

# Climate Change Adaptation vs. Mitigation: A Fiscal Perspective

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## Abstract

This study explores the implications of distortionary taxes for the tradeoff between climate change adaptation and mitigation. Public adaptation measures (e.g., seawalls) require government revenues. In contrast, mitigation through carbon taxes raises revenues, but interacts with the welfare costs of other taxes. This paper thus theoretically characterizes and empirically quantifies this tradeoff in a dynamic general equilibrium integrated assessment climate-economy model with distortionary Ramsey taxation. First, I find that public investments in adaptive capacity to reduce direct utility impacts of climate change (e.g., damages to national parks) are distorted at the optimum. The consumption of climate benefits is effectively taxed like other consumption goods. Second, public adaptation to reduce production impacts of climate change (e.g., damages to infrastructure) should be fully provided, even when they are financed through distortionary taxes. Third, the central quantitative finding is that the welfare costs of limiting climate policy to adaptation (i.e., failure to enact a carbon price) may be up to twice as high when the distortionary costs of adaptive expenditures are taken into account.

## 1 Introduction

Adaptation to climate change is increasingly recognized as an essential policy. In the United States, Federal government agencies have been required to produce climate change adaptation plans since 2009.<sup>1</sup> Governments at all levels are making plans and incurring expenditures for

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<sup>1</sup> As per Executive Order 13514 (October 5, 2009).

climate change adaptation,<sup>2</sup> such as New York City’s \$20 billion plan announced in 2013 in the aftermath of Hurricane Sandy.<sup>3</sup> While a growing academic literature has studied the role of adaptation in climate policy,<sup>4</sup> these studies have often abstracted from the fiscal implications of adaptation. In particular, many adaptive measures can only be (efficiently) provided by governments (Mendelsohn, 2000). However, when governments raise revenues with distortionary taxes, such as labor income taxes, interactions between climate and fiscal policy become welfare-relevant. For example, funding public adaptation projects, such as the construction of sea walls, requires the government to raise more revenue. To the extent that such adaptation policies thus require an increase in tax rates, they induce macroeconomic spillover effects that must be taken into account in climate policy design. A large literature<sup>5</sup> has already demonstrated the critical importance of distortionary taxes for the design of pollution *mitigation* policies, such as carbon taxes or emissions trading schemes (see, e.g., review by Bovenberg and Goulder, 2002). Expanding upon these findings, this paper studies the implications of the fiscal setting for the optimal policy mix between both climate change *mitigation and adaptation*. Specifically, I first theoretically characterize and then empirically quantify optimal adaptation and mitigation paths in a dynamic general equilibrium integrated assessment climate-economy model (IAM) with government spending requirements, social transfers, and (linear) distortionary taxes. More broadly speaking, this paper thus also builds on recent academic work on (i) climate policy in macroeconomic models (e.g., Golosov, Hassler, Krusell, and Tsyvinski, 2014; van der Ploeg and Withagen, 2012; Gerlagh and Liski, 2012; Acemoglu, Aghion, Bursztyn, and Hemous, 2011; Leach, 2009; etc.), (ii) optimal public goods provision in dynamic Ramsey models (e.g., Economides, Park, and Philippopoulos, 2011; Economides and Philippopoulos, 2008; Judd, 1999; etc.), (iii) the seminal climate-economy modeling work by Nordhaus (1991; 2000; 2008; 2010; 2013; etc.) as well as the broader IAM literature (e.g., PAGE2009, Hope, 2011; FUND 3.7, Tol and Anthoff, 2013; MERGE, Manne and Richels, 2005; etc.), and, of course, the growing literature on climate change adaptation versus mitigation.

The increasing policy and academic attention towards climate change adaptation is driven by

<sup>2</sup> For detailed listings of State and local plans in the U.S., see the Georgetown Law School Adaptation Clearinghouse <http://www.georgetownclimate.org/adaptation/state-and-local-plans>

<sup>3</sup> "Mayor Bloomberg Outlines Ambitious Proposal to Protect City Against the Effects of Climate Change to Build a Stronger, More Resilient New York" New York City Press Release PR- 201-13, June 11, 2013.

<sup>4</sup> Reviewed, e.g., by Agrawala, Bosello, Carraro, Cian, and Lanzi (2011), and discussed in more detail below.

<sup>5</sup> These include, inter alia: Sandmo (1975); Bovenberg and de Mooij (1994, 1997, 1998); Bovenberg and van der Ploeg (1994); Ligthart and van der Ploeg (1994); Goulder (1995; 1996; 1998); Bovenberg and Goulder (1996); Jorgenson and Wilcoxedn (1996); Parry, Williams, and Goulder (1999); Goulder, Parry, Williams, and Burtraw (1999); Schwarz and Repetto (2000); Cremer, Gahvari, and Ladoux (2001; 2010); Williams (2002); Babiker, Metcalf, and Reilley (2003); Bernard and Vielle (2003); Bento and Jacobsen (2007); West and Williams (2007); Carbone and Smith (2008); Fullerton and Kim (2008); Parry and Williams (2010); d’Autume, Schubert, and Withagen (2011); Kaplow (2013); Carbone, Morgenstern, Williams and Burtraw (2013); Barrage (2014); Goulder, Hafstead, and Williams (2014); etc.

three key factors. First, given the current state of international climate policy, substantial warming is projected by the end of the 21st Century, even with implementation of the Copenhagen Accord (Nordhaus, 2010).<sup>6</sup> Second, due to delays in the climate system, some warming from past emissions will continue even if greenhouse gas emissions stopped today. Third, adaptation plays a critical role in the fully optimized global climate policy mix (see, e.g., Mendelsohn, 2000) as some adaptation measures are comparatively low-cost. The literature has studied a variety of questions related to climate change adaptation (for a recent literature review, see, e.g., Agrawala, Bosello, Carraro, Cian, and Lanzi, 2011). These include the strategic implications of adaptation in non-cooperative settings (e.g., Antweiler, 2011; Buob and Stephan, 2011; Farnham and Kennedy, 2010); interactions between adaptation and uncertainty (Felgenhauer and de Bruin, 2009; Shalizi and Lecocq, 2007; Ingham, Ma, and Ulph, 2007; Kane and Shogren, 2000); comparative statics between macroeconomic variables and optimal adaptation (e.g., Bréchet, Hritonenko, and Yatsenko, 2013); and the optimal policy mix within the context of integrated assessment climate-economy models (e.g., Felgenhauer and Webster, 2013; Agrawala, Bosello, Carraro, de Bruin, De Cian, Dellink, and Lanzi, 2010; Bosello, Carraro, and De Cian, 2010; de Bruin, Dellink, and Tol, 2009; Tol, 2007; Hope, 2006.) There are also many empirical studies estimating the costs and/or benefits of adaptation in particular settings and sectors.<sup>7</sup> However, to the best of my knowledge, the academic literature has not formally considered the (differential) implications of the distortionary fiscal policy context for the climate change adaptation-mitigation tradeoff.

Of course, concerns about the fiscal impacts of climate change damages and adaptation needs have been voiced by a number of groups and authors. These include analyses by the U.S. Government Accountability Office (2013), the IMF (2008), and Egenhofer et al. (2010), who provide a detailed literature review, treatment of key issues, and several case studies focused on the European Union. Non-governmental organizations such as Ceres have also published reports emphasizing fiscal costs of climate change (Israel, 2013). Given the policy interest in this topic, along with the expectation of its importance based on the extensive literature on the implications of distortionary taxes for environmental policy design, this study thus seeks to contribute to the literature by formally exploring climate change costs and the optimal adaptation-mitigation policy mix in a dynamic general equilibrium climate-economy model with distortionary taxation. The model essentially integrates the COMET climate-economy model with linear distortionary taxes (Barrage, 2014) with a modified representation of the adaptation possibilities from the AD-DICE

<sup>6</sup> Specifically, Nordhaus (2010) predicts warming of  $3.5^{\circ}\text{C}$  by the year 2100 in the absence of climate policy, and that implementation of the Copenhagen Accord goals will reduce projected warming to only  $3.2^{\circ}\text{C}$  if emissions reductions are limited to wealthy countries.

<sup>7</sup> For reviews and aggregate studies, see, e.g., IPCC WGII (2007); Parry, Arnell, Berry, Dodman, Frankhauser, Hope, Kovats, and Nicholls (2009); World Bank EACC (2010); and Agrawala, Bosello, Carraro, Cian, and Lanzi (2011).

model (2010 version as presented in Agrawala, Bosello, Carraro, de Bruin, De Cian, Dellink, and Lanzi, 2010). Both the COMET and AD-DICE are IAMs based on the DICE/RICE modeling framework developed by Nordhaus (e.g., 2008; 2010). I follow AD-DICE in differentiating between adaptation capital investments (e.g., sea walls) and flow expenditures (e.g., increased fertilizer usage). However, as discussed below, my results confirm that I additionally need to differentiate between adaptive capacity to reduce climate change impacts on production (e.g., in agriculture) and direct utility losses (e.g., biodiversity existence values), respectively. The model thus seeks to account for these adaptation types separately.

Before summarizing the results, it should be emphasized that the literature's estimates of aggregate adaptation cost functions are at this stage still highly uncertain and require many strongly simplifying assumptions (Agrawala, Bosello, Carraro, Cian, and Lanzi, 2011). However, the main research question of this paper is how consideration of the fiscal setting *changes* the welfare implications and optimal mix of climate policy for a given adaptation technology assumed. That is, I take as given the literature's adaptation cost estimates, and focus on how fiscal considerations *alter* the optimal climate policy prescriptions associated with these cost estimates. The three main results are as follows.

First, public funding of flow adaptation inputs to reduce climate damages in the *final goods production sector* (e.g., sand bags to reduce storm damage to transport infrastructure) should remain undistorted regardless of the welfare costs of raising government revenues. Intuitively, while it is costly to raise revenues to fund these adaptation expenditures, they effectively 'pay for themselves' by increasing economic output. In fact, it is necessary for the government to dedicate the appropriate level of resources to these adaptation measures so as to ensure that the economy operates efficiently. That is, this first result reflects the well-known property that optimal tax systems must maintain aggregate production efficiency under fairly general conditions (Diamond and Mirrlees, 1971). By noting that public flow adaptation expenditures to reduce production damages are simply a public input to production, this result also follows directly from studies such as Judd (1999), who finds that public capital inputs to production should be fully provided even under distortionary Ramsey taxation.

Second, public funding for both flow and capital adaptation inputs to reduce direct utility losses from climate change (e.g., beach nourishment and sea walls to reduce sea-level rise impacts on archaeological sites) should be distorted when governments have to raise revenues with distortionary taxes. That is, some climate change impacts will affect environmental and cultural goods that may not be of productive value to the economy, but that society nonetheless values, such as cultural and archaeological sites, biodiversity existence values, etc. However, when governments have to raise revenues with distortionary taxes, the funding of public adaptation to reduce damages to these climate 'consumption goods' should be distorted. Intuitively, this is

because the government must distort the consumption of all goods in the economy, and consequently the enjoyment of the pure utility benefits of a healthy climate is effectively taxed as well. Perhaps surprisingly, I find that an intertemporal wedge remains between the marginal rates of transformation and substitution for adaptation capital investments to reduce utility damages from climate change, even when it is optimal to have no intertemporal distortions along any other margins (i.e., zero capital income taxes). That is, adaptation capital investments to reduce utility damages from climate change may be optimally distorted even when other capital investments should not be.

Third, the central quantitative finding is that the welfare costs of relying exclusively on adaptation to address climate change (i.e., without a carbon price) may be more than twice as large when distortionary tax instruments are used to raise the necessary revenues. In particular, at a global level, the welfare costs of relying only on adaptation and of not having a carbon price throughout the 21st Century are estimated to be \$22 trillion (\$2005) in a setting without distortionary taxes, \$23-24 trillion when additional revenue comes from labor or optimized distortionary taxes, and \$55 trillion when capital income taxes are used to raise additional funds.

The remainder of this paper proceeds as follows. Section 2 describes the model and derives the theoretical results. Section 3 discusses the COMET model the calibration of adaptation possibilities. Section 4 provides the quantitative results, and Section 5 concludes.

