h - 1}\left(\epsilon E^H\right)^{1-\eta_h}. \tag{38}$$

A.3 Proof for proposition 3

Given an arbitrary state vector (K_t, S_t), let $(K_t^{D*}, K_t^{R*}, L_t^{D*}, L_t^{R*}, E_t^{H*}, K_{t+1}^{*})$ denote the allocations that satisfy the following first-order conditions (FOCs) from the planner's problem in Section 3:

$$v'(C_t) = \beta \frac{\partial W_{t+1}}{\partial K_{t+1}}, \tag{39}$$

$$-\frac{\partial Y_t}{\partial L_t^Y} + \frac{\partial Y_t}{\partial E_t^Y} E_t \mathscr{S}_D \frac{1}{E_t^D}\frac{\partial E_t^D}{\partial L_t^D} = -\beta \frac{1}{v'(C_t)}\frac{\partial W_{t+1}}{\partial S_{t+1}} \vartheta_t \frac{\partial E_t^D}{\partial L_t^D}, \tag{40}$$

$$-\frac{\partial Y_t}{\partial L_t^Y} + \frac{\partial Y_t}{\partial E_t^Y} E_t \mathscr{S}_R \frac{1}{E_t^R}\frac{\partial E_t^R}{\partial L_t^R} = 0, \tag{41}$$

$$-\frac{\partial Y_t}{\partial K_t^Y} + \frac{\partial Y_t}{\partial E_t^Y} E_t \mathscr{S}_D \frac{1}{E_t^D}\frac{\partial E_t^D}{\partial K_t^D} = -\beta \frac{1}{v'(C_t)}\frac{\partial W_{t+1}}{\partial S_{t+1}} \vartheta_t \frac{\partial E_t^D}{\partial K_t^D}, \tag{42}$$

$$-\frac{\partial Y_t}{\partial K_t^Y} + \frac{\partial Y_t}{\partial E_t^Y} E_t \mathscr{S}_R \frac{1}{E_t^R}\frac{\partial E_t^R}{\partial K_t^R} = 0, \quad \text{and} \tag{43}$$

$$-\frac{\partial h(T_t, E_t^H)}{\partial E_t} = v'(C_t)\frac{\partial Y_t}{\partial E_t^Y}, \tag{44}$$

where

$$C_t = \left[1 - D(\zeta S_t)\right] F_t\Big(K_t - K_t^D - K_t^R, 1 - L_t^D - L_t^R, E_t\big(G_t^D(K_t^D, L_t^D), G_t^R(K_t^R, L_t^R)\big) - E_t^H\Big) + (1-\delta)K_t - K_{t+1}, \tag{45}$$

and

$$E_t(E_t^D, E_t^R) = \left[\kappa_R\left(E_t^R\right)^{\frac{\sigma_e-1}{\sigma_e}} + \kappa_D\left(E_t^D\right)^{\frac{\sigma_e-1}{\sigma_e}}\right]^{\frac{\sigma_e}{\sigma_e-1}}. \tag{46}$$

Using the optimal allocations, the value function W_t can be rewritten as

$$\begin{aligned} & W_t(K_t, S_t) = \qquad (47) \\ & v\left([1-D(\zeta S_t)]F_t\left(K_t - K_t^{D*} - K_t^{R*}, 1 - L_t^{D*} - L_t^{R*}, E_t\left(G_t^D(K_t^{D*}, L_t^{D*}), G_t^R(K_t^{R*}, L_t^{R*})\right) - E_t^{H*}\right) + (1-\delta)K_t - K_{t+1}^*\right) \\ & -\left[\theta h(\zeta S_t, E_t^{H*}) + [1-\theta]g(\zeta S_t)\right] + \beta W_{t+1}\left(K_{t+1}^*, S_t + G_t^D(K_t^{D*}, L_t^{D*})\right). \end{aligned}$$

As the optimizers satisfy the first-order conditions, the partial derivative of W_t with respect to K_t and S_t can be expressed as follows:

$$\frac{\partial W_t}{\partial K_t} = v'(C_t)\left[1 - \delta + \frac{\partial Y_t}{\partial K_t^Y}\right], \quad \text{and} \tag{48}$$

$$\frac{\partial W_t}{\partial S_t} = -\left[\theta \frac{\partial h(T_t, E_t^H)}{\partial T_t} + [1-\theta]\frac{dg(T_t)}{dT_t}\right]\zeta + v'(C_t)\frac{\partial Y_t}{\partial T_t}\zeta + \beta \frac{\partial W_{t+1}}{\partial S_{t+1}}. \tag{49}$$

Given $i \in \{R, D\}$, let

$$\mathscr{S}_i := \kappa_i(E_t^i)^{\frac{\sigma_e-1}{\sigma_e}} / \left[\kappa_R(E_t^R)^{\frac{\sigma_e-1}{\sigma_e}} + \kappa_D(E_t^D)^{\frac{\sigma_e-1}{\sigma_e}}\right]. \tag{50}$$

