

Dynamics of Global Emission Permit Prices and Regional Social Cost of Carbon under Noncooperation *

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Abstract

We build a dynamic multi-region model of climate and economy with emission permit trading among 12 aggregated regions in the world. We solve for the dynamic Nash equilibrium under noncooperation, wherein each region adheres to the emission cap constraints following commitments that were first outlined in the 2015 Paris Agreement and later strengthened under the Glasgow Pact. Our model shows that the emission permit price reaches \$845 per ton of carbon by 2050. We demonstrate that a regional carbon tax is complementary to the global cap-and-trade system, and the optimal regional carbon tax is equal to the difference between the regional marginal abatement cost and the permit price.

Keywords: Emission trading system, Paris Agreement, dynamic Nash equilibrium, integrated assessment model, carbon tax, social cost of carbon.

JEL Classification: C73, F18, Q54, Q58.

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1 Introduction

Climate change has been raising concerns of disastrous consequences, from rising sea levels to increases in the frequency and intensity of extreme weather events (Arias et al., 2021). International efforts to address climate change have evolved over the past three decades, commencing with the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, followed by the Kyoto Protocol in 1997, the Paris Agreement in 2015, and the Glasgow Pact in 2021. The policy outlined in the Paris Agreement codified an objective of “limiting global average temperature rise to well below 2 degrees Celsius above pre-industrial levels, with a pursuit of limiting it to the 1.5 degrees Celsius” (Article 2). To accomplish this objective, 194 countries (regions) committed to the Nationally Determined Contributions (NDCs) specifying their emission mitigation goals, which need to be updated every five years by strengthening emission cuts with more intensive measures. Most recently, the Glasgow Climate Pact, adopted at the UN Climate Change Conference in Glasgow (COP26) in November 2021, revisited Nationally Determined Contributions (NDCs), reaffirming the previous commitments made in the Paris Agreement and recognizing the need for more stringent efforts to attain the global target of 1.5 degrees Celsius.

Various market-based approaches to reduce emissions have been proposed, among which the most well-known are carbon tax regimes and emission trading systems (ETSs).¹ In a carbon tax regime, a tax is charged to firms for each unit of carbon emission. Previous studies have shown that the optimal global carbon tax rate is equal to the global social cost of carbon (SCC), which is the present value of global climate damages incurred by an additional unit of carbon emissions (Nordhaus, 2017). In an emission trading or a cap-and-trade system, on the other hand, the maximum amount of permissible emissions is fixed in an economy, and agents can sell and purchase emission permits (allowances) at the market price. In the absence of transaction costs and uncertainty, properly designed tax and trading regimes are argued to yield equivalent outcomes in several key aspects (e.g., incentives for emission reductions, aggregate abatement costs, and carbon leakage) (Montgomery, 1972; Goulder and Schein, 2013; Stavins, 2022). In 2005, the European Union (EU) first adopted a legally binding emission trading system among the EU members,² and as of the winter of 2024, the permit price stands at about 70 euros per ton of Carbon Dioxide (CO₂).³ Although

¹It has been documented that a total of 61 carbon pricing policies, consisting of 30 taxes and 31 ETSs, have been executed or are scheduled for implementation globally (Stavins, 2022).

²In addition to the EU ETS, other national or sub-national ETSs have been implemented or are in the process of development, including in Canada, China, Japan, New Zealand, South Korea, Switzerland, and the United States. For information on the most up-to-date policy in practice, see World Bank Carbon Pricing Dashboard (<https://carbonpricingdashboard.worldbank.org/>).

³Source of EU permit price: (<https://tradingeconomics.com/commodity/carbon>).

a global-level ETS is currently not in place, there have been longstanding discussions on its implementation as an international regime to address climate change, as implied by Article 17 of the Kyoto Protocol and Article 6 of the Paris Agreement. Prior works have emphasized the need for a global ETS or linking existing regional ETSs (Mehling et al., 2018) and for expanding the coverage of carbon trading in specific industries to different regions so as to enhance the global mitigation efforts and reduce carbon leakages (Piris-Cabezas et al., 2018).

In this study, we develop a dynamic multi-region model of climate and the economy under a global ETS with annual time steps, and use it to project global prices of emission permits and the regional SCC. In this integrated assessment framework, we form 12 aggregated regions by grouping 152 countries around the world. For these regions, we construct emission cap trajectories aligned with the latest NDC mitigation targets from the Paris Agreement and the Glasgow Climate Pact. These trajectories are based on near-term targets for 2025/2030 and long-term net-zero commitments for 2050–2070, and our model treats these trajectories as exogenous emission cap constraints. Assuming that all regions adhere strictly to their emission cap constraints without future revisions,⁴ our main analysis focuses on solving a dynamic Nash equilibrium under noncooperation, where each region makes optimal dynamic decisions on emission abatement, emission permit purchases, and capital investment to maximize its social welfare given the optimal choices of other regions. The emission permit price is endogenously determined by annual supply and demand in the global permit market.

Our study makes four contributions. The first contribution is demonstrating, both theoretically and numerically, that regional optimal taxes can be internally implemented under the global ETS. While a carbon tax and ETS have often been considered as potentially interchangeable or substitutable policies, we show that within the global ETS framework, a hybrid policy combining both ETS and carbon tax is optimal: the social planner of each region needs to introduce a carbon tax as a complementary policy tool under the global ETS in order to achieve its optimal level of emissions. The necessity of a carbon tax arises from the discrepancy in optimal emissions between the social planner’s choice and the market outcome under an ETS-only regime (i.e., firms’ choice under the ETS with an exogenous emission cap but no carbon tax). Specifically, when optimal emissions from the social planner’s perspective are strictly positive, the regional optimal carbon tax is equal to the difference between the regional MAC and the global permit price under the noncooperative Nash equilibrium with the ETS, thereby ensuring firms’ choice under the tax is consistent with the social

⁴In this paper, we assume that regions will not revise their NDC limits in future for the following reasons: (i) relaxing NDC limits could result in penalties from other regions or damage to the region’s reputation; (ii) reducing NDC limits would lead to a loss of benefits from selling emission permits or more cost from purchasing; and (iii) renegotiating NDC limits is often time-consuming and infrequent.

planner’s. We also numerically verify that the regional optimal carbon tax is equal to the regional SCC, the present value of future regional climate damages resulting from additional global emissions, provided emissions are strictly positive.

The second contribution of this study is a method to solve for the dynamic Nash equilibrium prices of emission permits under a global ETS. To the best of our knowledge, this is the first attempt to integrate an emission permit trading system with fully endogenous prices and emission abatements in a dynamic regional integrated assessment model (IAM) under noncooperation. Although some prior research has addressed regional integrated assessment models with a multi-region ETS, their solutions thus far have been obtained in a limited manner. One seminal work in IAMs is the Regional Integrated Model of Climate and the Economy (RICE; Nordhaus and Yang, 1996; Nordhaus, 2010b), but it did not provide a solution for the market-clearing equilibrium permit prices under noncooperation. Other studies have explored an ETS by extending the World Induced Technical Change Hybrid Model framework (WITCH; Bosetti et al., 2006), yet their permit prices and emission abatements are not fully endogenized as their prices are assumed to be equal to their regional MACs (De Cian and Tavoni, 2012; Massetti and Tavoni, 2012). While it has been long considered in the literature that the market equilibrium permit price is equalized to the regional MACs across all countries in an ETS regime (e.g., Keohane, 2009; Nordhaus, 2010b), our study shows that this does not hold. Specifically, the assumption that the permit price equals the regional MACs ignores the inconsistency between regional social planners’ choices internalizing the regional climate damages and firms’ choices ignoring the regional climate damages under the ETS regime. This can also be understood with an extreme case: if the emission caps are very large such that they are not binding for every region (which is equivalent to a case without emission caps), then both permit prices and trading quantities are zero, implying zero emission mitigation. However, it is well known that even without emission caps, there are still nonzero emission mitigations from the regional social planners’ perspectives and the optimal regional taxes are equal to the nonzero regional MACs under the Nash equilibrium (see, e.g., Nordhaus and Yang, 1996; Cai et al., 2023). That is, regions should impose an additional carbon tax on firms, contingent on their NDC commitments, such that the firms’ emission decisions are consistent with theirs.

We present a numerical algorithm for finding a Nash equilibrium solution where forward-looking regional social planners are making dynamic optimal decisions, and importantly, we show that the market clearing permit price is not equal to the regional MACs and the regional MACs are not equalized across regions under the Nash equilibrium. Under the baseline emission cap scenario based on the Paris Agreement and Glasgow Pact commitments, our simulation results show that the oversupply of global permits in the initial years results in

zero permit prices, but by 2050, the emission permit price can reach up to \$845 per ton of carbon.

The third contribution is that our model’s results are based on newly calibrated parameters and regional emission cap pathways under the Paris Agreement and the Glasgow Pact, making our findings directly relevant to real-world scenarios. We calibrate our model by fitting it to historical data and the recent predicted trends of regional climate damage, regional GDP, regional abatement costs, and population projections based on the Shared Socioeconomic Pathway 2 (SSP2; Samir and Lutz, 2017), also known as the “Middle-of-the-Road” scenario. Besides this calibration, our model uses a stylized but stable climate system, called the Transient Climate Response to Emissions (TCRE; Matthews et al., 2009), which assumes that increases in the global averaged atmospheric temperature have a nearly linear functional dependence on cumulative carbon emissions. We show that this temperature system can be calibrated to match closely with the various Representative Concentration Pathways (RCPs; Meinshausen et al., 2011). Due to its simplicity and effectiveness, the TCRE scheme has found applications in recent economic analyses, as evidenced by studies such as Brock and Xepapadeas, 2017; Dietz and Venmans, 2019; Mattauch et al., 2020; Barnett et al., 2020. Moreover, Dietz et al. (2021) show that the TCRE scheme does not lead to a large difference in economic analysis with the seminal DICE framework (Nordhaus, 2017), compared to other more complicated climate systems. Furthermore, our construction of emission cap pathways reflects the latest emission targets for 2030 and net-zero pledges for 2050-2070, contributing to the scant literature on evaluating the economic and environmental implications of these commitments (e.g., van de Ven et al., 2023; Meinshausen et al., 2022; den Elzen et al., 2022).

Our final contribution is a comprehensive comparative analysis of the roles of emission caps and the global ETS. We find that the global ETS leads to higher emissions under non-cooperation, because regions with binding emission caps can purchase permits from regions with less restrictive caps, exploiting the excessively abundant emission permits in the initial years. This implies that it is important to maintain a stringent emission cap at the global level to make the ETS work efficiently. Moreover, we show that a stricter emission cap leads to a higher permit price for every region. For example, if all the regions achieve net zero emissions in 2050, the emission permit price can reach up to \$1,539 per ton of carbon by 2049. However, even with this strict emission restriction, the global temperature is still projected to rise by 1.62 degrees Celsius by the end of this century. These findings suggest that achieving the global target of limiting the temperature rise to 1.5 degrees Celsius requires even stronger emission commitments than those outlined in the Glasgow Pact. Our results are in qualitative agreement with the analysis of other IAMs (van de Ven et al., 2023; Meinshausen et al., 2022; den Elzen et al., 2022), which find that the strengthened post-Glasgow

NDC targets, encompassing both near-term and long-term goals, are insufficient to limit warming to 1.5°C above pre-industrial levels, but, if fully implemented, could limit warming to below 2°C.

Our model framework is closely related to the RICE model (Nordhaus and Yang, 1996; Nordhaus, 2010b), an extension of the global DICE model (Nordhaus, 2014) in a multi-region framework, capturing interactions between economic growth and climate systems. In Nordhaus (2010b), carbon prices are obtained under a cooperative model where the global welfare is maximized with weights applied on regional utilities. Following the RICE model, a group of studies have explored climate policy in a dynamic multi-region framework under cooperation and noncooperation. For instance, Luderer et al. (2012) and Jakob et al. (2012) compare the long-term predictions of three regionalized energy-economy models, when certain environmental goals are set, like stabilizing the CO₂ levels to 450 ppm. However, these works do not incorporate actual NDC and net-zero year targets of the countries to study the region-wise emission-economy pathways. van der Ploeg and de Zeeuw (2016) and Jaakkola and Van der Ploeg (2019) focus on stochastic components, such as climate tipping points or technological breakthroughs, comparing the results under different levels of cooperation. Hambel et al. (2021) extend the RICE framework by integrating endogenous international trade under noncooperation and provide a closed-form analytical solution for the regional SCCs, under certain model assumptions. Iverson and Karp (2021) study a Markov Perfect equilibrium in a dynamic game with a social planner deciding climate policies and non-constant discount rates. Cai et al. (2023) build a dynamic IAM for two economic regions (North and Tropic/South) to compute regional SCCs under cooperation and noncooperation. Nonetheless, none of these works examine the dynamics of an international ETS with an endogenous market price of emission permits under a noncooperative setting. Our study builds on the concept of regional SCCs defined in van der Ploeg and de Zeeuw (2016) and Cai et al. (2023), and provides a comprehensive analysis of regional SCCs and their relation with the global ETS in a multi-region dynamic framework under noncooperation.

In the literature, ETSs have garnered attention as promising mechanisms for mitigating global emissions, along with carbon taxes, but there have been relatively limited attempts to comprehensively analyze ETSs as potential instruments for global climate policy. Among the most closely related studies are extended versions of the WITCH model (Bosetti et al., 2006): Massetti and Tavoni (2012) analyze an ETS for Asia in particular, where emission quotas are defined according to specific climate objectives, while De Cian and Tavoni (2012) study an ETS where countries can choose abatement and investment in innovation that lowers marginal abatement cost. As noted earlier, our solution mechanism differs from these studies and provides permit prices from a complete noncooperative dynamic optimization

problem. Carbone et al. (2009) present another relevant study, constructing a computable general equilibrium model incorporating countries' endogenous participation in an ETS and allocation of emission permits, solving for the equilibrium permit price. However, that study examines the ETS in a static setting, missing the critical dynamic aspects of climate change and lacking a connection with emission abatement decisions. Fischer and Springborn (2011) develop a dynamic stochastic general equilibrium model to compare outcomes of emission cap and tax policies, albeit without consideration of emission trading between regions. Other strand of studies have analyzed the potential efficiency gains from integrating regional ETSs into a global ETS (Habla and Winkler, 2018; Doda et al., 2019; Holtsmark and Weitzman, 2020; Holtsmark and Midttømme, 2021; Mehling et al., 2018).

More broadly, a substantial body of literature have examined ETSs from various perspectives. While in this study, we assume that emission permits are freely allocated to the regions following the voluntary commitments from the NDCs, several studies have analyzed how the initial allocation of permits affects the equilibrium outcomes (Hahn and Stavins, 2011), or have compared allocation methods between auctioning and free allocation (Goulder and Parry, 2008; Goulder et al., 2010). Other works have studied the relative efficiency of carbon policies under the existence of cost uncertainty, showing that carbon tax can be more efficient than ETS under certain conditions, and vice versa (Weitzman, 1974; Stavins, 1996; Karp and Traeger, 2024). In another strand of literature, a number of studies have focused on empirically analyzing the regional emission trading markets currently in practice, such as the EU ETS (Hitzemann and Uhrig-Homburg, 2018; Fuss et al., 2018; Perino et al., 2022), China ETS (Goulder et al., 2022), or California ETS (Borenstein et al., 2019). An important issue with regional ETSs is carbon leakage, which refers to the shift of emission intensive production to regions outside the jurisdiction of the ETS. Previous studies have compared different policy instruments aimed at mitigating this problem and providing a level-playing field to the firms operating within the ETS (Ambec et al., 2024; Böhringer et al., 2014; Farrokhi and Lashkaripour, 2021; Fowlie and Reguant, 2022; Levinson, 2023).