## 2 Model

The analytic framework extends the dynamic COMET (Climate Optimization Model of the Economy and Taxation) model of Barrage (2014) by adding several forms of adaptation. Her framework builds on the climate-economy models of Golosov, Hassler, Krusell, and Tsyvinski (2014) and Nordhaus (2008; 2011) by incorporating a classic dynamic optimal Ramsey taxation framework as presented by Chari and Kehoe (e.g., 1999). Barrage (2014) solves for optimal greenhouse gas mitigation policies across fiscal scenarios; here we consider four adaptation measures as an additional choice variables. Specifically, I consider both adaptation capital and flow inputs as modeled in the 2010 AD-DICE model (Agrawala, Bosello, Carraro, de Bruin, De Cian, Dellink, and Lanzi, 2010). In addition, I expand upon their framework by separately modeling adaptation to reduce the impacts of climate change on production possibilities and direct utility damages, respectively.

To briefly preview the model: an infinitely-lived, representative household has preferences over consumption, leisure, and the environment. In particular, climate change decreases his utility, but these impacts can be reduced through investments in utility adaptation. There are two production sectors. An aggregate final consumption-investment good is produced from

capital, labor, and energy inputs. Climate change affects productivity, but the impacts can be reduced through investments in production adaptation. Carbon emissions stem from a carbon-based energy input, which is produced from capital and labor. The government must raise a given amount of revenues as well as funding for climate change adaptation through distortionary taxes on labor, capital, and carbon emissions.<sup>8</sup>

The quantitative model accounts for additional elements such as exogenous land-based emissions, clean energy technology, population growth, and government transfers to households. However, these features are omitted from the analytic presentation since they do not affect the theoretical results.

## Households

A representative household has preferences over consumption  $C_t$ , leisure  $L_t$ , and the state of the climate  $T_t$ , along with adaptive capacity to reduce utility damages from climate change  $\Lambda_t^u$  (e.g., increased land conservation for species preservation). The household takes both the climate and adaptive capacity  $\Lambda_t^u$  as given. That is, adaptation  $\Lambda_t^u$  is publicly provided.

$$U_0 \equiv \sum_{t=0}^{\infty} \beta^t U(C_t, L_t, T_t, \Lambda_t^u) \quad (1)$$

Pure utility losses from climate change include biodiversity existence value losses, changes in the amenity value of the climate, disutility from human resettlement, and non-production aspects of health impacts from climate change, as discussed further below. The benchmark version of the model assumes additive separability between preferences over consumption, leisure, and the climate, and that adaptive capacity reduces the disutility from climate change via:<sup>9</sup>

$$U(C_t, L_t, T_t, \Lambda_t^u) = v(C_t, L_t) + h[(1 - \Lambda_t^u)T_t] \quad (2)$$

Intuitively, if adaptive capacity was at 100% ( $\Lambda_t^u = 1$ ), the impacts of any climate change  $T_t > 0$  on utility would thus be fully neutralized. Each period, the household allocates his income between consumption, the purchase of one-period government bonds  $B_{t+1}$  (at price  $\rho_t$ ), and investment in the aggregate private capital stock  $K_{t+1}^{pr}$ . The household's income derives from net-of-tax ( $\tau_{lt}$ ) labor income  $w_t(1 - \tau_{lt})L_t$ , net-of-tax ( $\tau_{kt}$ ) and depreciation ( $\delta$ ) capital income  $\{1 + (r_t - \delta)(1 - \tau_{kt})\} K_t^{pr}$ , government bond repayments  $B_t$ , and profits from the energy

<sup>8</sup> In particular, lump-sum taxes are assumed to be infeasible, in the Ramsey tradition. It is moreover assumed that the revenues raised from Pigouvian carbon taxes are insufficient to meet government revenue needs.

<sup>9</sup> The potential implications of non-separability between pollution, leisure, and consumption are theoretically well-known (see, e.g., Schwartz and Repetto, 2000; Carbone and Smith, 2008; or also discussion in Barrage, 2014). However, in line with the literature, I abstract from these issues here as the empirical values of these non-separabilities are essentially unknown.

production sector  $\Pi_t$ . The final consumption good is normalized to be the untaxed good. The household's flow budget constraint each period is thus given by:<sup>10</sup>

$$C_t + \rho_t B_{t+1} + K_{t+1}^{pr} \leq w_t(1 - \tau_{lt})L_t + \{1 + (r_t - \delta)(1 - \tau_{kt})\} K_t^{pr} + B_t + \Pi_t \quad (3)$$

As usual, the household's first order conditions imply that savings and labor supply are governed by the following decision rules:

$$\frac{U_{ct}}{U_{ct+1}} = \beta \{1 + (r_{t+1} - \delta)(1 - \tau_{kt+1})\} \quad (4)$$

$$\frac{-U_{lt}}{U_{ct}} = w_t(1 - \tau_{lt}) \quad (5)$$

where  $U_{it}$  denotes the partial derivative of utility with respect to argument  $i$  at time  $t$ .

## Production

The final consumption-investment good is produced with a constant returns to scale technology using capital  $K_{1t}$ , labor  $L_{1t}$ , and energy  $E_t$  inputs, assumed to satisfy the standard Inada conditions. In addition, output is affected by both the state of the climate  $T_t$  and adaptive capacity in final goods production,  $\Lambda_t^y$ :

$$\begin{aligned} Y_t &= F_{1t}(A_{1t}, L_{1t}, K_{1t}, E_t, T_t, \Lambda_t^y) \\ &= [1 - D(T_t)(1 - \Lambda_t^y)] \cdot \widetilde{F}_{1t}(A_{1t}, L_{1t}, K_{1t}, E_t) \end{aligned} \quad (6)$$

where  $A_{1t}$  denotes an exogenous total factor productivity parameter. Once again, if adaptive capacity were at 100% ( $\Lambda_t^y = 1$ ) this would imply that climate change impacts on production are fully neutralized. The modeling of climate production impacts as multiplicative factor was pioneered by Nordhaus (e.g., 1991). Production impacts include losses in sectors such as agriculture, fisheries, and forestry, changes in labor productivity due to health impacts, impacts of changes in ambient air temperatures on energy inputs required to produce a given amount of heating or cooling services, etc. (see, e.g., Nordhaus, 2007; Nordhaus and Boyer, 2000).

Profit maximization and perfect competition in final goods production imply that marginal products of factor inputs, denoted by  $F_{1it}$  for input  $i$  at time  $t$ , are equated to their prices in

<sup>10</sup> As in Barrage (2014), I assume that (i) capital holdings cannot be negative, (ii) consumer debt is bounded by some finite constant  $M$  via  $B_{t+1} \geq -M$ , (iii) purchases of government debt are bounded above and below by finite constants, and (iv) initial asset holdings  $B_0$  are given.

equilibrium. Letting  $p_{Et}$  denote the price of energy inputs, these conditions imply:

$$\begin{aligned} F_{1lt} &= w_t \\ F_{1Et} &= p_{Et} \\ F_{1kt} &= r_t \end{aligned} \tag{7}$$

Carbon-based energy inputs are assumed to be producible from capital  $K_{2t}$  and labor  $L_{2t}$  inputs through a constant returns to scale technology:

$$E_t = A_{2t} F_{2t}(K_{2t}, L_{2t}) \tag{8}$$

As discussed in Barrage (2014), consideration of non-renewable resource dynamics may change the optimal carbon tax level (to capture scarcity rents), but does not interact with the differential optimal policy treatment of production versus utility impacts of climate change. Consequently, I maintain the assumptions of perfect competition and constant returns to scale, which imply that profits from energy production  $\Pi_t$  will be zero in equilibrium:

$$\Pi_t = (p_{Et} - \tau_{Et})E_t - w_t L_{2t} - r_t K_{2t} \tag{9}$$

where  $p_{Et}$  represents the price of energy inputs and  $\tau_{Et}$  is the carbon tax.<sup>11</sup>

The numerical COMET model further considers an emissions reduction technology where a fraction of emissions  $\mu_t$  can be abated at a cost  $\Omega_t(\mu_t)$ , as in the DICE model (Nordhaus, 2008). For ease of illustration, and since it does not affect the analytic results, this section abstracts from a representation of this technology.

Both capital and labor are assumed to be perfectly mobile across sectors. Profit maximization thus implies that prices and marginal factors will be equated via:

$$\begin{aligned} (p_{Et} - \tau_{Et})F_{2lt} &= w_t \\ (p_{Et} - \tau_{Et})F_{2kt} &= r_t \end{aligned} \tag{10}$$

## Government: Fiscal and Climate Policy

The government faces two tasks: raising revenues to meet an exogenous sequence of expenditure requirements  $\{G_t > 0\}_{t=0}^{\infty}$  and choosing an optimal policy mix to address climate change. Following recent work in the adaptation-mitigation literature (e.g., Felgenhauer and Webster, 2013; Agrawala et al., 2010; de Bruin, 2011), I model adaptive capacity in sector  $i$ ,  $\Lambda_t^i$ , as an aggregate

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<sup>11</sup> Energy inputs are represented in terms of tons of carbon-equivalent; one unit of energy thus equals one ton of carbon emissions.



of both adaptation capital  $K_t^{\Lambda^i}$  (e.g., sea walls) and flow adaptation inputs  $\lambda_t^i$  (e.g., additional fertilizer):

$$\Lambda_t^i = f^i(K_t^{\Lambda^i}, \lambda_t^i) \quad (11)$$

Each period, the government thus needs revenues to finance government consumption  $G_t$ , the repayment of bonds  $B_t$ , flow adaptation expenditures  $\lambda_t^y$  and  $\lambda_t^u$ , and net new investment in adaptation capital stocks  $K_t^{\Lambda, i}$ . The government receives revenues from the issuance of new one-period bonds  $B_{t+1}$ , by levying linear taxes on labor and capital income, and through carbon taxes. The government's flow budget constraint is thus given by:

$$G_t + B_t + \lambda_t^y + \lambda_t^u + K_{t+1}^{\Lambda, y} + K_{t+1}^{\Lambda, u} \quad (12)$$

$$\leq \tau_{lt} w_t L_t + \tau_{Et} E_t + \tau_{kt} (r_t - \delta) K_t^{pr} + (1 - \delta)(K_t^{\Lambda, y} + K_t^{\Lambda, u}) + \rho_t B_{t+1} \quad (13)$$

The specification (12) differentiates itself from the standard Ramsey setup as in Chari and Kehoe (1999) through the inclusion of carbon taxes and adaptation expenditures, and differs from the climate-economy Ramsey model in Barrage (2014) through adaptation expenditures.

Given (12), we can summarize the market clearing conditions for the different capital stocks in the economy at time  $t$ :

$$K_t = K_{1t} + K_{2t} + K_t^{\Lambda, y} + K_t^{\Lambda, u} \quad (14)$$

$$= K_t^{pr} + K_t^{\Lambda, y} + K_t^{\Lambda, u} \quad (15)$$

Here, private capital is composed of final good and energy production sector capital:  $K_t^{pr} \equiv K_{1t} + K_{2t}$ . Specification (14) assumes that, over the 10-year time period considered in the model, capital is perfectly mobile across sectors. I moreover impose that depreciation rates are identical across sectors, although this assumption can easily be relaxed. Finally, I assume throughout that the government can commit to a sequence of tax rates at time zero.