Using the envelope condition for K_t, the FOCs can be rewritten as

$$v'(C_t) = \beta v'(C_{t+1})\left[1-\delta+\frac{\partial Y_{t+1}}{\partial K^Y_{t+1}}\right], \tag{51}$$

$$-\frac{\partial Y_t}{\partial L^Y_t}+\frac{\partial Y_t}{\partial E^Y_t}E_t\mathscr{S}_D\frac{1}{E^D_t}\frac{\partial E^D_t}{\partial L^D_t} = -\beta\frac{1}{v'(C_t)}\frac{\partial W_{t+1}}{\partial S_{t+1}}\vartheta_t\frac{\partial E^D_t}{\partial L^D_t}, \tag{52}$$

$$-\frac{\partial Y_t}{\partial L^Y_t}+\frac{\partial Y_t}{\partial E^Y_t}E_t\mathscr{S}_R\frac{1}{E^R_t}\frac{\partial E^R_t}{\partial L^R_t} = 0, \tag{53}$$

$$-\frac{\partial Y_t}{\partial K^Y_t}+\frac{\partial Y_t}{\partial E^Y_t}E_t\mathscr{S}_D\frac{1}{E^D_t}\frac{\partial E^D_t}{\partial K^D_t} = -\beta\frac{1}{v'(C_t)}\frac{\partial W_{t+1}}{\partial S_{t+1}}\vartheta_t\frac{\partial E^D_t}{\partial K^D_t}, \tag{54}$$

$$-\frac{\partial Y_t}{\partial K^Y_t}+\frac{\partial Y_t}{\partial E^Y_t}E_t\mathscr{S}_R\frac{1}{E^R_t}\frac{\partial E^R_t}{\partial K^R_t} = 0, \quad \text{and} \tag{55}$$

$$-\frac{\partial h(T_t,E^H_t)}{\partial E_t} = v'(C_t)\frac{\partial Y_t}{\partial E^Y_t}. \tag{56}$$

Consider competitive equilibrium. It follows from the Envelope theorem that

$$\frac{\partial V_t}{\partial K_t} = v'(C_t)[1+r_t]. \tag{57}$$

Using the envelope condition for K_t, the FOCs can be written as

$$[p^i_t-\tau^i_t]\frac{\partial E^i_t}{\partial K^i_t} = r_t+\delta \quad \forall i\in\{R,D\}, \tag{58}$$

$$[p^i_t-\tau^i_t]\frac{\partial E^i_t}{\partial L^i_t} = w_t \quad \forall i\in\{R,D\}, \tag{59}$$

$$p_t E_t\mathscr{S}_i\frac{1}{E^i_t} = p^i_t \quad \forall i\in\{R,D\}, \tag{60}$$

$$\frac{\partial Y_t}{\partial K^Y_t} = r_t+\delta, \tag{61}$$

$$\frac{\partial Y_t}{\partial L^Y_t} = w_t, \tag{62}$$

$$\frac{\partial Y_t}{\partial E^Y_t} = p^E_t, \tag{63}$$

$$v'(C_t) = \beta v'(C_{t+1})[1+r_{t+1}], \quad \text{and} \tag{64}$$

$$-\frac{\partial h(T_t,E^H_t)}{\partial E_t} = v'(C_t)p^E_t. \tag{65}$$

By substituting prices, the first-order conditions can be rewritten as follows:

$$v'(C_t) = \beta v'(C_{t+1})\left[1-\delta+\frac{\partial Y_{t+1}}{\partial K^Y_{t+1}}\right], \tag{66}$$

$$-\frac{\partial Y_t}{\partial L^Y_t}+\frac{\partial Y_t}{\partial E^Y_t}E_t\mathscr{S}_D\frac{1}{E^D_t}\frac{\partial E^D_t}{\partial L^D_t} = \tau^D_t\frac{\partial E^D_t}{\partial L^D_t}, \tag{67}$$

$$-\frac{\partial Y_t}{\partial L^Y_t}+\frac{\partial Y_t}{\partial E^Y_t}E_t\mathscr{S}_R\frac{1}{E^R_t}\frac{\partial E^R_t}{\partial L^R_t} = \tau^R_t\frac{\partial E^R_t}{\partial L^R_t}, \tag{68}$$

$$-\frac{\partial Y_t}{\partial K^Y_t}+\frac{\partial Y_t}{\partial E^Y_t}E_t\mathscr{S}_D\frac{1}{E^D_t}\frac{\partial E^D_t}{\partial K^D_t} = \tau^D_t\frac{\partial E^D_t}{\partial K^D_t}, \tag{69}$$

$$-\frac{\partial Y_t}{\partial K^Y_t}+\frac{\partial Y_t}{\partial E^Y_t}E_t\mathscr{S}_R\frac{1}{E^R_t}\frac{\partial E^R_t}{\partial K^R_t} = \tau^R_t\frac{\partial E^R_t}{\partial K^R_t}, \quad \text{and} \tag{70}$$

$$-\frac{\partial h(T_t,E^H_t)}{\partial E_t} = v'(C_t)\frac{\partial Y_t}{\partial E^Y_t}. \tag{71}$$