While there is no general agreement among economists on whether carbon tax or ETS is better (Stavins, 2022), the literature have often considered two pricing instruments (trading versus taxes) as policy substitutes. For instance, some studies support carbon tax over ETS, highlighting concerns about price volatility in ETS (Nordhaus, 2007), or the presence of uncertainty regarding emission abatement costs (Newell and Pizer, 2003). For instance, Newell and Pizer (2003) find that carbon taxes can yield higher welfare benefits than an ETS under such uncertainties. Conversely, other studies advocate ETS over tax because allocation of permits in ETS allows more flexibility, and ETS faces less uncertainty in controlling the cumulative amount of carbon emissions compared to taxes (Keohane, 2009). Harstad and

Eskeland (2010), Hahn and Stavins (2011), and Stavins (2022) argue that from a practical perspective, ETS may be a preferred instrument over tax, as free allowances could be negotiated among participating agents to redistribute burden and, thus, be used to gain political support. Additionally, Knopf et al. (2012) favor a global ETS because carbon taxes that increase over time may accelerate extraction of fossil fuels due to profit maximization of fossil fuel firms, an argument that has been made by other researchers as well (Sinn, 2008). In a global ETS, emission permits will be traded globally with one price for all nations based on market forces, which may alleviate the problem of carbon leakage (Fowlie et al., 2016). However, Harstad and Eskeland (2010) argue that although an ETS in a perfect market is the first-best system, frequent government interventions to redistribute allocations among firms results in distortions in the market allocation. For a comprehensive comparison on carbon tax and trading regimes, see e.g., Strand (2013); Schmalensee and Stavins (2017); Cai (2021); Stavins (2022). This study contributes to the literature by demonstrating that the two pricing instruments are not competing policies but rather complementary.

2 Optimal Carbon Tax under the ETS

While carbon taxes and ETS are often considered as substitutable policies, we demonstrate that each country needs to implement an optimal carbon tax as a complementary policy within a global ETS regime to achieve the optimal level of emissions. Before introducing the full multi-region dynamic general equilibrium model, it is helpful to first explore the additional optimal carbon tax within a static framework. Under the global ETS framework, we assume that each region i is allocated with an exogenous level of emission cap (\bar{E}_i), which is the upper limit of emissions allowed for that region and is strictly enforced. The region's gross emissions before abatement is E_i^{Gross} , its emissions net of abatement is E_i , the amount of emission permits purchased (or sold) in the market is E_i^P (if $E_i^P < 0$, it implies that the region sells emission permits) so we have the emission cap constraint $E_i \leq \bar{E}_i + E_i^P$, where the Nash equilibrium permit price is m under the market clearing condition $\sum_{j \in \mathcal{I}} E_j^P = 0$. Here we assume that each region is a price taker. The region's marginal abatement cost (MAC) function, denoted $\text{MAC}_i(E_i)$, is assumed to be monotonically decreasing over emissions E_i with $\text{MAC}_i(E_i^{\text{Gross}}) = 0$. A social planner of the region solves the following minimization problem

$$\min_{0 \leq E_i \leq \bar{E}_i + E_i^P} D_i \left(\sum_{j \in \mathcal{I}} E_j \right) + m E_i^P + \int_{E_i}^{E_i^{\text{Gross}}} \text{MAC}_i(E) dE, \quad (1)$$

where the first term of the objective function is the regional damage from the global emissions $\sum_{j \in \mathcal{I}} E_j$ (which is the present value of future damage from the global emissions), the second

term is the cost from purchasing permits at the price m (or the profit from selling permits), and the third term is the total abatement cost for reducing emissions by the amount $(E_i^{\text{Gross}} - E_i)$. For simplicity, we assume that emissions cannot be negative in our model.

In the static Nash equilibrium of all regional social planners, every region solves equation (1) simultaneously with the market clearing condition $\sum_{j \in \mathcal{I}} E_j^P = 0$, which implies $\sum_{j \in \mathcal{I}} E_j \leq \sum_{j \in \mathcal{I}} \bar{E}_j$. Let E_j^* be the Nash equilibrium emissions for each region j and let m^* be the Nash equilibrium price. Thus, from the Karush-Kuhn-Tucker conditions of (1), the solution to the region's optimal emissions leads to the following relationship between the marginal regional damage, the MAC, and the permit price:

$$D'_i \left(\sum_{j \in \mathcal{I}} E_j^* \right) = \text{MAC}_i(E_i^*) - m^*, \quad (2)$$

when $E_i^* > 0$. The marginal regional damage can also be regarded as the regional social cost of carbon (SCC). Note that in the static Nash equilibrium with $E_i^* > 0$, the permit price m^* should be equal to the shadow price of the inequality $E_i \leq \bar{E}_i + E_i^P$. That is, if the inequality $E_i \leq \bar{E}_i + E_i^P$ is not binding, or $\sum_{j \in \mathcal{I}} E_j^* < \sum_{j \in \mathcal{I}} \bar{E}_j$ (i.e., there is an over-supply of emission permits), then the permit price is zero. Alternative, if the permit price is nonzero, then the inequality $E_i \leq \bar{E}_i + E_i^P$ must be binding, so the supply of emission permits is equal to the demand (i.e., $\sum_{j \in \mathcal{I}} E_j^* = \sum_{j \in \mathcal{I}} \bar{E}_j$). We emphasize that the assumption commonly used in the literature—that the MAC equals the permit price (e.g., Keohane, 2009; Nordhaus, 2010b)—however, does not hold in this case, unless the regional marginal damage or SCC is zero, according to equation (2). Moreover, we also numerically verify in our dynamic Nash equilibrium that, when $E_i^* > 0$, the regional MAC is also strictly larger than the permit price, and the difference is the regional SCC.

An important issue arises when the regional social planner cannot directly enforce its optimal emissions level on firms, the actual emission producers in the economy. To address this, let us assume that the social planner can employ carbon taxation as a policy instrument to resolve the discrepancy in optimal emissions between the firms and the regional social planner. Consider a representative firm in region i that produces emissions and operates under the region's MAC function and emissions cap constraint in a static framework. Since the firm does not internalize the damage from emissions, we assume that the social planner of region i levies a tax on the firm of τ_i per unit of emissions. The firm solves the following minimization problem:

$$\min_{0 \leq E_i \leq \bar{E}_i + E_i^P} \quad \tau_i E_i + m E_i^P + \int_{E_i}^{E_i^{\text{Gross}}} \text{MAC}_i(E) dE, \quad (3)$$

where the first term of the objective function is the total tax on emissions. In the static Nash equilibrium of all representative firms, every firm solves equation (3) simultaneously with the market clearing condition $\sum_{j \in \mathcal{I}} E_j^P = 0$. Let $E_j^{*,\text{Firm}}$ be the Nash equilibrium emissions for each firm j and let $m^{*,\text{Firm}}$ be the Nash equilibrium price. Thus, from the Karush-Kuhn-Tucker conditions of (3), the solution to the optimal emissions of the firm leads to the following relationship between the carbon tax, the MAC, and the permit price:

$$\tau_i = \text{MAC}_i(E_i^{*,\text{Firm}}) - m^{*,\text{Firm}}, \quad (4)$$

when $E_i^{*,\text{Firm}} > 0$. If the regional social planner imposes the tax to be equal to the regional SCC, i.e., the regional marginal damage, then from equations (2) and (4), we have $E_i^{*,\text{Firm}} = E_i^*$ and $m^{*,\text{Firm}} = m$. In other words, the optimal regional carbon tax is endogenously determined by the gap between the MAC at the regional social planner's optimal emissions and the market price of emission permits, capturing the idea that the regional social planner can choose the level of carbon tax such that the firm can internalize the regional SCC and achieve its emissions level of $E_i^{*,\text{Firm}} = E_i^*$. When $E_i^{*,\text{Firm}} = 0$, the Karush-Kuhn-Tucker conditions of (3) shows that

$$\tau_i \geq \text{MAC}_i(E_i^{*,\text{Firm}}) - m^{*,\text{Firm}}. \quad (5)$$

That is, the carbon tax could be larger than the gap between the MAC of a region and the market price of emission permits. In particular, the regional $\text{MAC}_i(E_i^{*,\text{Firm}})$ at $E_i^{*,\text{Firm}} = 0$ could be smaller than the global permit price $m^{*,\text{Firm}}$, making the right hand side of the inequality (5) to be negative. However, when $E_i^* = 0$, a nonnegative carbon tax larger than $\text{MAC}_i(E_i^*) - m^*$ will not make $E_i^{*,\text{Firm}}$ to be negative, so the optimal carbon tax should be zero or the gap $\text{MAC}_i(E_i^*) - m^*$ if it is positive.

Therefore, for any regional social planner's optimal emissions $E_i^* \geq 0$, we have the following general formula to choose the optimal carbon tax:

$$\tau_i = \max\{0, \text{MAC}_i(E_i^*) - m^*\}, \quad (6)$$

such that the firm's optimal emissions are consistent with the social planner's (i.e., $E_i^{*,\text{Firm}} = E_i^*$). The simple relationship between the optimal carbon tax, the MAC, and the permit price is also verified in our numerical solutions of the dynamic regional model. Note that this tax is contingent on the imposition of the emission cap on the firm, and the tax level itself cannot make the firm's emissions to be E_i^* unless $m^* = 0$.

It can be easily shown that our argument is consistent with the existing literature when

there is no ETS. The cost minimization problem of the representative firm facing the emission cap regulation without the ETS becomes:

$$\min_{0 \leq E_i \leq \bar{E}_i} \tau_i E_i + \int_{E_i}^{E_i^{\text{Gross}}} \text{MAC}_i(E) dE. \quad (7)$$

From the Karush-Kuhn-Tucker conditions of (7), when the firm's optimal solution $E_i^{*,\text{Firm}} = E_i^*$ is not binding at its lower or upper bound, we have the well known equality:

$$\tau_i = \text{MAC}_i(E_i^*). \quad (8)$$

This implies that the optimal carbon tax should be set equal to the MAC at the regional social planner's optimal emissions E_i^* , provided E_i^* is not binding. This result has been widely used in the literature (e.g., Nordhaus, 2014; Cai et al., 2017; Cai and Lontzek, 2019). Note that our formula (6) under an ETS with zero permit price is consistent with (8) under no ETS.

A regional social planner in each region i has two targets: one is its exogenous NDC commitment \bar{E}_i , and the other is the regional social planner's endogenous optimal emission E_i^* after permit trading (note that \bar{E}_i and E_i^* are unequal in general⁵) in the Nash equilibrium of all 12 regional social planners. That is, the region i 's emissions should be E_i^* , which should also satisfy $E_i^* \leq \bar{E}_i + E_i^P$ after permit trading in the Nash equilibrium. Several policy instruments can be applied to enforce the firms to meet the targets, assuming that the firms can buy or sell emission permits. One such instrument is a quantity policy, in which the regional social planner distributes \bar{E}_i (e.g., by means of an auction or grandfathering) to its firms, ensuring the firms' aggregate emissions, $E_i^{*,\text{Firm}}$, do not exceed the exogenous allocated cap after permit trading (i.e., $E_i^{*,\text{Firm}} \leq \bar{E}_i + E_i^P$) in the Nash equilibrium of firms of all regions.⁶ However, under a quantity-only control policy, $E_i^{*,\text{Firm}}$ is not equal to E_i^* , as the zero-tax Nash equilibrium of the firms, $\{m^{*,\text{Firm}}, E_i^{*,\text{Firm}} : j \in \mathcal{I}\}$, is not the Nash equilibrium of the regional social planners, $\{m^*, E_j^* : j \in \mathcal{I}\}$. This becomes particularly evident in the following extreme case: assume that \bar{E}_i is larger than E_i^{Gross} for every region, which leads

⁵We believe this is a realistic consideration, as emission cap pathways may not always align precisely with regional optimal emissions over time. This discrepancy arises because the negotiation of emission permit allocations is often time-consuming and influenced by political considerations, which may not lead to economically optimal outcomes. Our model simulation shows that the emission cap pathways constructed from the Paris Agreement and the Glasgow Climate Pact indeed deviate from the optimal regional emissions.

⁶The representative firm framework can be generalized to an environment with multiple firms. Assume that there are n homogenous firms in the region i , each having \bar{E}_i/n as their caps, with a firm's MAC function at its emissions e is defined as $\text{MAC}_i(ne)$, where $\text{MAC}_i(\cdot)$ is consistent with the regional social planner's MAC function and $E = ne$ is the aggregate regional emissions. In this case, the Nash equilibrium of the economy with multiple firms is identical to the equilibrium with a representative firm.

to $m^* = 0$ under the ETS. The firms' Nash equilibrium without a tax yields $E_i^{*,\text{Firm}} = E_i^{\text{Gross}}$, with $\text{MAC}_i(E_i^{*,\text{Firm}}) = m^{*,\text{Firm}} = 0$. In contrast, the regional social planners' Nash equilibrium leads to $E_i^* < E_i^{\text{Gross}}$, with $\text{MAC}_i(E_i^*) > m^* = 0$ in general, similar to a model without emission caps. Note that this quantity policy cannot directly distribute E_i^* , as doing so would either result in the region violating its commitment if $E_i^* > \bar{E}_i$ or losing the benefit in selling permits if $E_i^* < \bar{E}_i$. Another instrument is a carbon tax policy, in which the region i imposes a carbon tax τ_i on the firms, e.g., $\tau_i = \text{MAC}_i(\bar{E}_i)$ or $\tau_i = \text{MAC}_i(E_i^*)$. However, a carbon tax policy alone can target only one emission level, either \bar{E}_i or E_i^* , in each region, while $\bar{E}_i \neq E_i^*$ in general. Therefore, neither instrument can achieve both targets simultaneously.

We argue that, in the presence of a global ETS, then it is optimal for each region i to impose both the quantity policy and an additional carbon tax policy simultaneously on firms to enforce both targets. Here the additional carbon tax for region i is chosen to be $\tau_i = \text{MAC}_i(E_i^*) - m^*$ when $E_i^* > 0$, under the Nash equilibrium of the planners, $\{m^*, E_j^* : j \in \mathcal{I}\}$. If some regions impose only the quantity policy while the others impose both policies, this leads to a Nash equilibrium of firms, which is not the Nash equilibrium of the planners. Note that a tax has no impact on the regional social planners' decisions; E_i^* remains the optimal decisions of the regional social planners regardless of the tax levels. However, the tax can influence the firms' decisions. Therefore, from the regional social planners' perspective, any Nash equilibrium of firms deviated from $\{m^*, E_j^* : j \in \mathcal{I}\}$ is worse, and the regions should always impose both the quantity policy and the optimal additional carbon taxes simultaneously on the firms to meet both targets.⁷

3 A Dynamic Regional Model of Climate and the Economy with an ETS

We now introduce a dynamic regional model of climate and the economy that integrates a global ETS between 12 aggregated regions. Our model framework extends the RICE model (Nordhaus and Yang, 1996; Nordhaus, 2010b) by incorporating the global ETS in a dynamic setting and the TCRE climate system with annual time steps. The main objective of this study is to present a potential dynamic path of carbon emission prices in a noncooperative environment where each region aims to maximize its own social welfare by choosing the optimal amount of emission abatement, emission permits purchased from the global permits market, and the amount of its consumption. The model is based on the assumption that fu-

⁷Our argument is based on the assumption that the emission caps are exogenous in the regional level.

ture regional emissions are strictly constrained by the emission caps set by the commitments under the Paris Agreement (and revised under the Glasgow Pact) and net zero emissions targets. In this study, we consider the case without uncertainty and without transaction cost in the global ETS.

The macroeconomic framework of our model employs a multi-regional representation of the Ramsey growth model. We follow the RICE model and assume that the world consists of 12 aggregated regions: the United States (US), the EU, Japan, Russia, Eurasia, China, India, Middle East (MidEast), Africa, Latin America (LatAm), Other High-Income countries (OHI) and other non-OECD Asia (OthAs).⁸ Each region is indexed by $i \in \mathcal{I}$, where \mathcal{I} is the set of regions. Time is discrete, with annual time steps indexed by $t = 0, 1, 2, \dots$, where the initial year is the year 2020. All regions are forward-looking with complete information.