## Climate System

The quantitative COMET model uses the 2010-DICE representation of the climate system and carbon cycle. However, for the purposes of this analytic section, the only assumption made is that temperature change  $T_t$  at time  $t$  is a function  $F_t$  of initial carbon concentrations  $S_0$  and all past carbon emissions:

$$T_t = F_t(S_0, E_0, E_1, \dots, E_t) \quad (16)$$

where:

$$\frac{\partial T_{t+j}}{\partial E_t} \geq 0 \quad \forall j, t \geq 0$$

## Competitive Equilibrium

A Competitive equilibrium ("CE") in this economy can now be defined as follows:

**Definition 1** *A competitive equilibrium consists of an allocation  $\{C_t, L_{1t}, L_{2t}, K_{1t+1}, K_{2t+1}, E_t, T_t, \lambda_t^y, \lambda_t^u, K_{t+1}^{\Lambda,y}, K_{t+1}^{\Lambda,u}\}$ , a set of prices  $\{r_t, w_t, p_{Et}, \rho_t\}$  and a set of policies  $\{\tau_{kt}, \tau_{lt}, \tau_{Et}, B_{t+1}^G\}$  such that:*

- (i) *the allocations solve the consumer's and the firm's problems given prices and policies,*
- (ii) *the government budget constraint is satisfied in every period,*
- (iii) *temperature change satisfies the carbon cycle constraint in every period, and*
- (iii) *markets clear.*

The social planner's problem in this economy is to maximize the representative agent's lifetime utility (1) subject to the constraints of (i) feasibility and (ii) the optimizing behavior of households and firms. I follow the *primal approach* (see, e.g., Chari and Kehoe, 1999), which solves for optimal allocations after having shown that and how one can construct prices and policies such that the optimal allocation will be decentralized by optimizing households and firms. The optimal allocation - the Ramsey equilibrium - is formally defined as follows:

**Definition 2** *A Ramsey equilibrium is the CE with the highest household lifetime utility for a given initial bond holdings  $B_0$ , initial aggregate private capital  $K_0^{pr}$  and abatement capital  $K_0^{\Lambda,y}$  and  $K_0^{\Lambda,u}$ , initial capital income tax  $\overline{\tau_{k0}}$ , and initial carbon concentrations  $S_0$ .*

Following the standard approach, one can now set up the primal planner's problem as per the following proposition:

**Proposition 1** *The allocations  $\{C_t, L_{1t}, L_{2t}, K_{1t+1}, K_{2t+1}, E_t, T_t, \lambda_t^y, \lambda_t^u, K_t^{\Lambda,y}, K_t^{\Lambda,u}\}$ , along with initial bond holdings  $B_0$ , initial aggregate private capital  $K_0^{pr}$  and adaptation capital  $K_0^{\Lambda,y}$  and  $K_0^{\Lambda,u}$ , initial capital income tax  $\overline{\tau_{k0}}$ , and initial carbon concentrations  $S_0$  in a competitive equilibrium satisfy:*

$$F_{1t}(A_{1t}, L_{1t}, K_{1t}, E_t, T_t, \lambda_t^y) + (1 - \delta)K_t \geq C_t + G_t + K_{t+1} + \lambda_t^y + \lambda_t^u \quad (\text{RC})$$

$$T_t \geq F_t(S_0, E_0, E_1, \dots, E_t) \quad (\text{CCC})$$

$$E_t \leq F_{2t}(A_{Et}, K_{2t}, L_{2t}) \quad (\text{ERC})$$

$$L_{1t} + L_{2t} \leq L_t \quad (\text{LC})$$

$$K_{1t} + K_{2t} + K_t^{\Lambda,y} + K_t^{\Lambda,u} \leq K_t \quad (\text{KC})$$

$$\begin{aligned}\Lambda_t^y &= f^y(K_t^{\Lambda y}, \lambda_t^y) \\ \Lambda_t^u &= f^u(K_t^{\Lambda u}, \lambda_t^u)\end{aligned}\tag{AdptC}$$

and

$$\sum_{t=0}^{\infty} \beta^t [U_{ct}C_t + U_{lt}L_t] = U_{c0} [K_0^{pr} \{1 + (F_{k0} - \delta)(1 - \tau_{k0})\} + B_0] \tag{IMP}$$

In addition, given an allocation that satisfies (RC)-(IMP), one can construct prices, debt holdings, and policies such that those allocations constitute a competitive equilibrium.

Proof: See Appendix. In words, *Proposition 1* implies that any allocation satisfying the six conditions (RC)-(IMP) can be decentralized as a competitive equilibrium through some set of prices and policies. For example, a sequence of carbon emissions satisfying (RC)-(IMP) can be implemented through some sequence of carbon taxes. Throughout the remainder of this paper, I assume that the solution to the Ramsey problem is interior and that the planner's first order conditions are both necessary and sufficient. The planner's problem is thus to maximize (1) subject to (RC)-(IMP) (see Appendix).

## Theoretical Results

Before discussing the results, one more definition is required. The *marginal cost of public funds* (*MCF*) is a measure of the welfare cost of raising an additional dollar of government revenues. When governments can use lump-sum taxes to raise revenues, then the marginal cost of public funds is equal to 1, as households give up \$1 in a pure transfer to the government. However, when revenues are raised through distortionary taxes, the costs of raising \$1 will equal \$1 plus the excess burden (or marginal deadweight loss) of taxation. Barrage (2014) presents a GDP-weighted estimate of the *MCF* based on a review of the literature estimating the *MCF* across countries and tax instruments equal to 1.5, implying that on average \$0.50 is lost for every \$1 of government revenue raised. Following the literature on optimal pollution taxes and distortionary taxes, formally define the marginal cost of public funds in this model as equal to the ratio of public to private marginal utility of consumption:

$$MCF_t \equiv \frac{\lambda_{1t}}{U_{ct}} \tag{17}$$

where  $\lambda_{1t}$  is the Lagrange multiplier on the resource constraint (RC) in the planner's problem. The wedge between the marginal utility of public and private income thus serves as a measure of the distortionary costs of the tax system.

Given (17), we can state the theoretical results. Consider first the optimal provision of flow adaptation inputs to reduce production damages from climate change (e.g., fertilizer subsidies,

sand bags, mosquito control sprayings, etc.):

**Result 1** *Public funding of flow adaptation inputs to reduce climate damages in the final goods production sector should remain undistorted regardless of the welfare costs of raising government revenues. That is, flow adaptation to reduce production damages should be fully provided.*

Before discussing this result in further detail, it is important to define the notion of "undistorted" provision of public goods. The actual dollar amount of optimal spending will differ depending on the fiscal setting. However, Result 1 implies that there is no "wedge" (or distortion) in the optimality condition for spending on flow adaptation inputs to reduce production damages from climate change: the government should spend resources on these adaptation goods until the additional benefits in terms of avoided output losses equals the marginal adaptation cost of producing this increased adaptive capacity. More formally, as shown in the Appendix, the optimal policy equates the marginal rate of transformation between  $C_t$  and adaptive capacity  $\Lambda_t^y$  through expenditures on flow adaptation inputs  $\lambda_t^y$  ( $\text{MRT}_{C_t, \Lambda_t^y}^{f_t^y}$ ) and avoided output losses from climate change in the final goods sector ( $\text{MRT}_{C_t, \Lambda_t^y}^{F_{1Tt}}$ ):

$$\underbrace{(-F_{1Tt}D(T_t))}_{\text{MRT}_{C_t, \Lambda_t^y}^{F_{1Tt}}} = \underbrace{\frac{1}{f_{\lambda_t}^y}}_{\text{MRT}_{C_t, \Lambda_t^y}^{f_t^y}} \quad (18)$$

Here,  $F_{1Tt}$  denotes the marginal production losses in the final output sector due to a change in temperature at time,  $t$  and  $D(T_t)$  is the damage function. The left-hand side of (18) consequently measures the increase in the final consumption good available due to a marginal increase in adaptive capacity in the final goods sector ( $\Lambda_t^y$ ). Conversely, the right-hand side represents the marginal rate of transformation between the consumption good  $C_t$  and adaptive capacity through flow adaptation expenditures  $\lambda_t^y$ : One unit of the final consumption good is required to increase flow adaptation expenditures by one unit, which, in turn, increases adaptive capacity through its marginal product in the adaptation production function,  $f_{\lambda_t}^y$ . While expression (18) will be evaluated at different allocations that depend on the tax system, a potential wedge between the private and public marginal utility of income (a  $MCF > 1$ ) does not lead to a wedge in expression (18). Distortions in the economy due to the tax code thus do not imply distortions in the optimal provision of flow adaptation expenditures to reduce production impacts of climate change. (Importantly, this result stands in contrast to other adaptation expenditures, as discussed below.) Intuitively, while it is costly for the government to raise revenues to fund

these adaptation expenditures, at the optimal level they 'pay for themselves' by increasing output

(and thereby also expanding the bases of labor and capital income taxes). This result is thus a consequence of the well-known property that optimal tax systems maintain aggregate production efficiency under fairly general conditions (Diamond and Mirrlees, 1971). By noting that public adaptation expenditures to reduce production damages are simply a public input to production, this result likewise follows from studies such as Judd (1999), who finds that public flow productive inputs should always be fully provided, regardless of the distortionary costs of raising revenues.

Next, and in contrast, consider the provision of flow adaptation expenditures to reduce utility impacts of climate change (e.g., beach nourishment to maintain public parks). While these expenditures increase utility, they do not yield a productivity benefit that could counteract the macroeconomic costs of raising the government revenues required to fund them. Consequently, I find that the optimal provision of these adaptation expenditures is distorted proportionally to the marginal cost of raising public funds. More specifically, as shown in the Appendix, the optimality condition governing these expenditures is given by:

$$\underbrace{\frac{(-U_{Tt}T_t)}{U_{ct}}}_{\text{MRS}_{C_t, \Lambda_t^u}} \underbrace{\frac{1}{MCF_t}}_{\text{wedge}} = \underbrace{\frac{1}{f_{\lambda_t}^u}}_{\text{MRT}_{C_t, \Lambda_t^u}^{f_t^u}} \quad (19)$$

The first term on the left-hand side of equation (19) is the representative household's marginal rate of substitution (MRS) between the final consumption good and adaptive capacity to reduce climate change utility impacts. The right-hand side equals the marginal cost of increasing this adaptive capacity, or the marginal rate of transformation (MRT) between the final consumption good and adaptive capacity (through increased flow expenditures  $\lambda_t^u$ ). However, contrary to equation (18) here there is a *wedge* between the MRS and MRT, proportional to the distortionary cost of the tax system.

**Result 2** *Public funding of flow adaptation inputs to reduce direct utility losses from climate damages should be distorted when governments have to raise revenues with distortionary taxes. That is, the provision and thus consumption of the climate adaptation good should be distorted alongside the consumption of other goods when governments must impose distortionary taxes.*

Intuitively, the wedge between the MRT and MRS for the flow adaptation good for utility damages in (19) can be thought of as an implicit tax on the consumption of the climate adaptation good. Just like any consumption good in this economy, the climate adaptation good will be 'taxed' by being less-than-fully provided (compared to a setting with lump-sum taxation).<sup>12</sup>

<sup>12</sup> As noted by the discussant of this chapter, Elisa Belfiori, in an analogous model where adaptation is privately purchased, the optimal policy implies an explicit tax on the adaptation good to reduce utility impacts of climate change.

Both Result 1 and Result 2 are closely related to a set of findings in the environmental tax interaction literature regarding the internalization of environmental impacts affecting utility versus production (Bovenberg and van der Ploeg, 1994; Williams, 2002; Barrage, 2014). These studies find that the optimal pollution tax formula internalizes production damages 'fully' (without a wedge), whereas a large literature has demonstrated that utility damages are 'less-than-fully' internalized (with a wedge) when there are other, distortionary taxes (see, e.g., review by Bovenberg and Goulder, 2002). However, as shown by Barrage (2014), additional considerations apply to dynamic environmental impacts of stock pollutants. As discussed below, I similarly find that the optimal policy rules governing investment in adaptation capital may differ from those for flow adaptation expenditures described above.

Consider first the decision to invest in private capital. The marginal rate of transformation between consumption in periods  $t$  and  $t + 1$  based on private capital investments in final goods production is given by:

$$MRT_{C_t, C_{t+1}}^{K_{1t}} = \frac{1}{F_{k_{t+1}} + (1 - \delta)} \quad (20)$$

The household's marginal rate of substitution between  $C_t$  and  $C_{t+1}$  is moreover given by:

$$MRS_{C_t, C_{t+1}} = \frac{\beta U_{ct+1}}{U_{ct}} \quad (21)$$

Investment decisions in private capital are undistorted if  $MRT_{C_t, C_{t+1}}^{K_{1t}} = MRS_{C_t, C_{t+1}}$ . As can readily be seen from a simple comparison of (20), (21), and the household's Euler Equation (4), undistorted investment margins require effective capital income taxes ( $\tau_{kt+1}$ ) to be equal to zero. As is well-known in the public finance literature, it is indeed optimal for the government to leave private investment decisions undistorted in a wide range of settings (see, e.g., Chamley, 1986; Judd, 1985; Atkeson, Chari, and Kehoe, 1999, Acemoglu, Golosov, Tsyvinski, 2011, etc.). A central finding of this section is that this condition determines optimal climate change adaptation investments as well.