Two sets of FOCs from the planning problem and competitive equilibrium are equal if and only if

$$\tau^R_t = 0 \quad \text{and} \quad \tau^D_t = -\beta\frac{1}{v'(C_t)}\frac{\partial W_{t+1}}{\partial S_{t+1}}\vartheta_t. \tag{72}$$

Using the envelope condition for S_t and iteration, τ^D_t can be rewritten as follows:

$$\tau^D_t = \begin{cases} \frac{1}{v'(C_t)}\sum_{s=t+1}^{\infty}\beta^{s-t}\left(\frac{dg(T_s)}{dT_s}-v'(C_s)\frac{\partial Y_s}{\partial T_s}\right)\zeta\vartheta_t & \text{if } \theta=0 \\ \frac{1}{v'(C_t)}\sum_{s=t+1}^{\infty}\beta^{s-t}\left(\frac{\partial h(T_s,E^H_s)}{\partial T_s}-v'(C_s)\frac{\partial Y_s}{\partial T_s}\right)\zeta\vartheta_t & \text{if } \theta=1 \end{cases} \quad \forall t=0,1,\cdots \tag{73}$$

Q.E.D.

A.4 Computation

The main computational challenge in this paper is that atmospheric carbon concentrations do not stabilize over time because carbon stock does not depreciate in a linear warming model. In addition, productivity systematically evolves over time. Consequently, the associated value and policy functions rely on time as well as state. Labor-augmenting technological progress cannot transform such an environment into a stationary one because the climate is inversely related to utility in a quadratic manner. To address this problem, I combine the Extended Function Path approach by Maliar et al. (2020) with the Envelope Condition Method by Maliar and Maliar (2013) and Arellano et al. (2016). Maliar et al. (2020) show that if the primary focus is on the evolution of a nonstationary economy with an infinite time horizon during the first t_0 periods, we can approximate its solution by solving a truncated version of the original model. It relies on the turnpike theorem, which states that the convergence of a truncated economy to its corresponding infinite-horizon model is insensitive to a sufficiently large enough terminal date and specific terminal conditions.

In this paper, I derive the optimal Pigouvian carbon taxes with adaptation towards the end of this century ($t_0 = 17$). I set a sufficiently long terminal period $T = 200$ (1,000 years) to minimize approximation errors. I assume that technological progress becomes stationary in the terminal period T and constructs a stationary solution. Given the terminal conditions, I solve the Bellman equations through backward inductions and construct a sequence of time-inhomogeneous policy functions. Beginning with an observable initial state, I simulate the economy forward and derive the optimal carbon taxes with adaptation.

In computing the competitive equilibrium, I find a fixed point of the path for global carbon emissions. Assuming rational expectations, each household correctly forecasts the trajectory of carbon emissions, but they ignore the influence of their own decisions on the emissions trajectory (Rezai et al., 2012; Krusell and Smith, 2022). To find a fixed point, I begin with an initial guess for the trajectory of carbon and iterate backward to solve for a sequence of policy functions. Next, I compute the assumed path for carbon emissions using the newly derived policy functions. By employing a convex combination of the previous guess and the newly generated emissions trajectory, I revise the guess for carbon trajectory. Using this updating rule, I continue iterating on the carbon trajectory until convergence.

A.5 Calibration for sensitivity analysis

Table 5: Model's fit for targeted moments and calibrated parameters

	Empirical	Benchmark	Alternative 1	Alternative 2	Alternative 3
Discount factor (β)		$(0.985)^5$	$(0.985)^5$	$(0.99)^5$	$(0.99)^5$
Elasticity of marginal utility of consumption (η_c)		1.5	2	1.5	2
Moment					
Ceteris paribus climate impacts on mortality (% of the world GDP)	8.32	8.44	8.20	8.14	8.25
Mortality reduction due to cooling in 2100 (% of the gross damage)	66.97	67.12	67.19	66.89	67.19
Climate-driven cooling demands (Giga tonnes of CO_2 per five years)	3.32	3.39	3.46	3.44	3.49
Asymptotic cumulative carbon emissions (Giga tonnes of carbon)	5,000	4,807	4,805	4,985	4,982
Calibrated parameter					
γ_h	-	0.0017	0.00017	0.0015	0.00016
ϵ	-	0.810	1.441e-04	0.824	1.441e-04
$1/\iota$	-	0.734	0.555	0.734	0.555
ω	-	0.053	0.011	0.054	0.011