3.1 Emissions

The gross carbon emissions before abatement, in gigatonnes of carbon (GtC), is assumed to be proportional to the gross output for region i at time t :

$$E_i^{\text{Gross}} = \sigma_{i,t} Q_{i,t}, \quad (9)$$

where $Q_{i,t}$ is the gross output, and $\sigma_{i,t} > 0$ is the exogenous carbon intensity, calibrated from the projections of GDP and emissions in Ueckerdt et al. (2019). We follow DICE and assume that the amount of emissions abated by each region, $E_{i,t}^A$, is expressed as a fraction of the gross emissions, with an emission control rate $\mu_{i,t} \in [0, 1]$.⁹ That is,

$$E_{i,t}^A = \mu_{i,t} \sigma_{i,t} Q_{i,t}. \quad (10)$$

Thus the emissions net of abatement, $E_{i,t}$, becomes

$$E_{i,t} = E_i^{\text{Gross}} - E_{i,t}^A. \quad (11)$$

We consider a global ETS, or a cap-and-trade system, in which each region is provided with an emission allowance and can trade emission permits with other regions. Regions with

⁸See Appendix 1 A.2 for the full list of countries and regional aggregation.

⁹Instead of an emission control rate, researchers also model abatement through reduced use of fossil fuel energy inputs in a production function (see, e.g., Bosetti et al., 2006; Bauer et al., 2012; Golosov et al., 2014; Baldwin et al., 2020). However, these models require disaggregation of fossil fuel energy firms, renewable energy firms, final-goods producing firms, and other sectors, so they are often complicated. The emission control rate concept simplifies this.

emissions exceeding the emission caps can purchase emission permits from other regions. Regions with emissions below their allowance can sell their emission permits to others. The emission cap constraint is represented by

$$E_{i,t} - E_{i,t}^P \leq \bar{E}_{i,t}, \quad (12)$$

where $\bar{E}_{i,t}$ is the emission cap assigned to region i at time t , and $E_{i,t}^P$ denotes the amount of emissions traded with other regions. Note that $E_{i,t}^P > 0$ indicates that region i is a net buyer of emission permits at time t , while $E_{i,t}^P < 0$ implies region i is a net seller of emission permits at time t . In a model that does not consider emission permit trade, we simply apply $E_{i,t}^P = 0$ for all i and t . The Paris Agreement establishes upper limits for emissions to ensure that the increase in global temperature remains well below 2 degrees Celsius above preindustrial levels by the end of this century.

3.2 Climate System

The global average temperature rises as carbon emissions accumulate in the atmosphere. We follow the TCRE climate system and assume that the global average temperature increase above the pre-industrial level is approximately proportional to cumulative global emissions \mathcal{E}_t , i.e.,

$$T_t = \zeta \mathcal{E}_t, \quad (13)$$

where the cumulative emissions at 2020, \mathcal{E}_0 , is chosen such that the initial global mean temperature T_0 is 1.2 degrees Celsius above the pre-industrial level. Here $\zeta = 0.0021$ is the contribution rate of CO₂ equivalent to temperature, calibrated with the projections of emissions and temperatures in the four Representative Carbon Concentration Pathways (RCPs): RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 (Meinshausen et al., 2011). Figure A.1 in Appendix A.3.1 shows that the calibrated TCRE climate system can match all four RCP temperature pathways using their associated RCP emission pathways. Cumulative global emissions evolve according to

$$\mathcal{E}_{t+1} = \mathcal{E}_t + \sum_{i \in \mathcal{I}} E_{i,t}. \quad (14)$$

3.3 Economic System

A representative consumer in region i has a power utility per period as follows:

$$u(c_{i,t}) = \frac{c_{i,t}^{1-\gamma}}{1-\gamma}, \quad (15)$$

where $c_{i,t}$ is per capita consumption and γ is the inverse of intertemporal elasticity of substitution. We follow DICE-2016R Nordhaus (2017) and set $\gamma = 1.45$.

The production technology follows a Cobb-Douglas function of capital and labor inputs. The gross output (in trillion USD), or pre-damage output, $Q_{i,t}$, is given by

$$Q_{i,t} = A_{i,t} K_{i,t}^\alpha L_{i,t}^{1-\alpha}, \quad (16)$$

where $K_{i,t}$ is capital stock, $L_{i,t}$ is labor, and $\alpha = 0.3$ (following Nordhaus (2017)) is the elasticity of gross output with respect to capital. The total factor productivity $A_{i,t}$ is assumed to follow an exogenous and deterministic time-varying trend, which is calibrated with the GDP projections in Burke et al. (2018). Labor $L_{i,t}$ is also assumed to follow the exogenous population path of region i from the SSP2 scenario (Samir and Lutz, 2017).

We denote $Y_{i,t}$ as the output net of damages induced by climate changes:

$$Y_{i,t} = \frac{1}{1 + \pi_{1,i}T_t + \pi_{2,i}T_t^2} Q_{i,t}, \quad (17)$$

where T_t is the global average temperature increase in degrees Celsius above the preindustrial level. We calibrate the climate damage parameters based on the projections of GDP in Burke et al. (2018). We follow DICE and assume emission abatement cost is

$$\Phi_{i,t} = b_{1,i,t} \mu_{i,t}^{b_{2,i}} Q_{i,t},$$

where $b_{1,i,t} = (b_{1,i} + b_{3,i} \exp(-b_{4,i}t))\sigma_{i,t}$. We calibrate the abatement cost parameters, $b_{1,i}$, $b_{2,i}$, $b_{3,i}$, and $b_{4,i}$, by exploiting the projections under different carbon tax scenarios in Ueckerdt et al. (2019), from which we recover the marginal abatement costs and calibrate the parameters we need.

The total consumption of each region under the ETS is obtained by

$$c_{i,t} L_{i,t} = Y_{i,t} - I_{i,t} - \Phi_{i,t} - m_t E_{i,t}^P, \quad (18)$$

where $I_{i,t}$ is investment and m_t is the market price of carbon emission permits. The cost of purchasing emission permits from other regions results in reduced consumption, while

selling emission permits increases consumption, but this impact is little as the cost or profit from permit trading is small relative to consumption or output. The capital stock evolves according to the standard neoclassical growth model:

$$K_{i,t+1} = (1 - \delta)K_{i,t} + I_{i,t}, \quad (19)$$

where $\delta = 0.1$ is the rate of depreciation of capital stock. We assume that the emission trading market clears in each period. That is,

$$\sum_{i \in \mathcal{I}} E_{i,t}^P = 0, \quad (20)$$

for each time period t .

4 Solving for the Equilibrium

Building on the model components outlined in Section 2, we now define the noncooperative equilibrium of our multi-region dynamic model with the ETS and present an algorithm used to obtain the Nash Equilibrium solution.

4.1 The Noncooperative Equilibrium

In the noncooperative model, the regional social planner of each region maximizes the region's own lifetime social welfare. The maximization problem for each region i is defined as

$$\max_{c_{i,t}, E_{i,t}^P, \mu_{i,t}} \sum_{t=0}^{\infty} \beta^t u(c_{i,t}) L_{i,t}, \quad (21)$$

where β is the discount factor. We follow DICE-2016R (Nordhaus, 2017) and set $\beta = 0.985$. Since one region's emissions will influence temperature, then other regions' output, the maximization problems of all regions have to be solved simultaneously as a dynamic game. Then we define the dynamic Nash equilibrium of the economy as follows.

DEFINITION: Given the initial capital and cumulative global emissions, $\{K_{i,0}, \mathcal{E}_0 : i \in \mathcal{I}\}$, and the exogenous paths of emission caps $\{\bar{E}_{i,t} : i \in \mathcal{I}, t \geq 0\}$, the dynamic Nash equilibrium for the noncooperative model is a sequence of quantities $\{c_{i,t}, E_{i,t}^P, \mu_{i,t}, K_{i,t}, \mathcal{E}_t, T_t : i \in \mathcal{I}, t \geq 0\}$ and prices $\{m_t : t \geq 0\}$ that simultaneously solve the maximization problem (21) for all regions subject to equations (15)-(20).

The optimal solution for this dynamic multi-region model involves three choice problems. First, as in the standard Ramsey-type growth model, each region faces an intertemporal choice problem in which there is a trade-off between current consumption and future consumption. Each region may sacrifice present consumption to make investments, which can contribute to higher consumption in the future. Second, the intertemporal choice problem is further compounded by climate damages. Current production increases the global temperature, which subsequently lowers future productivity. Since emissions abatement has positive externalities, a region's returns from abatement efforts may not be large enough to offset the cost of abatement. Therefore, the optimal solution of each region is highly dependent on the choices made by other regions. Lastly, the ETS allows each region to choose between purchasing emission permits from the market and undertaking further abatement. The ETS promotes efficient abatement globally by encouraging regions with better abatement technology or capacity (thus, with lower abatement cost) to conduct more abatement, and regions with less efficient abatement technology to purchase permits from other regions.

Note that the equilibrium concept in our noncooperative model is an Open-Loop Nash equilibrium (OLNE), which provides a solution path over time depending on the initial state. In an OLNE, regions commit to the strategies over time for their decision variables—consumption ($c_{i,t}$), emission purchase ($E_{i,t}^P$), and emission control rate ($\mu_{i,t}$)—at the initial period and cannot change their behavior over time. This concept contrasts with the Markov Perfect Equilibrium (MPE), where regions may make multiple decisions over time, allowing adaptation in their strategies. While the OLNE concept may be less satisfactory than the MPE concept (since OLNE is not subgame perfect), it has the computational advantages of solving open-loop versus feedback, particularly when the dimension of the state space is large and there are occasionally binding constraints as in our case.

4.2 The Algorithm for the Noncooperative Model

Obtaining the optimal solution of the dynamic model involving multiple regions under non-cooperation is challenging. In particular, finding an equilibrium solution for the emission permit prices that satisfies the optimality conditions for each region as well as the market clearing condition poses significant computational challenges. While several studies have incorporated emission prices in their models, no study has successfully solved for the emission permit price in a noncooperative context.

Here we outline the algorithm we develop to obtain the optimal solution for our model. Since $\gamma = 1.45$ implies utilities of per capita consumption have negative values and that long-run per capita consumption will be large, the long-run per-capita utility has a small

magnitude. Together with the discount factor $\beta = 0.985$, the discounted utilities after 300 years are nearly zero and have little impact on the solution in the first 100 years. Let

$$V_{i,300}(K_{1,300}, \dots, K_{12,300}, \mathcal{E}_{300}) = u\left(\frac{0.75Y_{i,300}}{L_{i,300}}\right) \frac{L_{i,300}}{1-\beta}$$

be a terminal value function at the terminal year 300, which approximates the present value of utilities after 300 years, assuming that consumption at any $t \geq 300$ is identical to 75 percent of the output $Y_{i,300}$ at $t = 300$ and that the exogenous population after 300 years stays at its value at $t = 300$. Note that $Y_{i,300}$ is computed with a function of the terminal state $K_{i,300}$ and \mathcal{E}_{300} . Thus, we can transform the infinite horizon models to finite horizon models, where region i 's social welfare is rewritten as

$$\sum_{t=0}^{299} \beta^t u(c_{i,t}) L_{i,t} + \beta^{300} V_{i,300}(K_{1,300}, \dots, K_{12,300}, \mathcal{E}_{300}),$$

We also numerically verify that this time horizon truncation at 300 years has little impact on the OLNE solution in the first 100 years, by solving the same model but with a time horizon truncation at 400 years. This time horizon truncation method is common in solving infinite-horizon nonstationary models. For example, DICE-2016 truncates its model's infinite horizon to 500 years, with a terminal value function being zero everywhere, for obtaining its numerical solution.

The algorithm to solve the noncooperative model is as follows:

Step 1. Initialization. Set an initial guess of permit prices $\{m_t^0 : t \geq 0\}$, and emissions $\{E_{i,t}^0 : t \geq 0\}$. Iterate through steps 2, 3 and 4 for $j = 1, 2, \dots$, until convergence.

Step 2. Maximization Step at iteration j . For each region i , solve the maximization problem (21) without the market clearing condition (20), assuming the permit prices $\{m_t^{j-1} : t \geq 0\}$ and other regions' emissions $\{E_{i',t}^{j-1} : i' \neq i, t \geq 0\}$ are given from the initialization step when $j = 1$ or Step 3 at iteration $j - 1$ when $j > 1$. The optimal emissions and permits purchased for region i are denoted $\{E_{i,t}^{*,j}, E_{i,t}^{P,j} : t \geq 0\}$.

Step 3. Update Step at iteration j . After solving for the optimization problem of all regions respectively in Step 2, update the permit prices and emissions as

$$\begin{aligned} m_t^j &= m_t^{j-1} \exp\left(\omega \sum_{i \in \mathcal{I}} E_{i,t}^{P,j}\right), \\ E_{i,t}^j &= \omega E_{i,t}^{*,j} + (1-\omega) E_{i,t}^{j-1}, \quad \forall i \in \mathcal{I}, \end{aligned}$$

where $\omega = 0.1$ is a weight parameter and $\sum_{i \in \mathcal{I}} E_{i,t}^{P,j}$ is the net quantity of traded emission permits.

Step 4. *Check the convergence criterion.* Check if $m_t^j \simeq m_t^{j-1}$, $E_{i,t}^j \simeq E_{i,t}^{j-1}$, and $E_{i,t}^{P,j} \simeq E_{i,t}^{P,j-1}$ for every region i and $t \geq 0$. If so, stop the iteration, otherwise go to Step 2 by increasing j with 1. Note that $m_t^j = m_t^{j-1}$ implies that the market clearing condition (20) holds at the solution.

This algorithm embodies the concept of market equilibrium. When there is a positive net quantity of traded emission permits in the market, indicating excess demand, we increase the permit prices. Conversely, when there is a negative net quantity of traded emission permits, indicating excess supply, we lower the permit prices. This mechanism ensures that the market reaches a balance between supply and demand, and thus the market clears. Furthermore, this algorithm guarantees that each region obtains its optimal solution and reaches an equilibrium state. In other words, no region has the incentive to deviate from the Nash equilibrium for the noncooperative model solution.

5 Data and Calibration

To calibrate our model with data, we have two objectives. The first objective is to generate regional emission cap pathways ($\bar{E}_{i,t}$) for future periods, constraining the constituent nations of each region to meet their emissions commitments under the Glasgow Pact and the long-term net zero emission targets. The second objective is to determine parameters for total factor productivity ($A_{i,t}$), carbon intensity ($\sigma_{i,t}$), abatement cost ($b_{1,i}$, $b_{2,i}$, $b_{3,i}$, $b_{4,i}$), and climate damage ($\pi_{1,i}$, $\pi_{2,i}$) that reflect the future projections provided in recent studies (Burke et al., 2018; Ueckerdt et al., 2019; Kahn et al., 2021). We obtain these region-specific parameters, which capture regional heterogeneities in GDP growth, emissions, technologies, and climate damages.

Our model's 12 regions are formed by aggregating 152 countries around the world, following the regional classification in the RICE model (Nordhaus and Yang, 1996; Nordhaus, 2010b). For the initial year 2020, we obtain country-level historical data on population (billions), capital (\$ trillions, 2020), GDP (\$ trillions, 2020), and emissions (GtC) from the World Bank. For future projections on population growth, we use the SSP2 scenario (Samir and Lutz, 2017).

5.1 Regional Emission Cap Pathways

Since there is no global cap-and-trade system or ETS currently in place, we consider the emission commitments outlined in the Paris Agreement and the COP26 Glasgow Climate Pact. Under the Paris Agreement, 195 countries or regions set Nationally Determined Contributions (NDCs) that specify their near-term targets for 2025 or 2030, along with long-term net-zero commitments for 2050 to 2070. These near-term targets were further strengthened during the Glasgow Climate Pact in 2021, with most countries and regions submitting updated or new NDCs.¹⁰ We collect reports of the most updated Nationally Determined Contributions (NDCs) after the Glasgow Climate Pact and obtain the target years to reach net zero emissions of different countries from Climate Action Tracker.¹¹ Based on these datasets, we create the baseline regional emission cap pathways for future periods following the strategy detailed below.