On the one hand, public investments in adaptation capital to reduce the *output losses* from climate change (e.g., sea walls to protect productive infrastructure) transform consumption in period  $t$  into additional output in period  $t + 1$ , just as private capital investments. More specifically, giving up 1 unit of  $C_t$  to invest in adaptation capital  $K_{t+1}^{\Lambda, y}$  increases adaptive capacity in the output sector at time  $t + 1$  by  $f_{K_{t+1}}^y$  units. In terms of the final consumption good, this investment thus yields a return of  $f_{K_{t+1}}^y \cdot \widetilde{D(T_{t+1})F_{1t+1}}(\cdot)$  units, plus the undepreciated capital. The marginal rate of transformation between  $C_t$  and  $C_{t+1}$  based on investments in production adaptation capital is thus given by:

$$MRT_{C_t, C_{t+1}}^{K\Lambda y} = \frac{1}{f_{K_{t+1}}^y D(T_{t+1}) \widetilde{F_{1t+1}}(.) + (1 - \delta)} \quad (22)$$

As shown in the Appendix, the optimal policy mix equates the returns to investing in private and public capital, (20) and (22), respectively. Importantly, this implies that public investment in production adaptation capital is undistorted ( $MRT_{C_t, C_{t+1}}^{K\Lambda y} = MRS_{C_t, C_{t+1}}$ ) whenever investment decisions in private capital are undistorted (i.e., when the government optimally sets capital income taxes to zero).

**Result 3** *The optimal policy in period  $t > 0$  features undistorted (full) public investment in adaptation capital to reduce production damages from climate change if the optimal policy leaves private capital investment undistorted (zero capital income tax). In this case, the government should invest fully in production adaptation capital even though the necessary revenues are raised with distortionary taxes.*

The intuition for this result is simple: if the structure of the economy is such that it is optimal not to distort productive investments, then this holds true for both private and public capital. The implementation of this undistorted allocation requires a zero effective capital income tax as well as full public provision of adaptation capital.

Finally, consider on the other hand investments in adaptation capital to reduce climate change utility damages. In contrast to production adaptation capital, the return to these investments consists of future environmental quality, rather than future consumption. That is, the relevant intertemporal margin is between  $C_t$  and  $-T_{t+1}$ .<sup>13</sup> With regards to the MRT, giving up 1 unit of  $C_t$  to marginally increase utility adaptation capital  $K_{t+1}^{\Lambda, u}$  decreases the effective amount of temperature change entering the utility function by  $f_{K_{t+1}}^u$ , and thus increases the climate amenity by a total of  $-T_{t+1} f_{K_{t+1}}^u$  units. In addition, this investment will leave  $(1 - \delta) K_{t+1}^{\Lambda, u}$  units of the final consumption-investment good available after depreciation. Denominated in equivalent units of the climate amenity, the value of this leftover capital after an increase in  $K_{t+1}^{\Lambda, u}$  by one unit is given by  $\frac{(1-\delta)U_{ct+1}}{-U_{Tt+1}}$ . In sum, the MRT between  $C_t$  and  $-T_{t+1}$  based on investments in adaptation capital is thus given by:

$$MRT_{C_t, T_{t+1}}^{K\Lambda u} = \frac{1}{-T_{t+1} f_{K_{t+1}}^u + \frac{(1-\delta)U_{ct+1}}{-U_{Tt+1}}} \quad (23)$$

The representative agent's MRS between  $C_t$  and  $-T_{t+1}$  is conversely given by:

$$MRS_{C_t, T_{t+1}} = \frac{\beta U_{Tt+1}}{U_{ct}} \quad (24)$$

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<sup>13</sup> Here, as temperature change  $T_{t+1}$  denotes an environmental bad, the reduction (or negative) of this bad  $-T_{t+1}$  represents an improvement in environmental quality, or the environmental consumption good.

Equating (23) and (24) and rearranging terms, one can see that, in order for investments in utility damages adaptation capital to be undistorted, it must be the case that:

$$\begin{aligned}
MRS_{C_t, T_{t+1}} &= MRT_{C_t, T_{t+1}}^{K\Lambda u} \\
&\Leftrightarrow \\
\frac{U_{ct}}{\beta U_{ct+1}} &= (1 - \delta) + \frac{(-U_{Tt+1}T_{t+1})}{U_{ct+1}} f_{Kt+1}^u
\end{aligned} \tag{25}$$

As shown in the Appendix, the government's optimality condition does not generally coincide with (25) when revenues are raised through distortionary taxes. That is, when the marginal cost of public funds exceeds unity ( $MCF_{t+1} > 1$ ), public investment in adaptation capital to reduce climate change utility damages is distorted at the optimum. For example, if preferences take one of the commonly used constant elasticity forms (27)-(28), the government's optimality condition for utility adaptation investment for  $t > 1$  becomes (see Appendix):

$$\frac{U_{ct}}{\beta U_{ct+1}} = (1 - \delta) + \left[ \frac{(-U_{Tt+1}T_{t+1})}{U_{ct+1}} \frac{1}{MCF_{t+1}} f_{Kt+1}^u \right] \tag{26}$$

A simple comparison of (25) and (26) thus demonstrates that the planner's optimality condition (26) for utility adaptation capital investments features a wedge between the  $MRS$  and  $MRT$ . Intuitively, this is because the planner values the household's future climate change disutility based on the public marginal utility of income, whereas the household values this disutility based on the private marginal utility of consumption. When there are distortionary taxes in the economy, there is an excess cost (deadweight loss) associated with the transfer of one dollar from households to the government. Consequently, the public and private marginal utilities of income diverge, and the optimal provision of public utility adaptation capital is distorted. This wedge in (26) also corresponds to an implicit tax on utility adaptation capacity, which is taxed (distorted) at the optimum just like all other consumption goods in the optimal tax code. As before, the contrast to the optimal treatment of output adaptation capital emerges because the optimal overall fiscal policy leaves productive investments and intermediate goods undistorted, and imposes all distortions on the consumption side of the economy. The final theoretical result can thus be summarized as follows:

**Result 4** *The optimal policy at time  $t > 0$  leaves investment in adaptation capital to reduce direct utility impacts from climate change distorted if governments raise revenues through distortionary taxes (specifically if  $MCF_{t+1} > 1$ ). In addition, optimal investment in utility adaptation capital remains distorted even if it is optimal for there to be no distortions on*



*investment in private capital (no capital income tax) and public adaptation capital to reduce production impacts of climate change.*

Finally, the four theoretical results can be formally summarized by the following proposition.

**Corollary 1** *If preferences are of either commonly used constant elasticity form,*

$$U(C_t, L_t, T_t, \Lambda_t^u) = \frac{C_t^{1-\sigma}}{1-\sigma} + \vartheta(L_t) + h(T_t(1 - \Lambda_t^u)) \quad (27)$$

$$U(C_t, L_t, T_t, \Lambda_t^u) = \frac{(C_t L_t^{-\gamma})^{1-\sigma}}{1-\sigma} + h(T_t(1 - \Lambda_t^u)) \quad (28)$$

*then, after period  $t > 1$  :*

*(i) investment in private capital should be undistorted (the optimal capital income tax is zero),*

*(ii) investment in public adaptation capital to reduce climate change production damages should be undistorted;*

*(iii) investment in public adaptation capital to reduce climate change direct utility damages in period  $t$  should be distorted in proportion to the marginal cost of public funds in period  $t + 1$ ;*

*(iv) public flow adaptation expenditures to reduce climate change production damages should be undistorted (satisfy productive efficiency);*

*(v) public flow adaptation expenditures to reduce climate change direct utility damages in period  $t$  should be distorted in proportion to the marginal cost of public funds in period  $t$ ; and:*

*(ii) the optimal carbon tax is implicitly defined by:*

$$\tau_{Et}^* = \tau_{Et}^{Pigou,Y} + \frac{\tau_{Et}^{Pigou,U}}{MCF_t} \quad (29)$$

Proof: See Appendix. Intuitively, the proof follows straightforwardly from Results 1 – 4. It should be noted that the optimality of zero capital income taxes in periods  $t > 1$  for these types of constant elasticity preferences is the classic Chamley-Judd result (Chamley, 1986; Judd, 1985) as subsequently demonstrated, e.g., by Chari and Kehoe (1999).

The expression implicitly defining the optimal carbon tax (29) is identical in form to the one presented by Barrage (2014) for this model without adaptation.<sup>14</sup> Introducing non-degenerate government revenue needs (to finance adaptation) does thus not lead to a change in the formulation defining the optimal carbon tax. Intuitively, this is the case because carbon taxes in this model fall on energy inputs, which are an intermediate good. Consequently, carbon is not a desirable tax base in excess of the internalization of the externality from climate change damages

<sup>14</sup> Of course, the value of the optimal tax will differ between the models as the implicit expression is evaluated at different allocations when there are adaptation possibilities.

(see, e.g., Diamond and Mirrlees, 1971; also discussion by Goulder, 1996). Consequently, useful additional revenues to finance adaptation will be raised through other means, such as labor income taxes.

The theoretical results presented in this Section are limited to qualitative statements based on implicit expressions. In order to solve the model and assess the quantitative importance of the fiscal context for the optimal adaptation-mitigation policy mix and the welfare costs of climate change, the next Section describes the numerical implementation and calibration of the model.

### 3 Adaptation Cost Function Calibration

Several special challenges arise in the calibration of adaptation cost functions. On the one hand, bottom-up studies are limited both in terms of sectors and regions covered. In addition, bottom-up studies often do not report their results in sufficiently comparable metrics that would permit straightforward integration into a single cost function. Finally, estimating adaptation costs in certain sectors is extraordinarily difficult. For example, with regards to ecosystems and species preservation, the best estimate identified by the UNFCCC (2007) was based on a study that estimated the costs of increasing the amount of globally protected lands. Whether and to which extent such a policy would reduce climate change impacts on ecosystems is extremely difficult to quantify. Consequently, existing aggregate adaptation cost functions are often acknowledged to be highly uncertain, and require many simplifying assumptions (see discussion by, e.g., Agrawala, Bosello, Carraro, Cian, and Lanzi, 2011).

A number of IAM studies on adaptation rely on cost functions backed out from the DICE/RICE model family (Nordhaus, 2011; Nordhaus and Boyer, 2000; Nordhaus, 2008, etc.) The DICE damage function uses adaptation-inclusive cost estimates in sectors such as agriculture. Studies such as de Bruin, Dellink, and Tol (2009) thus seek to split the DICE damage function into gross damages and adaptation costs, calibrating the model such that the benchmark result duplicates the DICE net damages path. As discussed by Agrawala, Bosello, Carraro, Cian, and Lanzi (2011), additional studies based on this kind of approach include Bahn et al. (2010), Hof et al. (2009), and Bosello et al. (2010). Other studies and models, notably the FUND model (Tol, 2007) features sector-specific adaptation to sea-level rise, based on bottom-up adaptation cost studies of specific measures such as building dikes. Finally, the PAGE model (Hope et al., 1993; Hope, 2006, 2011) features (exogenous) adaptation variables which can reduce climate damages in several distinct ways. The PAGE model also differentiates between adaptation to economic and non-economic impacts of climate change. This study uses a modified version of the adaptation cost and gross damage estimates underlying the calibration of the AD-DICE/-RICE model, as detailed in Agrawala, Bosello, Carraro, de Bruin, de Cian, Dellink, and Lanzi (2010).

The authors combine a backing-out procedure based on the DICE/RICE models with results from other adaptation studies (e.g., Tan and Shibasaki (2003) on agriculture) and modelers' judgment to provide adaptation cost and effectiveness estimates across the sectors and regions of the RICE model. The key modifications required to use their estimates in this paper is to separately estimate adaptation and gross damage functions for production and utility damages, and to recalibrate so as to reproduce benchmark results in the context of the COMET model.

I focus on public adaptation efforts. In reality, climate change adaptation consists of both public and private actions, as discussed by Mendelsohn (2000). I thus exclude adaptation to climate change impacts on the value of leisure time use, as those are unambiguously private (see AD-DICE 2010).<sup>15</sup> In the other sectors, adaptation will likely be a mix of public and private actions.<sup>16</sup> However, private adaptation costs that are borne by (competitive) firms are equivalent to public adaptation costs in the COMET model, as both figure analogously into the economy's resource constraint of the final consumption-investment good. In other words, since the government is assumed to have to raise a given amount of revenue regardless of climate change adaptation, decreasing aggregate output by one unit affects the problem equivalently to an increase in required government expenditure by one unit. The modeling of adaptation costs in the COMET is thus only with a loss of generality if those costs are actually borne by *households*. To the extent that the latter case would lead to non-separability between preferences over climate change, consumption, and leisure, this would be expected to change the results, as prior research on optimal emissions taxes and non-separability has shown (see, e.g., Schwarz and Repetto, 2002; Carbone and Smith, 2008). While this is an important area for future research, in the current setting I focus on adaptation costs borne by the public and production sectors as those are presumably much larger in magnitude than household-level adaptation costs.

## 4 Calibration

In order to assess the quantitative importance of the distortions discussed above, I integrate an explicit adaptation choice into the Climate Optimization Model of the Economy and Taxation (COMET) presented by Barrage (2014). The COMET is based on the seminal DICE climate-economy modeling framework (Nordhaus, 2008, 2010, etc.). It is a global growth model with two production sectors: a final consumption-investment good is produced using capital, labor, and energy inputs, and energy is produced from capital and labor. Production further depends on

<sup>15</sup> That is, for time use impacts, I exclude the estimated adaptation costs and retain *net* damages in the cost and damages aggregation based on AD-DICE 2010.

<sup>16</sup> For example, IFPRI (2009) estimates the costs of offsetting climate change impacts on nutrition through agricultural research, rural roads, and irrigation. Research and roads - presumably both public goods - are estimated to account for close to 60% of optimal adaptation efforts in 2050.

the state of the global climate. There is both clean and carbon-based energy. Consumption of the latter leads to carbon emissions which accumulate in the atmosphere and change the climate. The climate system is modeled exactly as in DICE, with three reservoirs (lower ocean, upper ocean/biosphere, atmosphere) and including exogenous land-based emissions. The COMET differs from DICE in several key ways necessary to incorporate a simple representation of fiscal policy. First, households have preferences over consumption, leisure, and the climate (separably). A globally representative government faces the dual task of raising revenues and addressing climate change. The government can issue bonds and impose linear taxes on labor, capital income, and energy inputs. It faces an exogenous sequence of government consumption requirements and household transfer obligations. These are calibrated based on IMF Government Finance Statistics to match globally representative government spending patterns. See Barrage (2014) for details.

Importantly, adaptation to climate change is only implicitly considered in the COMET through the damage function (based on DICE), which is net of adaptation. This study thus extends the COMET by adding gross damage functions and adaptation choice variables to reduce climate change impacts on both production processes and utility. In order to maintain comparability to the literature and as a benchmark, I calibrate the COMET gross damage and adaptation cost functions based on regional-sectoral estimates underlying the AD-DICE model and as presented by Agrawala, Bosello, Carraro, de Bruin, de Cian, Dellink, and Lanzi (2010). The AD-DICE model aggregates these estimates into a single gross damage and adaptation cost function; however in the setting with distortionary taxes, both damages and adaptation needs to be considered separately for production and utility impacts, as demonstrated in the theoretical section above. In order to provide separate estimates for production and utility damages, I thus disaggregate the AD-DICE estimates according to the same procedure as outlined in Barrage (2014). Specifically, the different sectoral damages are disaggregated according to:

Impact/ Adaptation Category	Classification
Agriculture	Production
Other vulnerable markets (energy services, forestry production, etc.)	Production
Sea-level rise coastal impacts	Production
Amenity value	Utility
Ecosystems	Utility
Human (re)settlement	Utility
Catastrophic damages	Mixed
Health	Mixed

Table 1: Climate Damage Categorization

Health impacts are classified as affecting both production and utility as losses in available time due to disease reduces both work time endowments and leisure time. The COMET consequently converts disease-adjusted years of life lost into an equivalent TFP loss from a reduction in the global aggregate labor time endowment, and values the non-work share of time losses at standard value of statistical life figures (see Barrage (2014) for details). I follow the same approach here to convert the gross (of adaptation) damage estimates presented by Agrawala et al. (2010) into gross production and utility losses from health impacts of climate change.

Catastrophic impacts of climate change are also assumed to affect both production possibilities and utility directly. I assume that the relative importance of production/utility impacts of a severe climate event in each region is proportional to the relative importance of production/utility impacts across the other sectors outlined in Table 1.<sup>17</sup> I weigh both damages and adaptation costs in each region by the predicted output based on the 2010-RICE model (Nordhaus, 2011) in the relevant calibration year. Re-aggregating across regions and sectors leads to the following results for climate change impacts and optimal adaptation at  $2.5^{\circ}C$  :

COMET Adaptation Calibration Estimates at  $2.5^{\circ}C$

	Production ( $Y$ )	Utility ( $U$ )	AD-DICE (Agg.)
Gross Damages (% GDP)	2.2%	0.7%	2.25%
Flow Adaptation Cost (% GDP)	0.24%	0.03%	0.17%
Stock Adaptation Cost (% GDP)	0.23%	0.12%	0.21%
Total Adaptation Cost (% GDP)	0.47%	0.15%	0.38%
Adaptation Effectiveness (% Damages Avoided)	52%	60%	46%
Residual Damages	1.1%	0.3%	1.21%

Table 2: Disaggregated Adaptation Estimates

The modified damage and adaptation estimates are thus generally higher than the aggregated results in AD-DICE. Such difference may arise, for example, due to alternative weights used in the global aggregation of damages, which in the COMET are based on predicted 2065 global output shares (that weight developing regions' impacts relatively more than 2010 weights). Additional challenges in directly adopting AD-DICE parameters arise from the generally different structure of the COMET which features endogenous investment, labor supply, energy production, etc. Table 3 summarizes the key moments I seek to match in the calibration of gross damages and adaptation costs, as well as the actual model output for the benchmark COMET model run

<sup>17</sup> However, as in Barrage (2014), time use values are excluded from the calculation of the distribution of catastrophic impacts across production/utility damages, as such severe events are assumed to affect predominantly the other impact sectors.

without distortionary taxes. That is, I seek to match the following moments in the COMET before introducing distortionary taxes (specifically while allowing lump-sum taxation).

Moment	Target	Model	Target Source:
Opt. max temperature change ( $^{\circ}C$ )	2.96	2.99	COMET without dist. taxes and without adaptation
Opt. $Y$ -adaptation effect at $\sim 2.5^{\circ}C$	52%	44%	Re-aggregation of AD-DICE Damages
Opt. $U$ -adaptation effect at $\sim 2.5^{\circ}C$	60%	47%	Re-aggregation of AD-DICE Damages
Opt. Y-adaptation cost at $\sim 2.5^{\circ}C$ (% GDP)	0.47%	0.32%	Re-aggregation of AD-DICE Damages
Opt. U-adaptation cost at $\sim 2.5^{\circ}C$ (% GDP)	0.16%	0.13%	Re-aggregation of AD-DICE Damages
Opt. Carbon Tax ( $\$/mtC$ in 2015)	70	68	COMET without dist. taxes and without adaptation

Table 3: COMET Adaptation Calibration Targets and Results

The functional forms used to model gross damages and adaptive capacity are chosen and modified relative to AD-DICE as follows. The AD-DICE model considers gross damages (as a fraction of GDP) given by  $GD = \alpha_1 T_t + \alpha_2 T_t^{\alpha_3}$ . I maintain their functional form to represent both production and utility damages, but adjust the damage function by parameters  $\theta^y$  and  $\theta^u$  in order to match benchmark estimates of gross damages at  $2.5^{\circ}C$  as discussed above. Specifically, I thus assume that net output is given by:

$$Y_t = \left( \frac{1}{1 + (1 - \Lambda_t^y) \cdot \theta^y [\alpha_1 T_t + \alpha_2 T_t^{\alpha_3}]} \right) \cdot A_t \widetilde{F}_1(K_{1t}, L_{1t}, E_t) \quad (30)$$

where  $\Lambda_t^y$  represents adaptive capacity (fraction of damages reduced) as in the theoretical model outlined above. Similarly, utility is modeled as having preferences over an environmental good that diminishes with climate change according to:

$$U = \frac{(C_t(1 - \phi l_t)^{\gamma})^{1-\sigma}}{1 - \sigma} + \frac{1}{1 - \sigma} \left( \frac{1}{1 + (1 - \Lambda_t^u) \cdot \theta^u [\alpha_1 + \alpha_2 T_t^{\alpha_3}]} \right)^{1-\sigma} \quad (31)$$

Finally, I use the AD-DICE functional form used to represent the adaptation technology:

$$\Lambda_t^i = \beta_1 \left( \beta_2 (\lambda_t^i)^{\rho} + (1 - \beta_2) (K_t^{\Lambda, i})^{\rho} \right)^{\frac{\beta_3}{\rho}} \quad (32)$$

In order to match the desired moments indicated above, I have to adjust several of the parameters in (30)-(32) relative to what is used in the AD-DICE model. With these adjustments, however, the benchmark (no distortionary taxes) COMET results arguably replicate the desired moments reasonably well, as shown in Table 3.

## 5 Quantitative Results

The analysis focuses on four central fiscal scenarios:

1. A "First-Best" scenario *without distortionary taxes*, where the government can raise revenues through lump-sum taxation. This is the benchmark scenario used to calibrate the model to match the literature, as discussed in the preceding section. The literature typically assumes no distortionary taxes.
2. A "Total Tax Reform" scenario with fully optimized distortionary taxes.
3. A "Green Tax Reform,  $\tau_k$  Revenue Recycle" scenario where labor income tax rates are held fixed at baseline levels (35.19%). Carbon tax revenues can be used ("recycled") to reduce capital income taxes and/or to finance adaptation expenditures.
4. A "Green Tax Reform,  $\tau_l$  Revenue Recycle" scenario where capital income tax rates are held fixed at baseline levels (39.35%). Carbon tax revenues can be used to reduce labor income taxes and/or to finance adaptation expenditures.

Figure 1 shows the evolution of optimal temperature change<sup>18</sup> across these four scenarios. While the differences across scenarios are small, I find that the optimal amount of climate change tolerated across scenarios is increasing in the welfare costs of distortionary taxes.

Intuitively, the reason for this finding is that carbon taxes exacerbate the welfare costs of other taxes. This finding is in line with the long-standing previous literature on this topic (see, e.g., Goulder, 1996; Bovenberg and Goulder, 2002, etc.). Indeed, I find that optimal climate change mitigation is lower, the more distortionary the tax system, as demonstrated in Figure 2.

The corresponding carbon tax schedules are depicted in Figure 3. Again, the key result is that optimal carbon levies are generally lower when there are other, distortionary taxes, in line with the previous literature.<sup>19</sup>

Finally, Figures 4 and 5 show the amount of adaptation to climate change impacts on production and utility, respectively. In particular, the graphs depict the fraction of climate change impacts avoided due to both flow and capital investments in adaptive capacity.

The results suggest that the government engages in more adaptation in the fiscal scenarios where the tax code is more distortionary. This result may seem counterintuitive in light of

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<sup>18</sup> Throughout this paper, temperature change refers to mean atmospheric surface temperature change over pre-industrial levels in degrees Celsius.

<sup>19</sup> It should be noted that the carbon tax is defined as the difference between total taxes imposed on carbon-based and clean energy. This is because, in the Green Tax Reform with  $\tau_k$  Revenue Recycling, the government imposes a tax on all types of energy in addition to the carbon tax. The reason for this tax is that both types of energy usage increase the tightness with which the fixed labor income tax constraint binds.