As the first step, we obtain the level of emission targets for each country. In their NDC reports, most countries expressed targets as a specific percentage reduction in emissions by 2030 (or, in some cases, 2025) compared to their Business As Usual (BAU) emission level at some base year. Some countries, including China, Chile, Malaysia, Singapore, and Tunisia specified their targets as a percentage reduction in carbon intensity instead of a percentage reduction in emissions. For the countries that did not make a specific emissions reduction pledge, we assume that their carbon intensity reduction and emission reduction percentages are the same as those of the most populous country in that region.

Next, we generate annual emission cap pathways based on the regions' historical emission levels (World Bank, 2020), their emission targets for 2030 (or 2025), and net zero emission target years. We use five-year emissions data (2014 - 2018) from the World Bank and the INDC emission targets in 2030 (or 2025) to fit a quadratic function and use this fitted function to project the emission pathways for the periods between 2018 and 2030. Emission projections for the years between 2030 (or 2025) and the net zero emission target year are obtained by linearly interpolating the emissions. After obtaining the country-level emission pathways, we aggregate them to find the regional emission cap pathways.¹² To assess the implications of varying stringency in the emission caps, we also create additional emission cap pathways by choosing alternative net zero scenarios, wherein we assume that all regions achieve net zero emissions by 2050 (most stringent), 2070, or 2090 (most lax). See Figures A.5 and A.6 in Appendix A.3.4 for the regional emission cap pathways in the baseline cap

¹⁰Individual NDC documents were obtained from the following source: UNFCCC NDC Registry (<https://unfccc.int/NDCREG>)

¹¹See <https://climateactiontracker.org/>.

¹²We also find that our aggregated regional emission cap pathways are close to those used in Nordhaus (2010b).

scenario and the different emission cap pathways at the global level.

5.2 Total Factor Productivity and Climate Damage

We follow Cai et al. (2023) to calibrate total factor productivity (TFP), $A_{i,t}$, and the climate damage parameters $\pi_{1,i}$ and $\pi_{2,i}$, based on Burke et al. (2018), who provide the projected GDP of 165 countries until 2099 assuming no climate-related impacts, and their GDP assuming the contemporaneous climate impact of the RCP4.5 temperature $T_t^{\text{RCP4.5}}$ ¹³ until 2049, under the SSP2 population pathway.¹⁴ We aggregate these projections according to our 12 regions and employ the SSP2 population scenario to obtain regional GDP per capita estimates, $y_{i,t}^{\text{BDD,NoCC}}$ under no climate impact and $y_{i,t}^{\text{BDD}}$ under climate impact, which are used to calibrate the regional TFP, $A_{i,t}$, and the climate damage parameters $\pi_{1,i}$ and $\pi_{2,i}$. For each region i , the dynamic path of the TFP is modeled by the relationship $A_{i,t+1} = A_{i,t} \exp(g_{i,t})$, where $g_{i,t}$ is the growth rate of $A_{i,t}$ at time t . When $t < 80$ (i.e., within this century), we assume

$$g_{i,t} = g_{i,0} \exp(-d_i t). \quad (22)$$

For $t \geq 80$ (i.e., beyond this century), since the cumulative effect is huge for a long horizon, it is often inappropriate to simply extrapolate TFP growth rate using the formula (22). Therefore, we follow RICE to generate $g_{t,i}$ for $t \geq 80$. See Appendix A.3.5 for the details.

In our structural estimation, we obtain $(g_{i,0}, d_i, \pi_{1,i}, \pi_{2,i})$ by solving the following minimization problem:

$$\min_{g_{i,0}, d_i, \pi_{1,i}, \pi_{2,i}} \sum_{t=0}^{79} \left(\frac{y_{i,t}^{\text{NoCC}}}{y_{i,0}^{\text{NoCC}}} - \frac{y_{i,t}^{\text{BDD,NoCC}}}{y_{i,0}^{\text{BDD,NoCC}}} \right)^2 + \sum_{t=0}^{29} \left(\frac{y_{i,t}}{y_{i,0}} - \frac{y_{i,t}^{\text{BDD}}}{y_{i,0}^{\text{BDD}}} \right)^2. \quad (23)$$

Here $y_{i,t}^{\text{NoCC}}$ is GDP per capita obtained under no climate impact by solving the following optimal growth model with a choice of $(g_{i,0}, d_i, \pi_{1,i}, \pi_{2,i})$ and its associated TFP $A_{i,t}$:

$$\begin{aligned} \max_{c_{i,t}} \quad & \sum_{t=0}^{\infty} \beta^t u(c_{i,t}) L_{i,t}, \\ \text{s.t.} \quad & K_{i,t+1} = (1 - \delta) K_{i,t} + (y_{i,t}^{\text{NoCC}} - c_{i,t}) L_{i,t}, \end{aligned} \quad (24)$$

¹³We choose the RCP4.5 scenario instead of the other RCP scenarios, because the RCP4.5 scenario is the closest which covers the range of temperature in our solution.

¹⁴It is nontrivial to use historical data to calibrate future TFP, particularly when we need to isolate the climate impacts from the data. For simplicity, we use the projected GDP for the calibration in this paper. We also use the TFP growth values in RICE to do sensitivity analysis, and find our results are still robust (see Appendix A.4.6).

where $y_{i,t}^{\text{NoCC}} = A_{i,t} K_{i,t}^\alpha L_{i,t}^{-\alpha}$ and $u(c_{i,t})$ is defined as in equation (15); and $y_{i,t}$ is GDP per capita under climate impact by solving the following optimal growth model:

$$\begin{aligned} \max_{c_{i,t}} \quad & \sum_{t=0}^{\infty} \beta^t u(c_{i,t}) L_{i,t}, \\ \text{s.t.} \quad & K_{i,t+1} = (1 - \delta) K_{i,t} + (y_{i,t} - c_{i,t}) L_{i,t}, \end{aligned} \quad (25)$$

where

$$y_{i,t} = \frac{1}{1 + \pi_{1,i} T_t^{\text{RCP4.5}} + \pi_{2,i} (T_t^{\text{RCP4.5}})^2} A_{i,t} K_{i,t}^\alpha L_{i,t}^{-\alpha}.$$

The initial TFP $A_{i,0}$ is chosen such that $A_{i,0} K_{i,0}^\alpha L_{i,0}^{-\alpha} / (1 + \pi_{1,i} T_0 + \pi_{2,i} T_0^2)$ is equal to the observed GDP per capita in 2020. Figures A.2 and A.3 in Appendix A.3.2 shows that with our calibrated $(g_{i,0}, d_i, \pi_{1,i}, \pi_{2,i})$, the GDP per capita $y_{i,t}^{\text{NoCC}}$ or $y_{i,t}$ matches well with the projected data $y_{i,t}^{\text{BDD, NoCC}}$ or $y_{i,t}^{\text{BDD}}$ from Burke et al. (2018), respectively, for all regions.

5.3 Carbon Intensity

To obtain the time-varying and region-specific carbon intensities $\sigma_{i,t}$, we use the projections of GDP and emissions in Ueckerdt et al. (2019), who report simulation results of future emissions and GDP under different scenarios based on climate policy regimes, technology portfolios, and carbon tax implementation. As the carbon intensity in our model reflects the zero-carbon tax regime, we employ results from the scenario defined as ‘FFrun451’ in Ueckerdt et al. (2019). Specifically, this FFRun451 scenario corresponds to weak policy baseline before Paris Agreement with limited renewable technology portfolio and zero carbon tax. Based on the equation (9), we calculate the carbon intensities as $\sigma_{i,t} = E_{i,t,\text{FFrun451}}^U / Q_{i,t,\text{FFrun451}}$, where $E_{i,t,\text{FFrun451}}^U$ and $Q_{i,t,\text{FFrun451}}$ are the projected regional emissions and GDP under the FFRun451 scenario for region i at time t .¹⁵

5.4 Abatement Cost

Our estimation of the abatement cost parameters $b_{1,i}$, $b_{2,i}$, $b_{3,i}$, and $b_{4,i}$ relies on the simulation results under ten different levels of carbon taxes in Ueckerdt et al. (2019). For each scenario j with associated carbon taxes $\tau_{t,j}^U$ for every region i , Ueckerdt et al. (2019) report the projected regional emissions net of abatement ($E_{i,t,j}^U$), for region i at time t . Since Ueckerdt

¹⁵Ueckerdt et al. (2019) provide data for 11 regions. Upon comparison, we find that the countries constituting the ‘Rest of the World (ROW)’ region are the ones that are in the ‘Other High Income (OHI)’ and ‘Eurasia’ region in our study. Therefore, the carbon intensity obtained from the ROW in Ueckerdt et al. (2019) corresponds to that of OHI and Eurasia regions in our work.

et al. (2019) do not consider an ETS, according to the discussion in Section 2, we can assume that their carbon taxes $\tau_{t,j}^U$ are equal to the marginal abatement costs when emissions are strictly positive. That is,

$$\tau_{t,j}^U = \frac{1,000b_{2,i}\mu_{i,t,j}^{b_{2,i}-1}b_{1,i,t}}{\sigma_{i,t}} = 1,000b_{2,i}\mu_{i,t,j}^{b_{2,i}-1}(b_{1,i} + b_{3,i}\exp(-b_{4,i}t)), \quad (26)$$

for $\mu_{i,t,j} \in (0, 1)$. Therefore, we can use their simulation results under different carbon tax levels to estimate $b_{1,i}$, $b_{2,i}$, $b_{3,i}$, and $b_{4,i}$. At first, we estimate the associated emission control rate $\mu_{i,t,j}^U$ using the equations (9)-(11) as follows:

$$\mu_{i,t,j}^U = 1 - \frac{E_{i,t,j}^U}{E_{i,t,\text{FFrun451}}^U}, \quad (27)$$

where $E_{i,t,\text{FFrun451}}^U$ is the regional emissions from the FRun451 scenario with zero carbon tax (see Ueckerdt et al. (2019) for details). Then we use the computed $\mu_{i,t,j}^U$ and the associated carbon tax $\tau_{t,j}^U$ to find the abatement cost coefficients— $b_{1,i}$, $b_{2,i}$, $b_{3,i}$, and $b_{4,i}$ —such that the equality (26) can hold in an approximate manner for every scenario j and time t .

6 Results

In this section, we discuss our simulation results. We first present the results of the noncooperative model under the baseline emission cap scenario for the period from 2020 to 2100. Next, we compare the economic outcomes across different models, examining the presence of emission caps and the implementation of a global ETS. Lastly, we present simulation results with the different emission cap scenarios assuming the net zero target year to be 2050, 2070, and 2090, respectively, for all 12 regions.

6.1 Key Results under the Baseline Emission Caps

Figure 1 displays simulation results at the global level, from the noncooperative model with the ETS under the baseline emission cap scenario. Until 2100, we can delineate three periods according to the global emission trading patterns. Prior to 2027, global emissions do not reach the global emission caps and therefore the permit price remains zero, implying an excess supply of emission permits in the initial years (Figure 1 top-left and bottom-left), as the emission caps in the initial years are large while they become much smaller over time (Figure A.5). This result is not surprising, considering that an oversupply of emission permits has been observed in the EU ETS (Fuss et al., 2018), resulting in zero or very low

permit prices. This is also consistent with our theoretical analysis for the regional social planners' Nash equilibrium in Section 2. During this period, the volume of global emission abatement and its associated abatement cost remain at low levels (Figure 1 top-left and bottom-right). This result implies that the global emission cap should be set at a level such that there is no over-supply of emission permits, so that permit prices are strictly positive under noncooperation and the ETS.

Global emissions are constrained by the global emission caps starting from 2025. To comply with the monotonically decreasing emission caps, the regions undertake additional abatement efforts and/or purchase emission permits. This results in a substantial increase in the volumes of both emission abatement and traded permits, along with their associated costs. The decrease in global emissions is mainly achieved by the concomitant increase in global abatement, which peaks by around 2060 (Figure 1 top-left). The global abatement cost also increases steeply to reach its maximum value of \$5.45 trillion by 2070, and then decreases as the world reaches net zero emissions by 2070. The emission permit trade, which rises from 2020, gradually decreases to zero by 2070 (Figure 1 top-left). As the emission cap becomes tighter over the years, the permit price increases to \$845 per ton of carbon in 2050 and \$2,059 in 2069 (Figure 1 bottom-left). The kinks in the permit price path in 2050 and 2060 are a result of some regions achieving net zero emissions, as shown in Figure A.5. Essentially, binding emission caps lead to a rise in the overall emission abatement, while the steep increase in the permit price limits the trading of emission permits.

Post-2070 is the period when global emissions are net zero. For this period, emission permits are no longer traded and all emissions are abated in each region.¹⁶ By the end of this century, the atmospheric temperature is projected to reach 1.7 degrees Celsius above the pre-industrial level, which is driven by net positive emissions before 2070 (Figure 1 top-right), restricted by the emission caps.¹⁷ Lastly, the global climate damage rises almost linearly over the entire period (Figure 1 bottom-right). Overall, our noncooperative model simulation predicts that the global emission caps set by the Paris Agreement and Glasgow Pact are not restrictive enough to achieve the global target of limiting the temperature rise to 1.5 degrees Celsius.

It is instructive to examine the trading patterns of different regions in the emission permit market over the years to identify the permit buyers and sellers. Figure 2 displays the volumes of traded emission permits for each region over time, with a positive value denoting permit purchase and a negative value indicating permit sales. Before 2025, although there is an

¹⁶In the bottom-left panel of Figure 1, we plot the emission permit price only when the traded volume is positive.

¹⁷If there is no emission cap, then the temperature anomaly will be much higher. This can be seen in a later discussion with alternative emission caps.

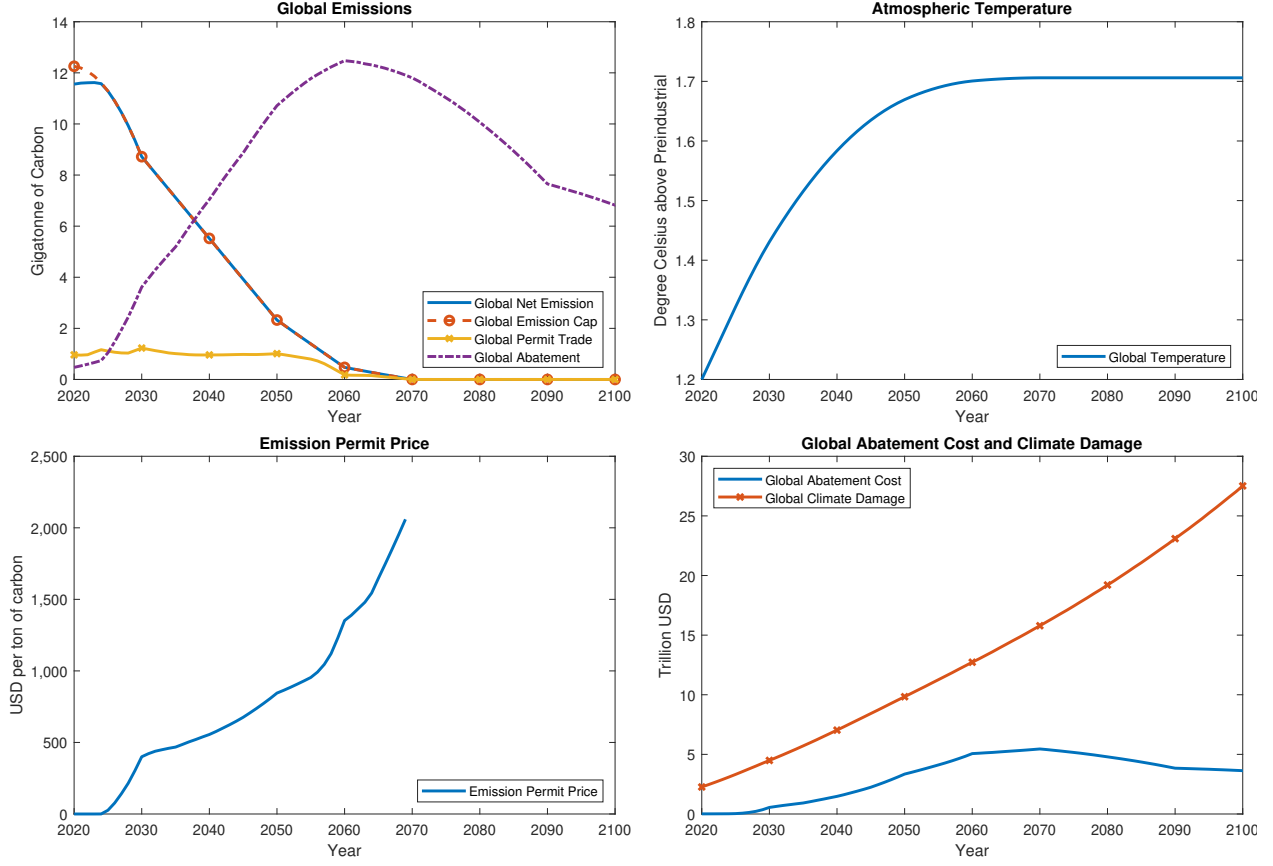


Figure 1: Simulation results at the global scale under the baseline emission cap scenario.

excess permit supply at the global level, the emission cap constraint is effective for some regions, such as China and Latin America, as these regions become permit buyers at this early stage. After 2025, when the global emission cap constraint becomes binding, the group of permit buyers consists of the US, EU, India, and OHI regions; the group of permit sellers consists of Russia, China, and Eurasia, with China being the largest permit provider after 2036. Japan is expected to be involved in a relatively small volume of permit trading, and the other regions (Africa, MidEast, Latin America, and OthAs) change their status along time.