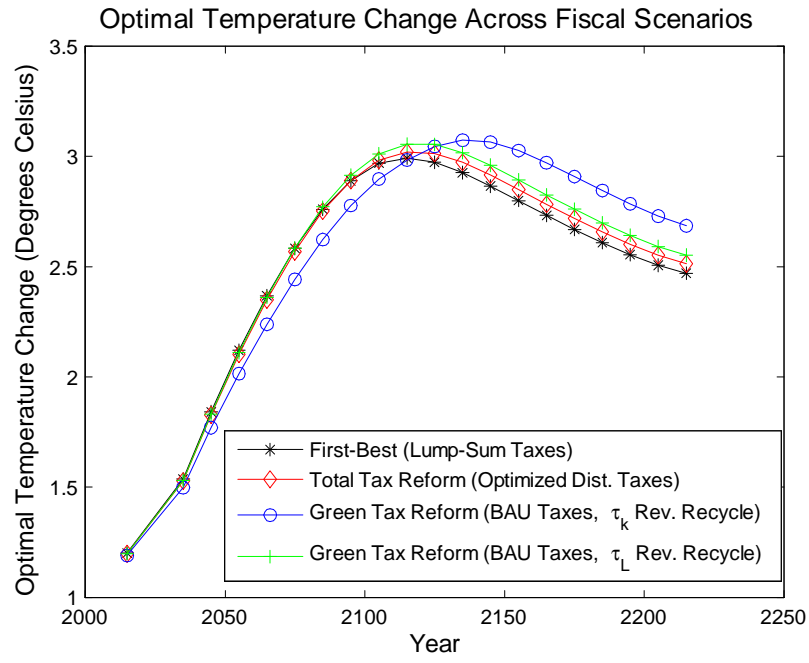


Figure 1: Figure 1

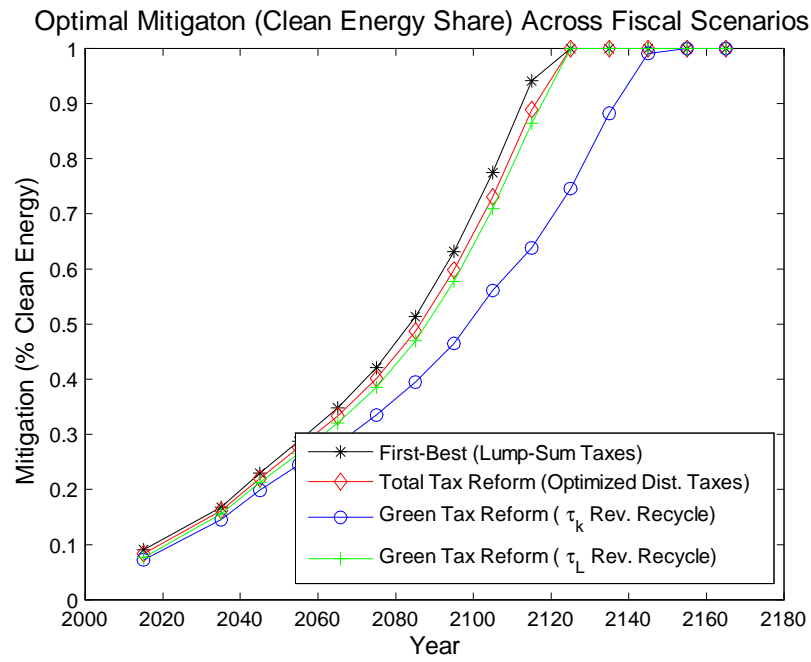


Figure 2: Figure 2



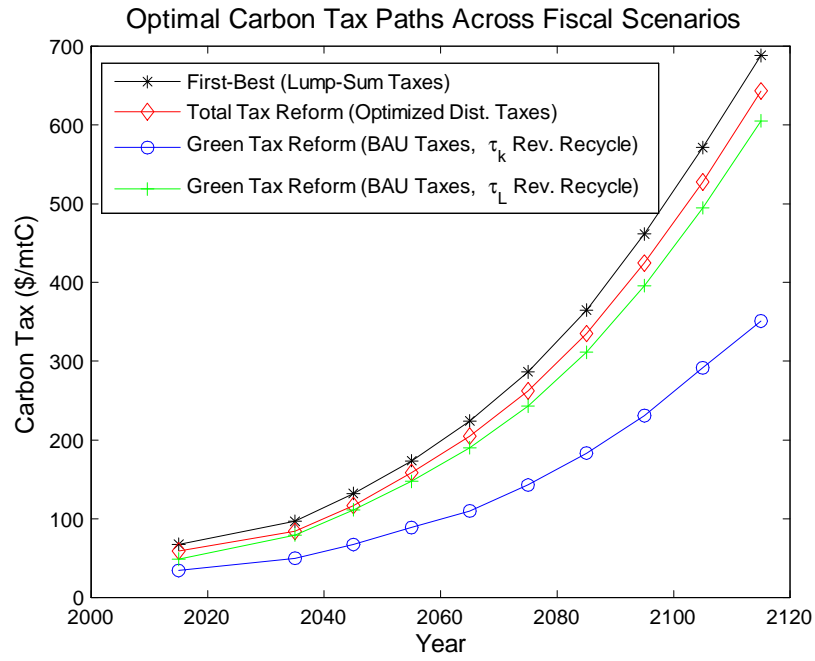


Figure 3: Figure 3

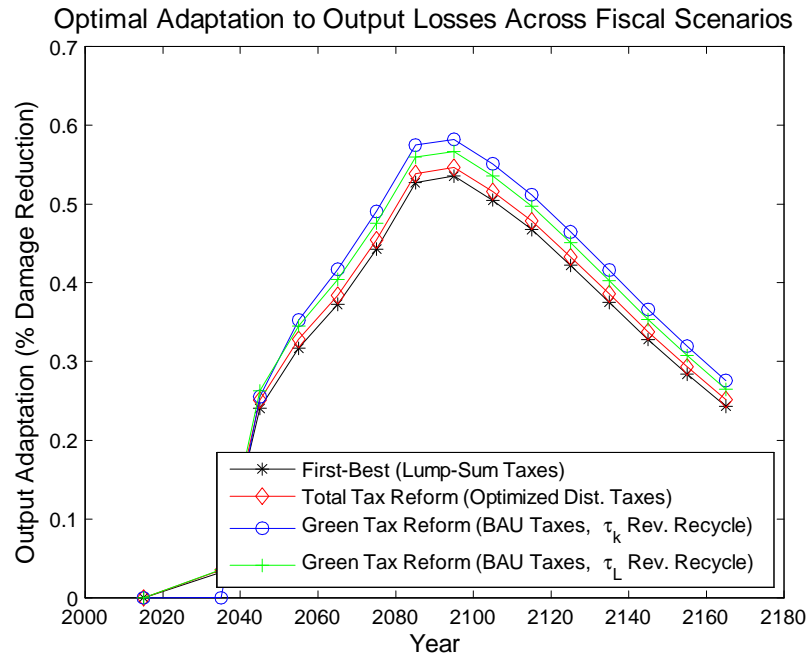


Figure 4: Figure 4

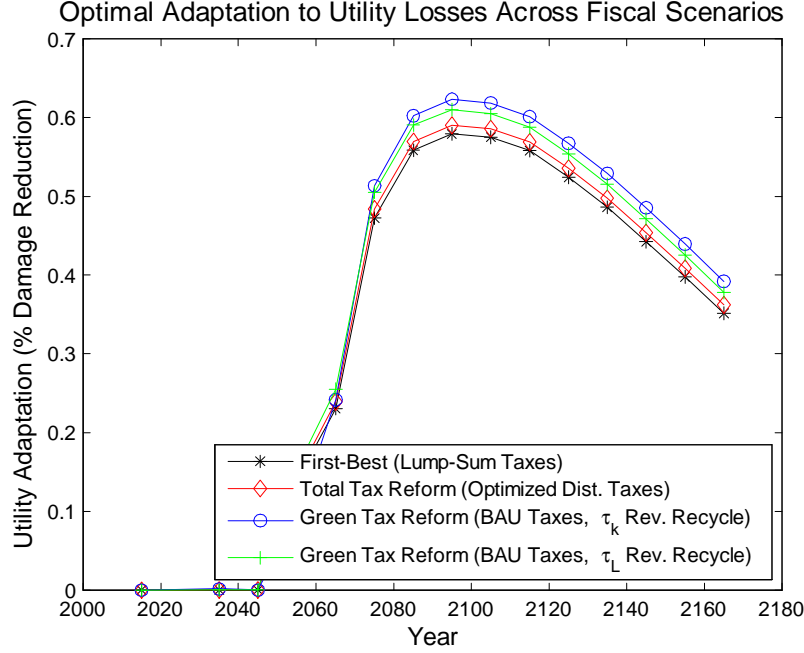


Figure 5: Figure 5

the theoretical results, which demonstrated that both flow and capital investments in utility adaptation should be distorted in proportion to the marginal cost of public funds. However, it is important to remember that these distortions are only relative to the relevant marginal rates of transformation *within* a given fiscal scenario. In general equilibrium, these values change across scenarios. Indeed, the theoretical results demonstrated that investments in adaptation to reduce output losses from climate change should maintain productive efficiency regardless of the tax system. Consequently, the differences in optimal adaptation across fiscal scenarios for output losses depicted in Figure 4 are due to general equilibrium differences across the fiscal scenarios, rather than due to wedges affecting the government's adaptation decisions.

Many of the current climate change policy efforts in the United States (and other countries) focus on adaptation rather than mitigation. As a final quantitative exercise, I thus compute the global welfare costs of failing to engage in mitigation over the 21st Century, and of pursuing an adaptation-only policy. For each fiscal scenario, these calculations compare welfare with optimized carbon taxes against a scenario where the planner cannot enact carbon prices until 2115. Welfare is measured as equivalent variation change in initial period aggregate consumption ( $\Delta C_{2015}$  in \$2005). Table 4 provides the results.

Policy Scenario:		$\Delta$ Welfare <sup>1</sup>
Income Taxes:	Carbon Tax:	\$2005 bil.
First-Best	None (until 2115)	-
First-Best	Optimized	21,663
Optimized	None (until 2115)	-
Optimized	Optimized	23,596
BAU+ RR( $\tau_k$ ) <sup>2</sup>	None (until 2115)	-
BAU+ RR( $\tau_k$ ) <sup>2</sup>	Optimized	54,634
BAU+ RR( $\tau_l$ ) <sup>2</sup>	None (until 2115)	-
BAU+ RR( $\tau_l$ ) <sup>2</sup>	Optimized	22,734

<sup>1</sup>Equivalent variation change in agg. initial consumption  $\Delta C_{2015}$

Table 4: Welfare Costs of Adaptation-Only Policy

The results presented in Table 4 suggest that the welfare costs of addressing climate change only through adaptation may be more than twice as large when the revenues to finance adaptation measures are raised through distortionary taxes. The welfare costs of failure to engage in carbon taxes over the 21st Century are estimated to be \$22 trillion (\$2005 present value equivalent variation) in the benchmark setting with lump-sum taxation. When adaptation measures have to be financed through either labor taxes or an optimized tax mix, this cost increases to around \$23-24 trillion. However, perhaps most importantly, when adaptation is paid for through increased capital income taxes, the welfare costs of an adaptation-only climate policy increases to \$55 trillion. While the optimal amount of adaptation pursued is thus slightly higher when there are distortionary taxes, the welfare costs of pursuing this policy may be considerably larger. While there are tremendous quantitative uncertainties surrounding the estimates presented in this section, this finding arguably presents at least a notable warning that the public financing of climate change adaptation expenditures warrants further attention.

## 6 Conclusion

Adaptation to climate change impacts is increasingly recognized as a critical public policy issue. Even countries with limited mitigation policies, such as the United States, are working towards integrated adaptation policies, as exemplified by President Obama’s *Task Force on Climate Preparedness and Resilience*. A growing academic literature has explored the policy tradeoffs between adaptation and mitigation from a variety of perspectives, such as based on strategic implications (e.g., Antweiler, 2011; Buob and Stephan, 2011).