6.2 SCC, MAC, and the Optimal Carbon Tax

Based on the simulation results under the baseline emission cap scenario, this section examines the relationship between the MAC, regional social cost of carbon (SCC), and the optimal carbon tax under the global ETS regime. The MAC captures the additional cost incurred due to an increase in emission abatement. From our model equation (10), the total abatement cost is $TAC_{i,t} = b_{1,i,t} \mu_{i,t}^{b_{2,i}} Q_{i,t}$, in trillions of USD. Thus, the MAC, in 2020 USD

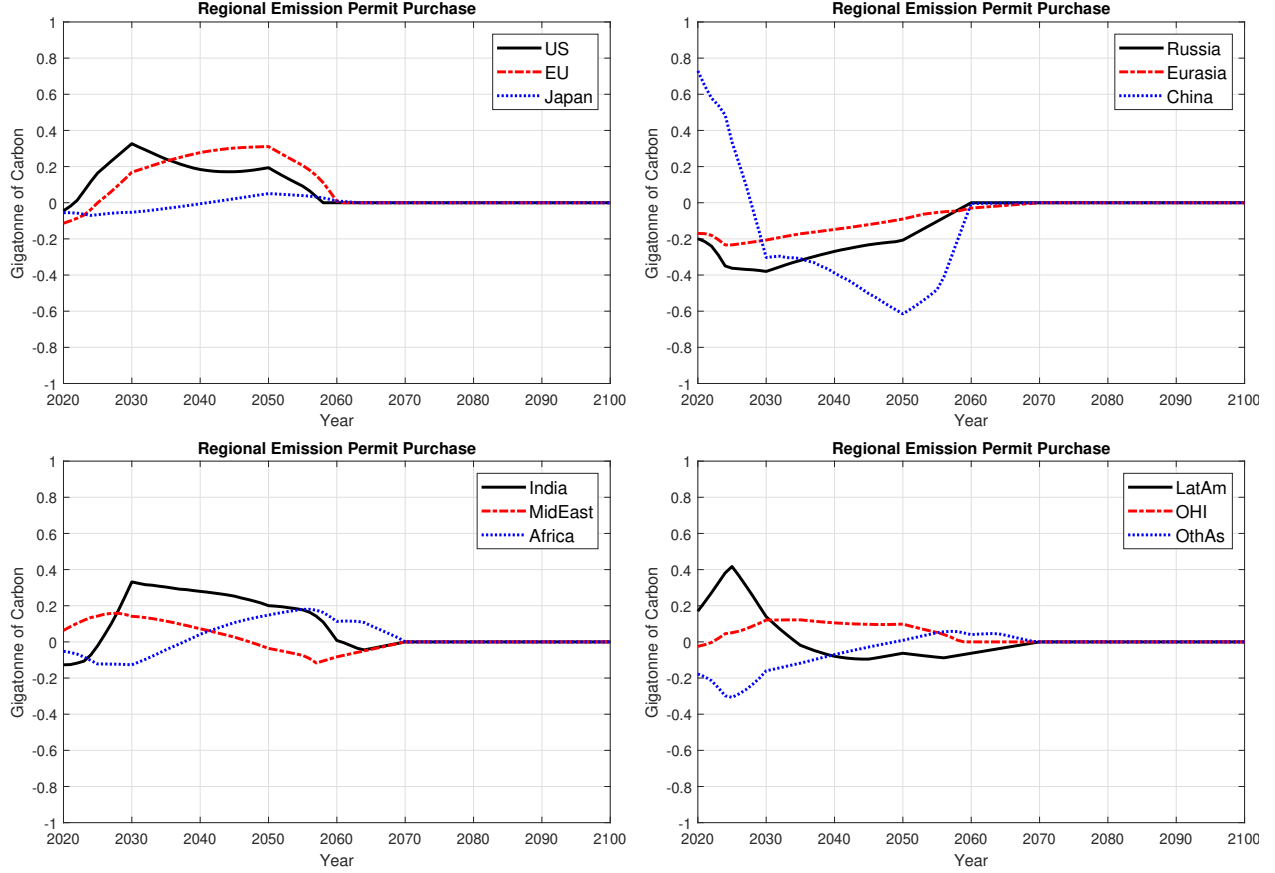


Figure 2: Simulation results of regional emission permit purchase under the baseline emission cap scenario.

per ton of carbon, is obtained as follows:

$$\text{MAC}_{i,t} = 1,000 \left(\frac{\partial \text{TAC}_{i,t}}{\partial E_{i,t}^A} \right) = 1,000 \left(\frac{b_{1,i,t} b_{2,i} \mu_{i,t}^{b_{2,i}-1}}{\sigma_{i,t}} \right). \quad (28)$$

With $b_{1,i,t} > 0$ and $b_{2,i} > 2$, MAC is strictly increasing on emission control rate $\mu_{i,t} \in [0, 1]$.¹⁸ Figure 3 displays the regional MAC along with the market equilibrium price of emission permits. We find that, for every region, the MAC increases drastically and remains strictly greater than the permit price until the emissions hit zero by 2050s or 2060s.¹⁹ As discussed in Section 2, $\text{MAC}(E_{i,t}^*) > m_t$ implies that the optimal emissions for the regional social planner do not align with the optimal emissions for the representative firm under no tax in each region. Therefore, the optimal regional carbon tax can be introduced at $\tau_{i,t} = \text{MAC}(E_{i,t}^*) - m_t$, so that the firm's emissions are equal to the regional social planner's optimal

¹⁸See Table A.2 in Appendix A.1 for the list of our calibrated abatement cost parameters.

¹⁹For regional optimal emissions, see Figure 11 in Appendix A.4.1.

emissions $E_{i,t}^*$ for region i at time t before 2050s. Russia is an exception, where the MAC falls below the permit prices starting in 2025, even though it has nonzero emissions until 2050, because global warming leads to increase in productivity rather than causing climate damages in Russia. This result is strongly influenced by the climate damage parameters, calibrated using projections from Burke et al. (2018).

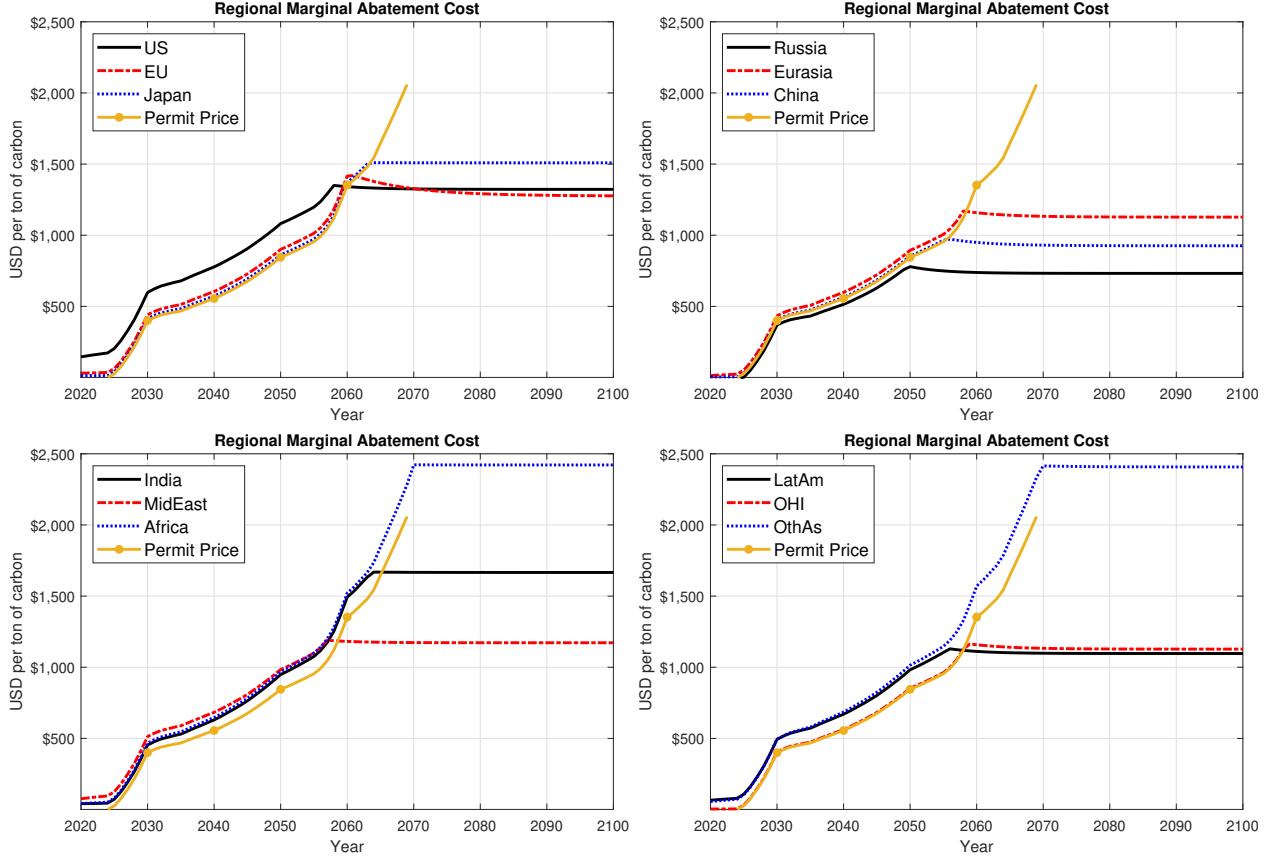


Figure 3: Simulation results of regional MAC under the baseline emission cap scenario.

In Figure 3, the MAC of each region gradually decreases below the permit price after its net zero emissions (before trading of permits) is achieved. Russia is the first region to achieve net zero emissions (before trading of permits) in 2050 (as shown in Figure A.7 in Appendix A.4.1). However, Russia continues to sell permits afterwards, as shown in Figure 2, because its after-trade net zero emission target year is 2060, under the baseline emission cap scenario. After 2050, Russia's MAC begins to decline slightly and stabilizes over time, as its emission control rate reaches its upper limit.²⁰ Similar trends are followed by other regions as they attain net zero emissions (before trading of permits) in the 2050s (China, the US, the EU, the OHI, MidEast, Eurasia, and Latin America) and the 2060s (Japan, India,

²⁰When emission control rates are one, the MACs are $1,000b_{2,i}(b_{1,i} + b_{3,i} \exp(-b_{4,i}t))$, and they are nearly constant when t is large.

Africa, and OthAs). Africa and OthAs are the last group of regions to achieve net zero emissions (before trading of permits) by 2070, after which emission permits are no longer traded, and the MACs of all regions decline slowly over time. Recall that, when the regional net zero emissions (before trading of permits) are achieved (i.e., $E_{i,t}^* = 0$), the regional optimal carbon tax should be larger than the gap between the regional MAC and permit price, i.e., $\tau_{i,t} \geq \text{MAC}(E_{i,t}^*) - m_t$. Note that if a region's after-permit-trade zero emission cap constraint is binding (i.e., the inequality (12) is binding with $\bar{E}_{i,t} = 0$), then even when its regional MAC is smaller than the permit price, the region will not be able to sell emission permits, otherwise it will violate the constraint.

Given the simulation results for the optimal carbon tax, we now turn to a discussion of the relationship between the optimal carbon tax and the regional social cost of carbon (SCC). The SCC, a central concept in the climate change literature, is widely used to quantify the present value of climate damages induced by an additional unit of carbon emissions. While the SCC is often calculated in a global social planner's problem (e.g., the DICE model), we consider the SCC for each region. Similar to van der Ploeg and de Zeeuw (2016) and Cai et al. (2023), we define the noncooperative SCC of a region as the marginal rate of substitution between global emissions and regional capital as follows:

$$\text{SCC}_{i,t} = \frac{-1,000(\partial V_{i,t}/\partial \mathcal{E}_t)}{\partial V_{i,t}/\partial K_{i,t}}, \quad (29)$$

where $V_{i,t}$ is the value function of the noncooperative model at time t for region i , depending on the state variables $\{K_{i,t}, \mathcal{E}_t : i \in \mathcal{I}\}$; that is,

$$V_{i,t}(K_{1,t}, \dots, K_{12,t}, \mathcal{E}_t) = \max_{c_{i,s}, E_{i,s}^P, \mu_{i,s}} \sum_{s=t}^{\infty} \beta^{s-t} u(c_{i,s}) L_{i,s},$$

for each region i under the open loop Nash equilibrium. Since our cumulative global emissions are measured in gigatonnes of carbon (GtC) and capital is measured in trillions of USD, our SCC is measured in 2020 USD per ton of carbon.²¹

Our concept of the regional SCC differs from the definition in Nordhaus (2017) and Ricke et al. (2018), where the regional SCC is defined as the present value of future climate damages in a region resulting from an additional unit of global emissions released in the current period, but their social discount rates are exogenous. We define the regional noncooperative SCC as the marginal rate of substitution between cumulative global emissions and regional capital

²¹To compute the regional SCC in the noncooperative model, it is equivalent to replace the numerator in equation (29) with the shadow price of the transition equation of cumulative global emissions (14) at time t , and replace the denominator with the shadow price of the regional capital transition equation (19) for each region.

under the Nash equilibrium. With our definition, the regional noncooperative SCC is equal to the optimal regional carbon tax under noncooperation when the regional emissions is not binding at zero (i.e., the regional emission control rate is less than one), or is larger than the optimal regional carbon tax when the regional emissions is binding at zero. This pattern is consistent with the relation between the global SCC and the optimal global carbon tax as shown in Cai et al. (2017) and Cai and Lontzek (2019).²²