This study revisits this question from a fiscal perspective. In particular, when governments raise revenues through distortionary taxes, the fiscal costs of climate policy become welfare-relevant. On the one hand, public financing for adaptive capacity requires government revenues. On the other hand, mitigation policies such as carbon taxes raise revenues, but are also well-known to exacerbate the welfare costs of other taxes (see, e.g., Goulder, 1996; Bovenberg and Goulder, 2002). I therefore use a dynamic general equilibrium climate-economy model with linear distortionary taxes to theoretically characterize and empirically quantify these tradeoffs.

First, I find that both flow and capital expenditures towards adaptation to reduce direct utility impacts of climate change (e.g., biodiversity existence value losses) are distorted at the optimum. Furthermore, an intertemporal wedge between the marginal rates of transformation and substitution for adaptation capital investments to reduce utility damages from climate change remains even when other intertemporal margins are optimally left undistorted (e.g., zero capital income tax).

Second, adaptation to reduce climate change impact on final goods production should be fully provided to maintain productive efficiency, regardless of the welfare costs of raising government revenues. This result follows directly from studies such as Judd (1999), and is based on the well-known property of Ramsey tax systems that they maintain aggregate production efficiency under mild conditions (Diamond and Mirrlees, 1971).

Third, the quantitative analysis suggests that the welfare costs of relying exclusively on adaptation to address climate change (i.e., without a carbon tax) may be up to twice as large in a setting with distortionary taxes. The benchmark model runs suggest a global welfare costs of an adaptation-only policy throughout the 21st Century to be \$22 trillion in a setting without distortionary taxes, \$23-24 trillion when additional revenue comes from labor or optimized distortionary taxes, and \$55 trillion when capital income taxes are used to raise additional funds (\$2005, equivalent variation change in initial consumption at the global level). While these figures are based on highly uncertain adaptation cost estimates, they nonetheless show that the fiscal setting warrants further attention in considering the tradeoff between climate change adaptation and mitigation.

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## 7 Appendix

### 7.1 Proof of Proposition 1

This proof follows closely the one presented by Barrage (2014), but adds the adaptation variables of this study. In addition, let  $\Omega_t$  denote public transfers to households. These are not in the analytic model above but are featured in the quantitative COMET model and thus incorporated in the proof here.

Before proceeding, it is useful to write out the firm's and household's first order conditions. Given the appropriate convexity assumptions, I can assume that the solution to the problem is interior. Let  $\gamma_t$  denote the Lagrange multiplier on the consumer's flow budget constraint (3) in period  $t$ , his first order conditions are given by:

$[C_t] :$

$$\gamma_t = \beta^t U_{ct} \quad (33)$$

$[L_t] :$

$$\frac{-U_{lt}}{U_{ct}} = w_t(1 - \tau_{lt}) \quad (34)$$

$[K_{t+1}^{pr}] :$

$$\gamma_t = \beta \gamma_{t+1} \{1 + (r_{t+1} - \delta)(1 - \tau_{kt+1})\} \quad (35)$$

$[B_{t+1}] :$

$$U_{ct} \rho_t = \beta U_{ct+1} \quad (36)$$

The climate variable  $T_t$  and utility adaptation  $\Lambda_t^u$  do not enter his problem directly because he takes both values as given, and because of the additive separability in preferences we have assumed in (2).

Next, the final goods producer's problem is to select  $L_{1t}$ ,  $K_{1t}$ , and  $E_t$  to solve:

$$\max F_{1t}(L_{1t}, K_{1t}, E_t, T_t, \Lambda_t^y) - w_t L_{1t} - p_{Et} E_t - r_t K_{1t}$$

where the firm takes the climate  $T_t$  and public adaptation  $\Lambda_t^y$  as given.

Defining  $F_{jt}$  as the first derivative of the production function with respect to input  $j$ , the firm's FOCs are:

$$\begin{aligned} F_{1lt} &= w_t \\ F_{1Et} &= p_{Et} \\ F_{1kt} &= r_t \end{aligned} \quad (37)$$

The energy producer's problem is to maximize:

$$\max(p_{Et} - \tau_{Et}) E_t - w_t L_{2t} - r_t K_{2t}$$

subject to:

$$E_t = F_{2t}(L_{2t}, K_{2t})$$

With FOCs:

$$\begin{aligned}(p_{Et} - \tau_{Et})F_{2lt} &= w_t \\ (p_{Et} - \tau_{Et})F_{2kt} &= r_t\end{aligned}\tag{38}$$

**Proof Part 1: If the allocations and initial conditions constitute a competitive equilibrium, then the constraints (RC)-(IMP) are satisfied.** In a competitive equilibrium, the consumer's FOCs (33)-(36) must be satisfied. Multiplying both sides of (35) by  $K_t$  gives:

$$[\gamma_t - \gamma_{t+1} \{1 + (r_{t+1} - \delta)(1 - \tau_{kt+1})\}] K_{t+1}^{pr} = 0\tag{39}$$

Equivalently, for bond holdings, we find:

$$[\gamma_t \rho_t - \gamma_{t+1}] B_{t+1} = 0\tag{40}$$

Next, consumer optimization dictates that the transversality conditions must hold in a competitive equilibrium:

$$\begin{aligned}\lim_{t \rightarrow \infty} \gamma_t B_{t+1} &= 0 \\ \lim_{t \rightarrow \infty} \gamma_t K_{t+1}^{pr} &= 0\end{aligned}\tag{41}$$

Lastly, the consumer's flow budget constraint (3) holds in competitive equilibrium. Multiplying both sides of the flow budget constraint in each period by the Lagrange multiplier  $\gamma_t$  leads to:

$$\gamma_t [C_t + \rho_t B_{t+1} + K_{t+1}^{pr}] = \gamma_t [w_t(1 - \tau_{lt})L_t + \{1 + (r_t - \delta)(1 - \tau_{kt})\} K_t^{pr} + B_t + \Omega_t + \Pi_t]\tag{42}$$

As discussed above, the assumptions of perfect competition and constant returns to scale in the energy sector imply that equilibrium profits will be equal to zero.<sup>20</sup> Summing equation (42)

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<sup>20</sup> One can formally confirm this by substituting the energy producer's FOCs for labor and capital inputs into the definition of energy sector profits:

$$\Pi_t = (p_{Et} - \tau_{Et})F(K_{2t}, L_{2t}) - F_{l2t}(p_{Et} - \tau_{Et})L_{2t} - F_{k2t}(p_{Et} - \tau_{Et})K_{2t}$$

If  $F(K_{2t}, L_{2t})$  exhibits constant returns to scale, then by Euler's theorem for homogenous functions,  $(F(K_{2t}, L_{2t}) = F_{l2t}L_{2t} + F_{k2t}K_{2t})$ , and the profits expression reduces to zero.

over all  $t$  thus yields:

$$\sum_{t=0}^{\infty} \gamma_t [C_t + \rho_t B_{t+1} + K_{t+1}^{pr} - w_t(1 - \tau_{lt})L_t - \{1 + (r_t - \delta)(1 - \tau_{kt})\} K_t^{pr} - B_t - \Omega_t] = 0 \quad (43)$$

All terms relating to capital and bond holdings after period zero cancel out of equation (43) out as can be seen by substituting in from (39), (40) and the transversality conditions (41). We thus end up with:

$$\sum_{t=0}^{\infty} \gamma_t [C_t - w_t(1 - \tau_{lt})L_t - \Omega_t] = \gamma_0 [K_0^{pr} \{1 + (r_0 - \delta)(1 - \tau_{k_0})\} + B_0] \quad (44)$$

Finally, one can substitute out for the remaining prices  $\gamma_t$ ,  $w_t(1 - \tau_{lt})$ , and  $r_0$  in (44) from the consumer's and firm's FOCs in order to obtain the implementability constraint (IMP):

$$\sum_{t=0}^{\infty} \beta^t [U_{ct}C_t + U_{lt}L_t - U_{ct}\Omega_t] = U_{c0} [K_0^{pr} \{1 + (F_{k0} - \delta)(1 - \tau_{k_0})\} + B_0] \quad (45)$$

We have demonstrated that the implementability constraint is satisfied in a competitive equilibrium.

The last step is where adaptation comes into play directly. We need to show that the final goods resource constraint (RC) holds in competitive equilibrium. Start by adding up the consumer and government flow budget constraints (3) and (12) with the addition of transfers to households  $\Omega_t$  in each. Canceling redundant terms on each side leaves:

$$G_t + \lambda_t^y + \lambda_t^u + K_{t+1}^{abt} + C_t + K_{t+1}^{pr} = w_t L_t + \tau_{Et} E_t + \Pi_t + (1 - \delta + r_t) K_t^{pr} + (1 - \delta) K_t^{abt}$$

Next, invoking the definition of energy sector profits, substituting in based on the labor and capital market clearing conditions, and substituting in for factor prices based on the energy producer's FOCs (38) changes the RHS to:

$$G_t + \lambda_t^y + \lambda_t^u + K_{t+1}^{abt} + C_t + K_{t+1}^{pr} = w_t L_{1t} + p_{Et} E_t + r_t K_{1t} + (1 - \delta) K_t^{pr} + (1 - \delta) K_t^{abt} \quad (46)$$

By Euler's theorem for homogenous functions, (46) becomes the resource constraint, as desired:

$$G_t + \lambda_t^y + \lambda_t^u + K_{t+1}^{abt} + C_t + K_{t+1}^{pr} = Y_t + (1 - \delta) K_t^{pr} + (1 - \delta) K_t^{abt} \quad (47)$$

Finally, the carbon cycle constraint (CCC) and the energy producer's resource constraint (ERC) hold by definition in competitive equilibrium.

**Direction: If constraints(RC)-(IMP) are satisfied, one can construct competitive equilibrium.** I proceed with a proof by construction. First, set factor prices as equal to their marginal products evaluated at the optimal allocation:

$$\begin{aligned} F_{1lt} &= w_t \\ F_{1Et} &= p_{Et} \\ F_{1kt} &= r_t \end{aligned} \tag{48}$$

These factor prices are clearly consistent with profit maximization in the final goods sector, as needed in a competitive equilibrium. Next, set the return on bonds based on the consumer's intertemporal first order conditions for bond holdings (36):

$$\rho_t = \beta U_{ct+1}/U_{ct}$$

Again, this price is obviously consistent with utility maximization. Proceed similarly in setting the labor income tax based on the household's labor supply and consumption FOCs:

$$\begin{aligned} -U_{lt}/U_{ct} &= (1 - \tau_{lt})F_{lt} \\ 1 + \frac{U_{lt}/U_{ct}}{F_{lt}} &= \tau_{lt} \end{aligned}$$

Next, let the tax rate on capital income for each time  $t > 0$  be defined by the household's Euler equation and the firm's capital holdings FOC:

$$\begin{aligned} U_{ct} &= \beta U_{ct+1} \{1 + (F_{1kt+1} - \delta)(1 - \tau_{kt+1})\} \\ \tau_{kt+1} &= 1 - \frac{U_{ct}/\beta U_{ct+1} - 1}{(F_{1kt+1} - \delta)} \end{aligned}$$

As before, being defined by the consumer and firm's FOCs these tax rates will clearly be consistent with utility and profit maximization.

Proceeding in the same manner, define the carbon tax based on the energy and final goods producers' FOCs (38) and (37) as:

$$\tau_{Et} = p_{Et} - \frac{F_{1lt}}{F_{2lt}}$$

Finally, in order to construct bond holdings in period  $t$ , multiply the consumer budget con-

straint (3) by its Lagrange multiplier  $\gamma_t$  and sum over all periods *from period  $t$  onwards*:

$$\sum_{s=t}^{\infty} \gamma_s [C_s + \rho_s B_{s+1} + K_{s+1}^{pr} - w_s(1 - \tau_{ls})L_s - \{1 + (r_s - \delta)(1 - \tau_{ks})\} K_s^{pr} - B_s - \Pi_s - \Omega_t] = 0 \quad (49)$$

The consumer's FOCs and transversality conditions (41) must necessarily hold in a competitive equilibrium, indicating that all future terms relating to capital and bond holdings in (49) cancel out. We are thus left with:

$$\sum_{s=t}^{\infty} \gamma_s [C_s - w_s(1 - \tau_{ls})L_s - \Pi_s - \Omega_t] + \gamma_t \{1 + (r_t - \delta)(1 - \tau_{kt})\} K_t^{pr} = \gamma_t B_t \quad (50)$$

Use the agent's and the firms' FOCs once again to substitute out prices in equation (50) finally leads to:<sup>21</sup>

$$\sum_{s=t}^{\infty} \frac{\beta^{s-t} U_{cs}}{U_{ct}} \left[ C_s + \frac{U_{ls}}{U_{cs}} L_s - \Omega_s \right] + \frac{U_{ct-1}}{\beta U_{ct}} K_t^{pr} = B_t$$

Given allocations, this equation defines the unique bond holdings that are consistent with a competitive equilibrium.