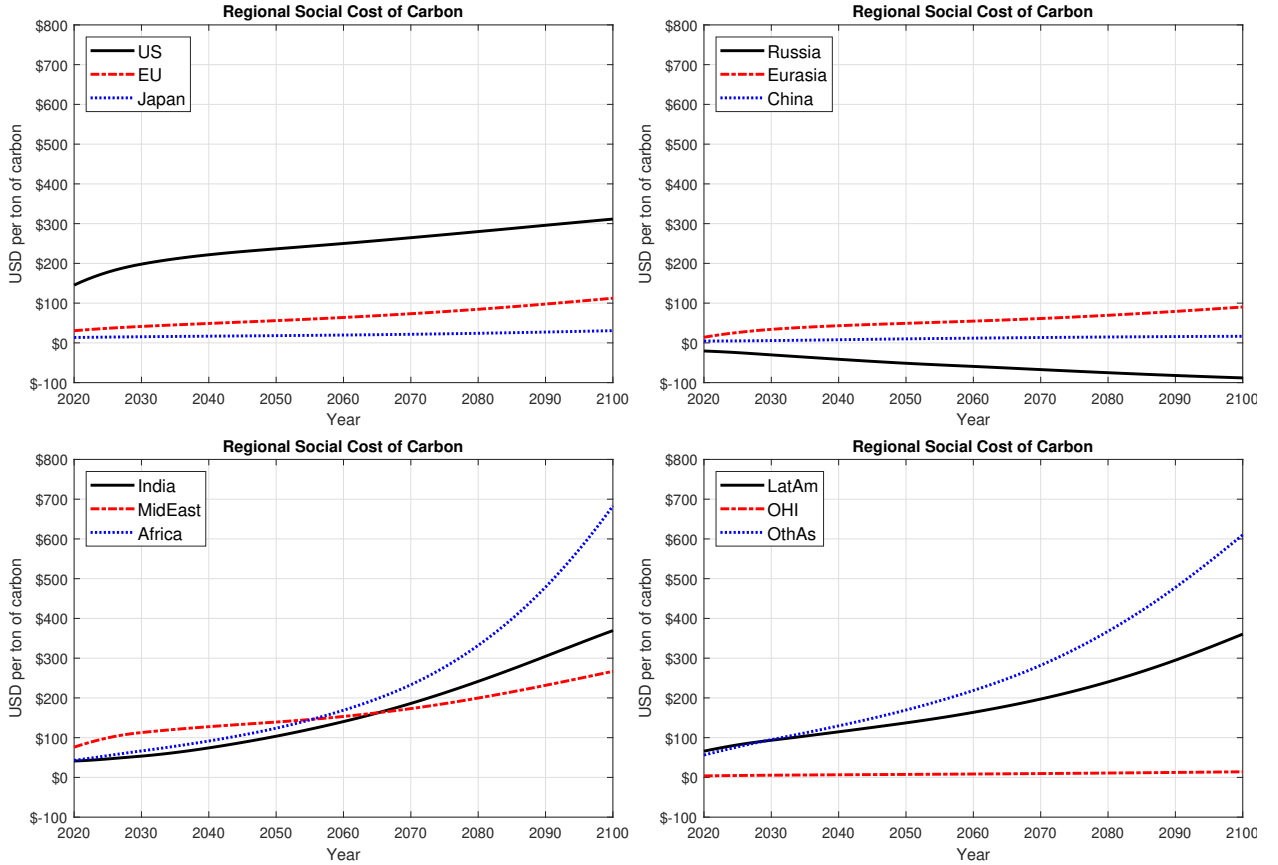


Figure 4: Simulation results of regional SCC under the baseline emission cap scenario.

The simulation results confirm the relationship between the optimal regional carbon tax and the regional SCC under noncooperation with the ETS. Figure 4 shows that when the emissions of a region are strictly positive, the regional SCC is exactly equal to the optimal carbon tax, which is equal to the gap between the regional MAC and the permit price in

²²We also verified numerically that our regional noncooperative SCC is equal to the present value of future climate damages in the region resulting from an additional unit of global emissions released in the current period, with our social discount rates $r_{i,t+1}$ defined endogenously with the following formula:

$$r_{i,t+1} = \frac{u'(c_{i,t})}{\beta u'(c_{i,t+1})} - 1,$$

where $c_{i,t}$ are the optimal per-capita consumptions.

Figure 3. For example, in 2050, the MAC for the US is \$1,081 per ton of carbon, the permit price is \$845, and their difference is exactly equal to the regional SCC of the US, \$236. Figure 4 also shows that when the regional emissions is zero, the regional SCC is larger than the gap, which could be negative. Among all regions, the US has the highest SCC in the near term, at around \$198 per ton of carbon in 2030. However, the SCCs of Africa and non-OECD Asia are expected to experience substantial increases, reaching \$682 for Africa and \$610 for non-OECD Asia by the end of the century. Russia, with the lowest SCC, experiences a steady negative SCC, reaching (-\$88) per ton of carbon by the end of the century, indicating that it benefits from global warming throughout the entire period. Our results show considerable heterogeneity in the SCC across regions and suggest that significant regional carbon tax implementation is required, not only for developed countries such as the US, but also for developing countries like Africa, India, and non-OECD Asia under the global ETS with the baseline emission cap scenario.

6.3 Effects of ETS Implementation

We next examine the economic and climate implications of the ETS implementation by comparing the global economy with and without the ETS regime, while maintaining the baseline emission caps in both economies. The top two panels of Figure 5 show that the ETS implementation results in slightly higher emissions and temperature increases compared to the case without the ETS. This occurs because, under the ETS, regions with binding regional emission cap constraints now have the option to purchase permits from regions with less restrictive emission caps, fully exploiting the total amount of permits allowed at the global level. This pattern persists until 2043. In the bottom two panels of Figure 5, we compare the MAC and the SCC using the US as an illustrative example. The MAC is higher in an economy without the ETS for the US until 2057, reflecting that the US becomes a permit buyer under the ETS regime. The SCC comparison demonstrates that the ETS has little impact on the regional SCC. This pattern holds for the other regions as well, as shown in Figure A.10. This finding reflects that the regional noncooperative SCC is the present value of future climate damages in the region resulting from an additional unit of global emissions released in the current period, and the ETS has little impact on the marginal damages and our endogenous social discount rates.

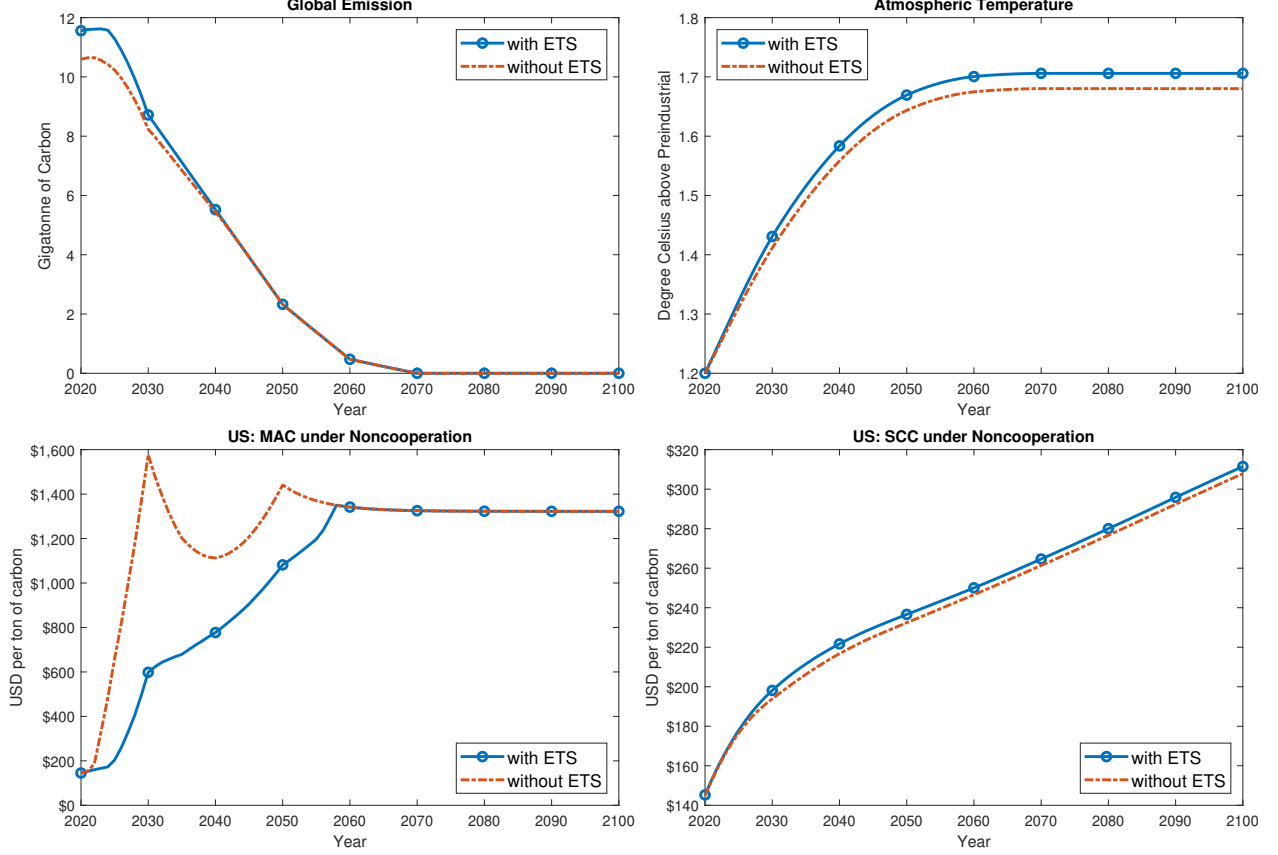


Figure 5: Comparative analysis: effects of the ETS implementation.

What are the welfare implications of implementing the global ETS? To quantify these effects, we compute a compensating variation (CV) associated with the ETS implementation. Specifically, the CV for region i is computed by solving the following equation:

$$W_{i,0}(\mathbf{c}_i^1 - CV) = W_{i,0}(\mathbf{c}_i^0), \quad (30)$$

where $\mathbf{c}_i^1 = (c_{i,0}^1, \dots, c_{i,t}^1, \dots, c_{i,T}^1)$ represents the vector of optimal consumption per capita under the ETS implementation, $\mathbf{c}_i^0 = (c_{i,0}^0, \dots, c_{i,t}^0, \dots, c_{i,T}^0)$ is the vector of optimal consumption per capita without the ETS implementation, and

$$W_{i,0}(\mathbf{c}_i) = \sum_{t=0}^T \beta^t u(c_{i,t}) L_{i,t}$$

is the social welfare associated with the vector of consumption per capita $\mathbf{c}_i = (c_{i,0}, \dots, c_{i,t}, \dots, c_{i,T})$ with the terminal time $T = 299$. Note that a direct comparison of the noncooperative model with the ETS to the noncooperative model without the ETS does not provide a clear picture of the welfare effects of the ETS under the current baseline emission cap scenario, as

the global emissions and resulting climate damages differ across the two economies. That is, the differences between \mathbf{c}_i^1 and \mathbf{c}_i^0 depend on both the emission caps and the ETS implementation. Compared with the economy without the ETS, temperature under the ETS implementation could be higher as shown in Figure 5. Consequently, some regions may experience additional climate damages greater than the reduced abatement cost from purchasing permits or the additional profit from selling permits, leading to negative welfare effects of the ETS implementation. To isolate the impact of the ETS, we adjust the emission caps $\bar{E}_{i,t}$ in the noncooperative model with the ETS to $\bar{E}'_{i,t}$, which are the optimal emission levels obtained from the noncooperative model with the emission caps $\bar{E}_{i,t}$ but without the ETS, then we compare economies with and without the ETS under the emission caps $\bar{E}'_{i,t}$ as these two economies have the same global emission levels and temperatures.

Table 1 shows the CV in 2020 USD, and its share (%) out of per capita consumption in each region at $t = 0$, when the ETS implementation does not impact temperature. The findings indicate that the welfare impacts of the global ETS are strictly positive for all regions, irrespective of whether they are permit sellers or buyers, with considerable heterogeneity in the magnitude of these effects across the regions. For example, in the United States, the CV is \$87.22 per capita, which is a relatively small fraction of per capita consumption (0.2%). Among the 12 regions, Russia experiences the largest welfare improvement, with a CV of \$183.53 per capita, equivalent to 2.2% of its per capita consumption. In contrast, Africa and non-OECD Asia have the smallest welfare gains from the global ETS. These results highlight that the principle of gains from trade applies to emissions trading as well, driven by efficiency gains achieved through the reallocation of emission abatement efforts across regions.

Table 1: Welfare effects of ETS implementation.

	US	EU	Japan	Russia	Eurasia	China
CV (\$)	87.22	86.43	35.12	183.53	50.96	24.93
CV (%)	0.201	0.344	0.124	2.225	1.017	0.250
	India	MidEast	Africa	LatAm	OHI	OthAs
CV (\$)	37.09	54.96	13.06	56.93	69.33	8.15
CV (%)	2.374	0.590	0.857	0.865	0.201	0.348

7 Sensitivity Analysis

We perform sensitivity analyses to evaluate alternative emission cap scenarios and to examine the influence of key parameters—climate damages and emission abatement—on our

simulation results.

7.1 Alternative Emission Cap Scenarios

Along with the baseline emission cap scenario, we further analyze simulation results for the noncooperative model with alternative emission cap paths, defined by the net zero emission targets in 2050, 2070, and 2090, where all regions achieve net zero emissions by the specified year. The top-left and top-right panels in Figure 6 display the emission permit prices and expected temperature increases under different emission cap scenarios. Under the net zero 2050 scenario, which is the most strict emission cap schedule, the emission permit price reaches \$1,539 per ton of carbon in 2049, and the temperature rise is restricted to 1.62 degrees Celsius by the end of this century. Net zero 2070 and net zero 2090 are more relaxed scenarios, leading to permit prices at \$514 and \$335 per ton of carbon in 2049, respectively. In these scenarios, the temperature rise by the end of the century is expected to reach 1.80 degrees Celsius and 1.98 degrees Celsius above the pre-industrial level, respectively. This result shows that the global target of restricting the temperature rise to 1.5 degrees Celsius is unattainable in a noncooperative world, even under the most restrictive net zero 2050 scenario, suggesting that stronger measures are needed to effectively regulate global emissions.

The bottom-left and bottom-right panels in Figure 6 show the regional MAC and SCC, taking the US as an example. The comparison of the regional SCC and MAC for all other regions are available in Appendix A.4.3, which show the same patterns as the US. Our results show that stricter emission caps lead to higher MACs. Specifically, the MAC of the US under the net zero 2050 scenario can reach up to \$1,471 per ton of carbon in 2048, compared to the peak of \$1,322 in 2086 under the net zero 2090 scenario. This is because more rigorous emission caps imposed on each region entail additional abatement efforts, resulting in a higher MAC. We also find that more stringent emission caps result in a smaller SCC: the SCC of the US is \$226 per ton of carbon in 2050 in the net zero 2050 scenario, while it is \$270 in 2050 in the net zero 2090 scenario. This is because the permit price grows more quickly over time and even faster than the MAC (recall that the optimal carbon tax is equal to the gap between the MAC and permit price when emissions are strictly positive). Our finding suggests that under a stricter regulation on emission caps, carbon taxation becomes a less important policy instrument to control emissions.

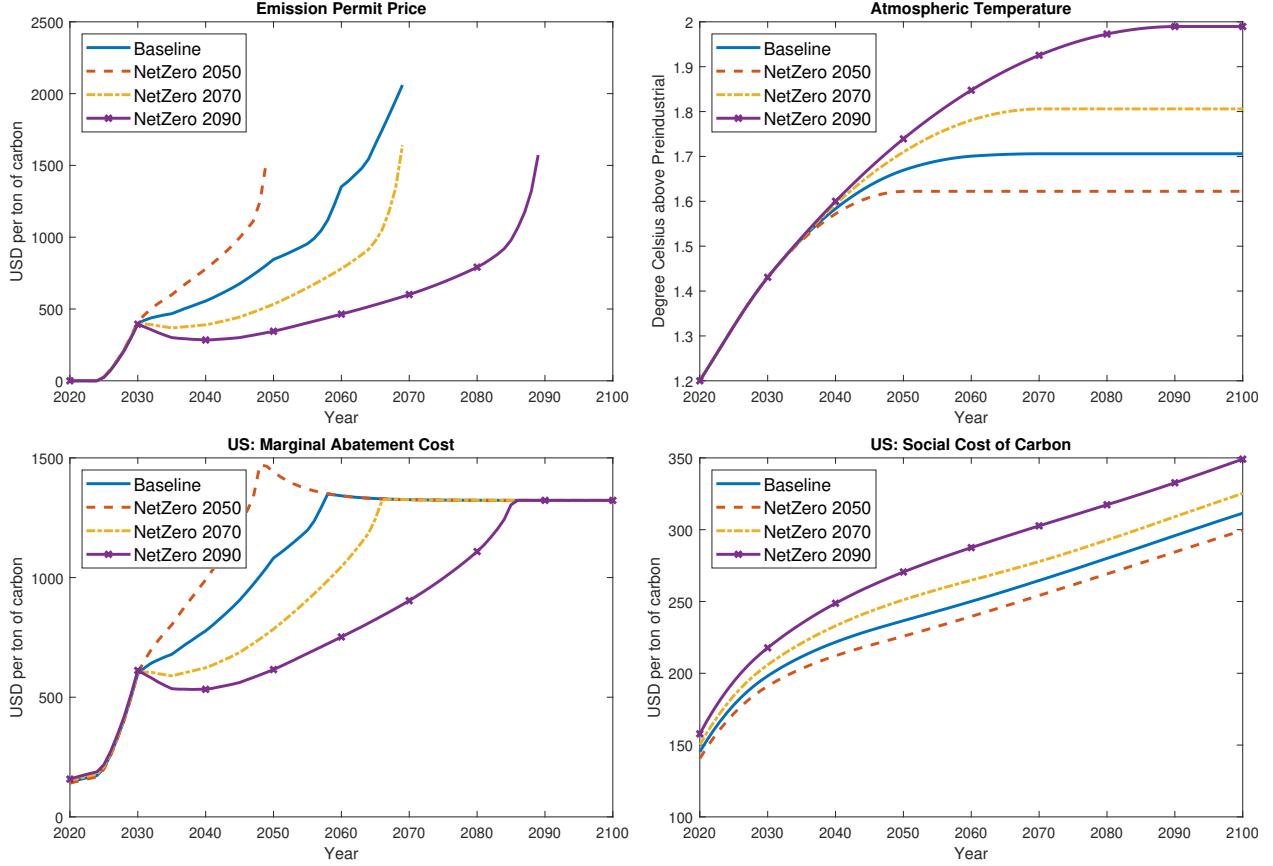


Figure 6: Sensitivity analysis: alternative emission cap scenarios.

7.2 Alternative Climate Damages and Abatement Costs

Lastly, recognizing that climate damages and emission abatement costs are key drivers of our model outcomes, including permit prices, MAC, and the SCC, we conduct sensitivity analyses on the parameters for climate damages ($\pi_{1,i}$, $\pi_{2,i}$) and emission abatement ($b_{1,i}$, $b_{2,i}$, $b_{3,i}$, $b_{4,i}$). While we incorporate climate damage projections from Burke et al. (2018) as our baseline model simulation, we additionally consider projections from Kahn et al. (2021) and Nordhaus (2010a). Specifically, we calibrate the climate damage parameters to match the projections from Kahn et al. (2021) and directly adopt the parameters from Nordhaus (2010a). Figure 7 demonstrates the key economic and climate outcomes under different climate damage assumptions. The baseline climate damage parameters from Burke et al. (2018) result in slightly lower emission permit prices, reaching \$2,059 by 2069, compared to \$2,282 under the damage parameters estimated from Kahn et al. (2021) and \$2,294 under the damage parameters from Nordhaus (2010a). With the same emission cap constraints imposed, the global temperature outcomes remain unaffected despite variations in damage parameters. For the US, the baseline climate damage estimation from Burke et al. (2018)

leads to higher MAC and higher SCC, indicating that the baseline marginal climate damages are relatively higher than those projected by Kahn et al. (2021) and Nordhaus (2010a). However, regional heterogeneity exists; for example, Russia experiences negative SCC under the baseline parameter values, while experiencing small but positive SCC under the parameter values estimated from Kahn et al. (2021) and Nordhaus (2010a). See Appendix A.4.4 for a comparison across all 12 regions.

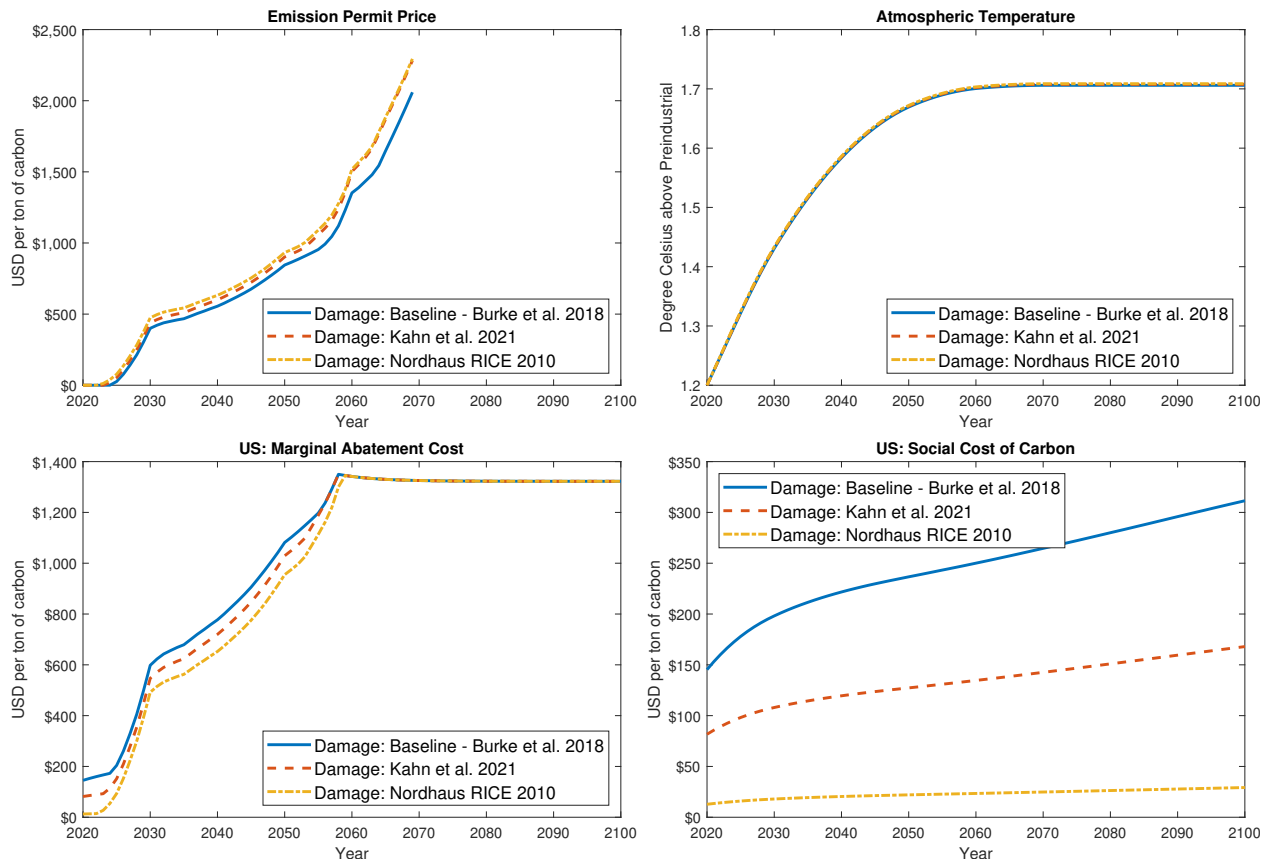


Figure 7: Sensitivity analysis: alternative climate damage parameters.

For our sensitivity analysis of the emission abatement cost parameters, we consider the parameter values from Nordhaus (2010a) in addition to the baseline parameter values calibrated from Ueckerdt et al. (2019), both of which share the same functional form of abatement cost. As shown in Figure 8, the permit price rises to \$1,767 by 2069 under the abatement cost estimate of Nordhaus (2010a), approximately 85% of the permit price projected under the baseline scenario. Despite the lower permit price, the global temperature increase remains similar to the baseline simulation, reaching 1.70 degrees Celsius by the end of the century, due to the emission cap constraints. The lower emission permit price under the abatement cost estimate of Nordhaus (2010a) reflects lower MAC, as illustrated with the US case in

Figure 8, with similar patterns observed across most regions (see Appendix A.4.5). Lastly, the SCC is also lower under Nordhaus (2010a) parameters, with the SCC of the US reaching \$101 by 2100—just 32% of the baseline scenario.

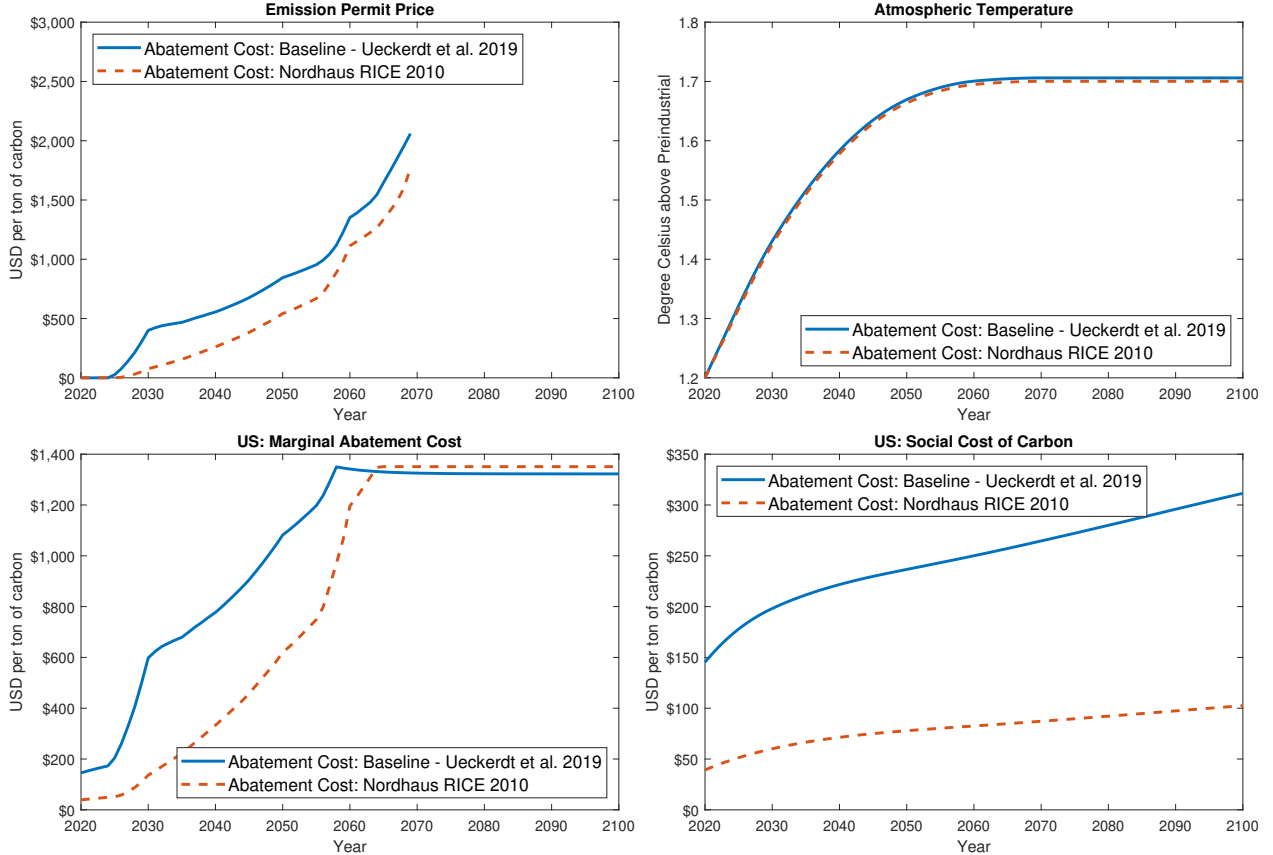


Figure 8: Sensitivity analysis: alternative abatement cost parameters

8 Conclusion

In this work, we build a dynamic multi-region model of climate and the economy with a global emission cap-and-trade system. In our integrated assessment framework, 12 aggregated regions are allocated emission caps in line with the emission targets of the NDCs and net zero commitments, as established under the Paris Agreement and the Glasgow Pact. We solve for the market prices of emission permits under the dynamic Nash equilibrium in a noncooperative setting. The permit prices are endogenously determined by demand and supply of emission permits in the global permits market, reflecting regional heterogeneity in future productivity growth, abatement technologies, climate damage, and population growth. We further show that carbon taxation can be introduced under the global ETS as a complementary policy to help the social planner of each region achieve their optimal

emissions. For strictly positive emissions, we have shown both theoretically and numerically that the optimal carbon tax is equal to the difference between the regional MAC and the market price of permits.

This work has several policy implications. First, our results indicate that the current global target of restricting the global temperature rise to 1.5 degrees Celsius above pre-industrial levels by 2100 is unattainable under noncooperation, even with the current emission commitments outlined in the Paris Agreement and the Glasgow Pact. Our findings suggest that more stringent emission reduction targets and global cooperation are needed to curb the trend of rising global temperature. Second, our baseline simulation shows that the current emission commitments lead to excess emission permit supply in the initial years, resulting in permit prices of zero. This finding suggests that effective implementation of the global ETS requires stricter emission caps so that the global supply of permits does not exceed the global demand of permits. Third, we demonstrate that the global ETS is not a pure substitute for the carbon tax, but instead that both can be implemented together to improve the efficiency of global climate policies.

References

- Ambec, S., Esposito, F., and Pacelli, A. (2024). The economics of carbon leakage mitigation policies. *Journal of Environmental Economics and Management*, page 102973.
- Arias, P., Bellouin, N., Coppola, E., Jones, R., Krinner, G., Marotzke, J., Naik, V., Palmer, M., Plattner, G.-K., Rogelj, J., et al. (2021). Climate change 2021: The physical science basis. contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change; technical summary.
- Baldwin, E., Cai, Y., and Kuralbayeva, K. (2020). To build or not to build? capital stocks and climate policy. *Journal of Environmental Economics and Management*, 100(Article 102235).
- Barnett, M., Brock, W., and Hansen, L. P. (2020). Pricing Uncertainty Induced by Climate Change. *The Review of Financial Studies*, 33(3):1024–1066.
- Bauer, N., Baumstark, L., and Leimbach, M. (2012). The REMIND-R model: the role of renewables in the low-carbon transformation—first-best vs. second-best worlds. *Climatic Change*, 114(1):145–168.
- Böhringer, C., Fischer, C., and Rosendahl, K. E. (2014). Cost-effective unilateral climate policy design: Size matters. *Journal of Environmental Economics and Management*, 67(3):318–339.
- Borenstein, S., Bushnell, J., Wolak, F. A., and Zaragoza-Watkins, M. (2019). Expecting the Unexpected: Emissions Uncertainty and Environmental Market Design. *American Economic Review*, 109(11):3953–3977.
- Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., and Tavoni, M. (2006). WITCH: A world induced technical change hybrid model. *The Energy Journal*, 27:13–37.
- Brock, W. and Xepapadeas, A. (2017). Climate change policy under polar amplification. *European Economic Review*, 99:93–112.
- Burke, M., Davis, W. M., and Diffenbaugh, N. S. (2018). Large potential reduction in economic damages under UN mitigation targets. *Nature*, 557(7706):549–553.
- Cai, Y. (2021). The role of uncertainty in controlling climate change. *Oxford Research Encyclopedia of Economics and Finance*.