Since the prices and policies defined as outlined above are all based on household and firm optimality conditions, they are clearly consistent with utility and profit maximization. It thus remains to be shown that the constraints necessary for competitive equilibrium are satisfied as well. First, the final goods resource constraint, the carbon cycle constraint, the energy production resource constraints, and the factor market clearing conditions for labor and different capital types all hold by assumption. If we can show that the consumer budget constraint is satisfied, then by Walras' law it follows that the government budget constraint must be satisfied also. Following the standard line of reasoning (see, e.g., Chari and Kehoe, 1999), we can note the following. First, only the consumer's competitive equilibrium-budget constraint is relevant to show that our constructed prices, bond holdings, and policies are constitute a competitive equilibrium. In a competitive equilibrium, the household's intertemporal budget constraint must hold, along

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<sup>21</sup> For the capital return in period  $t$ , note that the substitution derives from:

$$\begin{aligned} & \gamma_t [r_{kt}(1 - \tau_{kt}) + (1 - \delta)] K_t^{pr} \\ &= \beta^t U_{ct} \left[ \frac{U_{ct-1}}{\beta U_{ct}} \right] K_t^{pr} \\ &= \beta^{t-1} U_{ct-1} K_t^{pr} \end{aligned}$$

with the consumer's FOCs and the consumer's transversality conditions. Consequently, (39) and (40) must hold in a competitive equilibrium as well. However, as shown in the first part of this proof, at the prices selected above, the consumer's competitive equilibrium-budget constraint is identical to the implementability constraint, which holds by assumption. The competitive equilibrium budget constraint at the chosen prices is thus satisfied, as was to be shown  $\square$ .

## 7.2 Proof of Theory Results

The social planner's problem is given by:

$$\begin{aligned}
& \max_k \sum_{t=0}^{\infty} \beta^t \underbrace{[v(C_t, L_t) + h[(1 - \Lambda_t^u)T_t] + \phi [U_{ct}C_t + U_{lt}L_t]]}_{\equiv W_t} \\
& + \sum_{t=0}^{\infty} \beta^t \lambda_{1t} \left[ \left\{ [1 - D(T_t)(1 - \Lambda_t^y)] \cdot A_{1t} \widetilde{F}_{1t}(L_{1t}, E_t, K_{1t}) \right\} + (1 - \delta)K_t \right. \\
& \quad \left. - C_t - K_{t+1} - G_t - \lambda_t^y - \lambda_t^u \right] \\
& + \sum_{t=0}^{\infty} \beta^t \xi_t [T_t - F_t(S_0, E_0, E_1, \dots, E_t)] \\
& + \sum_{t=0}^{\infty} \beta^t \lambda_{lt} [L_t - L_{1t} - L_{2t}] \\
& + \sum_{t=0}^{\infty} \beta^t \lambda_{kt} \left[ K_t - K_{1t} - K_{2t} - K^{\Lambda, y} - K_t^{\Lambda, u} \right] \\
& + \sum_{t=0}^{\infty} \beta^t \omega_t [F_{2t}(A_{Et}, K_{2t}, L_{2t}) - E_t] \\
& + \sum_{t=0}^{\infty} \beta^t \eta_{yt} \left[ f^y(K_t^{\Lambda, y}, \lambda_t^y) - \Lambda_t^y \right] \\
& + \sum_{t=0}^{\infty} \beta^t \eta_{ut} \left[ f^u(K_t^{\Lambda, u}, \lambda_t^u) - \Lambda_t^u \right] \\
& - \phi \{ U_{c0} [K_0 \{ 1 + (F_{k0} - \delta)(1 - \tau_{k0}) \}] \}
\end{aligned} \tag{51}$$

The associated first-order conditions for periods  $t > 0$  are as follows:

$[E_t]$  :

$$\lambda_{1t} F_{Et} - \sum_{t=0}^{\infty} \xi_{t+j} \frac{\partial T_{t+j}}{\partial E_t} = \omega_t \tag{52}$$

$[T_t]$  :

$$U_{Tt} + \lambda_{1t} F_{1Tt} = \xi_t \tag{53}$$



$[L_t] :$

$$U_{lt} = -\lambda_{lt}$$

$[L_{2t}] :$

$$\lambda_{lt} = \omega_t F_{2lt} \quad (54)$$

$[L_{1t}] :$

$$\lambda_{1t} F_{1lt} = \lambda_{lt} \quad (55)$$

Conditions (52)-(55) can be used to derive an expression implicitly defining the optimal carbon tax. Specifically, combining (54) and (55) yields:

$$\frac{\lambda_{1t} F_{1lt}}{F_{2lt}} = \omega_t \quad (56)$$

Combining (56) with the FOCs for energy inputs (52) and temperature change  $T_t$  (53), we obtain:

$$F_{Et} - \sum_{j=0}^{\infty} \beta^j \left[ \frac{U_{Tt+j}}{\lambda_{1t}} + \frac{\lambda_{1t+j}}{\lambda_{1t}} F_{1Tt+j} \right] \frac{\partial T_{t+j}}{\partial E_t} = \frac{F_{1lt}}{F_{2lt}} \quad (57)$$

Comparison between (57) and the energy firm's optimality condition (10) at equilibrium factor prices (which are equated with marginal products), it thus immediately follows that the optimal carbon tax is implicitly defined by:

$$\tau_{Et}^* = \sum_{j=0}^{\infty} \beta^j \left[ \frac{U_{Tt+j}}{\lambda_{1t}} + \frac{\lambda_{1t+j}}{\lambda_{1t}} F_{1Tt+j} \right] \frac{\partial T_{t+j}}{\partial E_t} \quad (58)$$

In words, expression (58) is the present value sum of all future marginal utility and production damages associated with an additional ton of carbon emissions in period  $t$ . This expression is analogous to the one derived in Barrage (2014); however it will be evaluated at a different allocation due to the introduction of adaptation possibilities.

Next, consider the following additional FOCs for the planner's problem, again for  $t > 0$  :

$[\Lambda_t^u] :$

$$-U_{Tt} T_t = \eta_{ut} \quad (59)$$

$[\lambda_t^u] :$

$$\lambda_{1t} = \eta_{ut} f_{\lambda_t}^u \quad (60)$$

$[\Lambda_t^y] :$

$$\lambda_{1t} D(T_t) \tilde{Y}_t = \eta_{yt} \quad (61)$$

where  $\tilde{Y}_t$  denotes gross output (before climate damages).

$[\lambda_t^y] :$

$$\lambda_{1t} = \eta_{yt} f_{\lambda_t}^y \quad (62)$$

Combining (59)-(60) yields the optimality condition for public provision of flow adaptation inputs  $\lambda_t^u :$

$$\frac{-U_{Tt} T_t}{\lambda_{1t}} = \frac{1}{f_{\lambda_t}^u} \quad (63)$$

$$\frac{(-U_{Tt} T_t)/U_{ct}}{MCF_t} = \frac{1}{f_{\lambda_t}^u} \quad (64)$$

Multiplying the left-hand side of (63) by  $U_{ct}/U_{ct}$  and invoking the definition of the  $MCF$  in (17) thus yields the desired result of equation (19).

Similarly, combining (61)-(62) yields the optimality condition for flow adaptation inputs for production damages  $\lambda_t^y :$

$$D(T_t) \tilde{Y}_t = \frac{1}{f_{\lambda_t}^y} \quad (65)$$

Finally, consider the planner's FOCs relating to optimal adaptation capital for  $t > 0 :$

$[K_t^{\Lambda, y}] :$

$$\lambda_{kt} = \eta_{yt} f_{K_t}^y$$

$[K_t^{\Lambda, u}] :$

$$\lambda_{kt} = \eta_{ut} f_{K_t}^u$$

$[K_{t+1}] :$

$$\lambda_{1t} = \beta \lambda_{1t+1} (1 - \delta) + \beta \lambda_{kt+1} \quad (66)$$

$[K_{1t}] :$

$$\lambda_{1t} F_{1kt} = \lambda_{kt} \quad (67)$$

Based on these equations, we can derive intertemporal optimality conditions for the economy's capital stocks. First, for private productive capital, combining (66) and (67) yields the standard optimality condition:

$$\frac{\lambda_{1t}}{\beta \lambda_{1t+1}} = (1 - \delta) + F_{1kt+1} \quad (68)$$

Next, for production adaptation, we have that:

$$\lambda_{1t} = \beta \lambda_{1t+1} (1 - \delta) + \beta [\eta_{yt+1} f_{K_{t+1}}^y] \quad (69)$$

Substituting in based on the shadow value of production adaptation (61), equation (69) becomes:

$$\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = (1 - \delta) + \left[ D(T_{t+1}) \widetilde{Y_{t+1}} f_{K_{t+1}}^y \right] \quad (70)$$

Comparing the optimality conditions for private and public adaptation capital in the final output sector, (68) and (70), respectively, we see that the returns to these investments are equated at the optimum. Consequently, if investments in private capital are left undistorted by the optimal tax code, then public spending in productive adaptation capital should likewise be undistorted.

In contrast, for utility adaptation capital, the first order conditions yield:

$$\lambda_{1t} = \beta\lambda_{1t+1}(1 - \delta) + \beta [\eta_{ut+1} f_{K_{t+1}}^u]$$

Again substituting in based on the shadow value of utility adaptation from (60) leads to:

$$\begin{aligned} \lambda_{1t} &= \beta\lambda_{1t+1}(1 - \delta) + \beta [(-U_{Tt+1}T_{t+1}) f_{K_{t+1}}^u] \\ &= \beta\lambda_{1t+1}(1 - \delta) + \lambda_{1t+1}\beta \left[ \frac{(-U_{Tt+1}T_{t+1})}{\lambda_{1t+1}} f_{K_{t+1}}^u \right] \end{aligned}$$

Consequently, invoking again the definition of the  $MCF$  in (17) leads to the desired result:

$$\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = (1 - \delta) + \left[ \frac{(-U_{Tt+1}T_{t+1})}{U_{ct+1}} \frac{1}{MCF_{t+1}} f_{K_{t+1}}^u \right] \quad (71)$$

As derived in the text, the condition for an undistorted margin for investments in utility adaptation capital is given by:

$$\frac{U_{ct}}{\beta U_{ct+1}} = (1 - \delta) + \frac{(-U_{Tt+1}T_{t+1})}{U_{ct+1}} f_{K_{t+1}}^u$$

For public investment in utility adaptation capital, a wedge in the form of  $(1/MCF_{t+1})$  thus remains in the optimality condition (71) even if other investments are undistorted and  $\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = \frac{U_{ct}}{\beta U_{ct+1}}$ . That is, as is well known, with constant elasticity preferences of the commonly used forms,

$$U(C_t, L_t, T_t, \Lambda_t^u) = \frac{C_t^{1-\sigma}}{1-\sigma} + \vartheta(L_t) + h(T_t(1 - \Lambda_t^u)) \quad (72)$$

$$U(C_t, L_t, T_t, \Lambda_t^u) = \frac{(C_t L_t^{-\gamma})^{1-\sigma}}{1-\sigma} + h(T_t(1 - \Lambda_t^u)) \quad (73)$$

for periods  $t > 1$ , we have that  $\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = \frac{U_{ct}}{\beta U_{ct+1}}$ . Consequently, investment in private capital should be undistorted and capital income taxes should be optimally set to zero, as can be

readily seen from substituting  $\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = \frac{U_{ct}}{\beta U_{ct+1}}$  into the private capital optimality condition (68) and comparing it with the household's Euler Equation. However, even in this case, the wedge ( $1/MCF_{t+1}$ ) remains in the optimality condition for public investments in utility adaptation capital (71).