- Cai, Y., Brock, W., and Xepapadeas, A. (2023). Climate change impact on economic growth: Regional climate policy under cooperation and noncooperation. *Journal of the Association of Environmental and Resource Economists*, 10(3):569–605.
- Cai, Y., Judd, K. L., and Lontzek, T. S. (2017). The social cost of carbon with economic and climate risks. Hoover economics working paper 18113.
- Cai, Y. and Lontzek, T. S. (2019). The social cost of carbon with economic and climate risks. *Journal of Political Economy*, 127(6):2684–2734.
- Carbone, J. C., Helm, C., and Rutherford, T. F. (2009). The case for international emission trade in the absence of cooperative climate policy. *Journal of environmental economics and management*, 58(3):266–280.
- De Cian, E. and Tavoni, M. (2012). Do technology externalities justify restrictions on emission permit trading? *Resource and Energy Economics*, 34(4):624–646.
- den Elzen, M. G. J., Dafnomilis, I., Forsell, N., Fragkos, P., Fragkiadakis, K., Hohne, N., Kuramochi, T., Nascimento, L., Roelfsema, M., van Soest, H., and Sperling, F. (2022). Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep paris goals within reach. *Mitigation and Adaptation Strategies for Global Change*, 27(5):33.
- Dietz, S., van der Ploeg, F., Rezai, A., and Venmans, F. (2021). Are Economists Getting Climate Dynamics Right and Does It Matter? *Journal of the Association of Environmental and Resource Economists*, 8(5):895–921.
- Dietz, S. and Venmans, F. (2019). Cumulative carbon emissions and economic policy: in search of general principles. *Journal of Environmental Economics and Management*, 96:108–129.
- Doda, B., Quemin, S., and Taschini, L. (2019). Linking permit markets multilaterally. *Journal of Environmental Economics and Management*, 98:102259.
- Farrokhi, F. and Lashkaripour, A. (2021). Can trade policy mitigate climate change. *Unpublished Working Paper*.
- Fischer, C. and Springborn, M. (2011). Emissions targets and the real business cycle: Intensity targets versus caps or taxes. *Journal of Environmental Economics and Management*, 62(3):352–366.

- Fowlie, M., Reguant, M., and Ryan, S. P. (2016). Market-based emissions regulation and industry dynamics. *Journal of Political Economy*, 124(1):249–302.
- Fowlie, M. L. and Reguant, M. (2022). Mitigating emissions leakage in incomplete carbon markets. *Journal of the Association of Environmental and Resource Economists*, 9(2):307–343.
- Fuss, S., Flachsland, C., Koch, N., Kornek, U., Knopf, B., and Edenhofer, O. (2018). A framework for assessing the performance of cap-and-trade systems: insights from the european union emissions trading system. *Review of Environmental Economics and Policy*.
- Golosov, M., Hassler, J., Krusell, P., and Tsyvinski, A. (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88.
- Goulder, L. H., Hafstead, M. A., and Dworsky, M. (2010). Impacts of alternative emissions allowance allocation methods under a federal cap-and-trade program. *Journal of Environmental Economics and management*, 60(3):161–181.
- Goulder, L. H., Long, X., Lu, J., and Morgenstern, R. D. (2022). China’s unconventional nationwide CO2 emissions trading system: Cost-effectiveness and distributional impacts. *Journal of Environmental Economics and Management*, 111:102561.
- Goulder, L. H. and Parry, I. W. (2008). Instrument choice in environmental policy. *Review of environmental economics and policy*.
- Goulder, L. H. and Schein, A. R. (2013). Carbon taxes versus cap and trade: a critical review. *Climate Change Economics*, 4(03):1350010.
- Habla, W. and Winkler, R. (2018). Strategic delegation and international permit markets: Why linking may fail. *Journal of environmental economics and management*, 92:244–250.
- Hahn, R. W. and Stavins, R. N. (2011). The effect of allowance allocations on cap-and-trade system performance. *Journal of Law and Economics*, 54:S267–S294. A-73.
- Hambel, C., Kraft, H., and Schwartz, E. (2021). The social cost of carbon in a non-cooperative world. *Journal of International Economics*, 131:103490.
- Harstad, B. and Eskeland, G. S. (2010). Trading for the future: Signaling in permit markets. *Journal of public economics*, 94(9-10):749–760.
- Hitzemann, S. and Uhrig-Homburg, M. (2018). Equilibrium price dynamics of emission permits. *Journal of Financial and Quantitative Analysis*, 53(4):1653–1678.

- Holtsmark, B. and Weitzman, M. L. (2020). On the effects of linking cap-and-trade systems for co 2 emissions. *Environmental and Resource Economics*, 75(3):615–630.
- Holtsmark, K. and Midttømme, K. (2021). The dynamics of linking permit markets. *Journal of Public Economics*, 198:104406.
- Iverson, T. and Karp, L. (2021). Carbon taxes and climate commitment with non-constant time preference. *The Review of economic studies*, 88(2):764–799.
- Jaakkola, N. and Van der Ploeg, F. (2019). Non-cooperative and cooperative climate policies with anticipated breakthrough technology. *Journal of Environmental Economics and Management*, 97:42–66.
- Jakob, M., Luderer, G., Steckel, J., Tavoni, M., and Monjon, S. (2012). Time to act now? assessing the costs of delaying climate measures and benefits of early action. *Climatic Change*, 114(1):79–99.
- Kahn, M. E., Mohaddes, K., Ng, R. N., Pesaran, M. H., Raissi, M., and Yang, J.-C. (2021). Long-term macroeconomic effects of climate change: A cross-country analysis. *Energy Economics*, 104:105624.
- Karp, L. and Traeger, C. (2024). Taxes versus quantities reassessed. *Journal of Environmental Economics and Management*, 125:102951.
- Keohane, N. O. (2009). Cap and trade, rehabilitated: Using tradable permits to control u.s. greenhouse gases. *Review of Environmental Economics and Policy*, 3(1):42–62.
- Knopf, B., Kowarsch, M., Lüken, M., Edenhofer, O., and Luderer, G. (2012). A global carbon market and the allocation of emission rights. *Climate change, justice and sustainability: Linking climate and development policy*, pages 269–285.
- Levinson, A. (2023). Are developed countries outsourcing pollution? *Journal of Economic Perspectives*, 37(3):87–110.
- Luderer, G., Bosetti, V., Jakob, M., Leimbach, M., Steckel, J. C., Waisman, H., and Edenhofer, O. (2012). The economics of decarbonizing the energy system—results and insights from the recipe model intercomparison. *Climatic Change*, 114:9–37.
- Masseti, E. and Tavoni, M. (2012). A developing asia emission trading scheme (asia ets). *Energy Economics*, 34:S436–S443. The Asia Modeling Exercise: Exploring the Role of Asia in Mitigating Climate Change.

- Mattauch, L., Matthews, H. D., Millar, R., Rezai, A., Solomon, S., and Venmans, F. (2020). Steering the Climate System: Using Inertia to Lower the Cost of Policy: Comment. *American Economic Review*, 110(4):1231–1237.
- Matthews, H. D., Gillett, N. P., Stott, P. A., and Zickfeld, K. (2009). The proportionality of global warming to cumulative carbon emissions. *Nature*, 459(7248):829–832.
- Mehling, M. A., Metcalf, G. E., and Stavins, R. N. (2018). Linking climate policies to advance global mitigation. *Science*, 359(6379):997–998.
- Meinshausen, M., Lewis, J., McGlade, C., Gutschow, J., Nicholls, Z., Burdon, R., Cozzi, L., and Hackmann, B. (2022). Realization of paris agreement pledges may limit warming just below 2 C. *Nature*, 604(7905):304–309.
- Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L., Lamarque, J.-F., Matsumoto, K., Montzka, S. A., Raper, S. C., Riahi, K., et al. (2011). The rcp greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic change*, 109:213–241.
- Montgomery, W. D. (1972). Markets in licenses and efficient pollution control programs. *Journal of Economic Theory*, 5(3):395–418.
- Newell, R. G. and Pizer, W. A. (2003). Regulating stock externalities under uncertainty. *Journal of environmental economics and management*, 45(2):416–432.
- Nordhaus, W. (2010a). *Excel file for RICE model as of April 26, 2010*.
- Nordhaus, W. (2014). *A question of balance: Weighing the options on global warming policies*. Yale University Press.
- Nordhaus, W. D. (2007). To tax or not to tax: Alternative approaches to slowing global warming. *Review of Environmental Economics and Policy*, 1(1):26–44.
- Nordhaus, W. D. (2010b). Economic aspects of global warming in a post-copenhagen environment. *Proceedings of the National Academy of Sciences*, 107(26):11721–11726.
- Nordhaus, W. D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 114(7):1518–1523.
- Nordhaus, W. D. and Yang, Z. (1996). A regional dynamic general-equilibrium model of alternative climate-change strategies. *The American Economic Review*, pages 741–765.

- Perino, G., Willner, M., Quemin, S., and Pahle, M. (2022). The european union emissions trading system market stability reserve: does it stabilize or destabilize the market? *Review of Environmental Economics and Policy*, 16(2):338–345.
- Piris-Cabezas, P., Lubowski, R., and Leslie, G. (2018). Carbon prices under carbon market scenarios consistent with the paris agreement: Implications for the carbon offsetting and reduction scheme for international aviation (corsia). *New York*.
- Ricke, K., Drouet, L., Caldeira, K., and Tavoni, M. (2018). Country-level social cost of carbon. *Nature Climate Change*, 8(10):895.
- Samir, K. and Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, 42:181–192.
- Schmalensee, R. and Stavins, R. N. (2017). Lessons learned from three decades of experience with cap and trade. *Review of Environmental Economics and Policy*.
- Sinn, H.-W. (2008). Public policies against global warming: a supply side approach. *International tax and public finance*, 15:360–394.
- Stavins, R. N. (1996). Correlated uncertainty and policy instrument choice. *Journal of Environmental Economics and Management*, 30(2):218–232.
- Stavins, R. N. (2022). The relative merits of carbon pricing instruments: Taxes versus trading. *Review of Environmental Economics and Policy*, 16(1):62–82.
- Strand, J. (2013). Strategic climate policy with offsets and incomplete abatement: Carbon taxes versus cap-and-trade. *Journal of Environmental Economics and Management*, 66(2):202–218.
- Ueckerdt, F., Frieler, K., Lange, S., Wenz, L., Luderer, G., and Levermann, A. (2019). The economically optimal warming limit of the planet. *Earth System Dynamics*, 10(4):741–763.
- van de Ven, D.-J., Mittal, S., Gambhir, A., Lamboll, R. D., Doukas, H., Giarola, S., Hawkes, A., Koasidis, K., Koberle, A. C., McJeon, H., Perdana, S., Peters, G. P., Rogelj, J., Sognaes, I., Vielle, M., and Nikas, A. (2023). A multimodel analysis of post-glasgow climate targets and feasibility challenges. *Nature Climate Change*, 13(6):570–578.
- van der Ploeg, F. and de Zeeuw, A. (2016). Non-cooperative and cooperative responses to climate catastrophes in the global economy: A north–south perspective. *Environmental and Resource Economics*, 65:519–540.

Weitzman, M. L. (1974). Prices vs. Quantities. *The Review of Economic Studies*, 41(4):477–491.

World Bank (2020). Total greenhouse gas emissions (kt of CO₂ equivalent).

Appendix for Online Publication

A.1 List of Parameters

Table A.1 lists the key parameters and their values.

Table A.1: Key parameters.		
Parameter	Value	Description
1) Economic system parameters (from Nordhaus (2017))		
β	0.985	Annual discount factor
γ	1.45	Elasticity of marginal utility
α	0.3	Output elasticity of capital
δ	0.1	Annual depreciation rate of capital
2) Climate system parameters		
ζ	0.0021	Contribution rate of carbon emissions to temperature

Table A.2 lists the values of the baseline abatement cost parameters calibrated from Ueckerdt et al. (2019). The values of carbon intensity at annual time steps will be provided upon request.

Table A.2: Abatement cost parameters (baseline) calibrated from Ueckerdt et al. (2019)

	US	EU	Japan	Russia	Eurasia	China
$b_{1,i}$	0.462	0.477	0.750	0.292	0.347	0.328
$b_{2,i}$	2.859	2.670	2.011	2.499	3.243	2.822
$b_{3,i}$	9.920	5.832	2.492	7.625	7.966	7.189
$b_{4,i}$	0.182	0.114	0.2	0.2	0.168	0.168
	India	MidEast	Africa	LatAm	OHI	OthAs
$b_{1,i}$	0.594	0.455	0.665	0.286	0.347	0.602
$b_{2,i}$	2.802	2.574	3.636	3.828	3.243	3.995
$b_{3,i}$	6.336	11.205	6.558	11.496	7.966	6.518
$b_{4,i}$	0.2	0.2	0.2	0.2	0.168	0.163

Table A.3 lists the calibrated values of the climate damage parameters used in the baseline analysis.

Table A.3: Climate damage parameters (baseline) calibrated from Burke et al. (2018)

	US	EU	Japan	Russia	Eurasia	China
$\pi_{1,i}$	0.0842	0.0489	0.0090	-0.4169	0.2678	0.0003
$\pi_{2,i}$	0.0096	0.0011	0.0748	0.3094	0.0002	0.0008
	India	MidEast	Africa	LatAm	OHI	OthAs
$\pi_{1,i}$	0.0017	0.3595	0.1886	0.1801	0.0123	0.2161
$\pi_{2,i}$	0.3276	0.0088	0.0764	0.0030	0.0044	0.0224

Table A.4 lists the values of the TFP parameters calibrated from Burke et al. (2018).

Table A.4: TFP parameters calibrated from Burke et al. (2018)

	US	EU	Japan	Russia	Eurasia	China
$g_{i,0}$	0.0033	0.0089	0.0085	0.0170	0.0094	0.0345
d_i	0.0011	0.0010	0.0010	0.0154	0.0010	0.0308
	India	MidEast	Africa	LatAm	OHI	OthAs
$g_{i,0}$	0.0332	0.0093	0.0218	0.0134	0.0076	0.0221
d_i	0.0151	0.0010	0.0013	0.0010	0.0010	0.0062

A.2 List of Countries

Table A.5: List of countries for regional aggregation

Region	Constituent Countries
Africa	Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Republic of the Congo, Cote d'Ivoire, Djibouti, Arab Republic of Egypt, Ethiopia, Gabon, Gambia, The Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Libya, Madagascar, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Rwanda, Senegal, Sierra Leone, South Africa, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe.
European Union ²³ .	Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Greenland, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Romania, Slovak Republic, Spain, Sweden, United Kingdom.
Eurasia	Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Estonia, Georgia, Kazakhstan, Kyrgyz Republic, FYR Macedonia, Moldova, Serbia, Slovenia, Tajikistan, Turkey, Ukraine, Uzbekistan.
Latin America	Argentina, Bahamas, The Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Trinidad and Tobago, Uruguay.
Middle East	Cyprus, Islamic Republic of Iran, Iraq, Israel, Jordan, Lebanon, Oman, Qatar, Saudi Arabia, United Arab Emirates,
Other Non-OECD Asia	Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, Fiji, Indonesia, Malaysia, Mongolia, Nepal, Pakistan, Philippines, Samoa, Solomon Islands, Sri Lanka, Thailand, Vanuatu, Vietnam.
Other High-Income	Australia, Canada, Iceland, Republic of Korea, New Zealand, Norway, Switzerland.

²³The current EU does not contain the United Kingdom, but in this paper we still assume the United Kingdom is in the EU for convenience.

A.3 Details about Calibration and Data

A.3.1 Calibration of the TCRE Climate System

Each of the four RCP scenarios (Meinshausen et al., 2011) — RCP 2.6, RCP 4.5, RCP 6, and RCP 8.5 — provide their pathways of emissions, atmospheric carbon concentration, radiative forcing, and atmospheric temperature anomaly. When we calibrate the contribution rate of carbon emissions on temperature, ζ , in a climate system, we use the pathways of emissions and atmospheric temperature anomaly of the four RCP scenarios. Figure A.1 shows that our calibrated TCRE climate system provides a very good projection of the atmospheric temperature anomaly (increase relative to pre-industrial levels) based on cumulative emissions only.

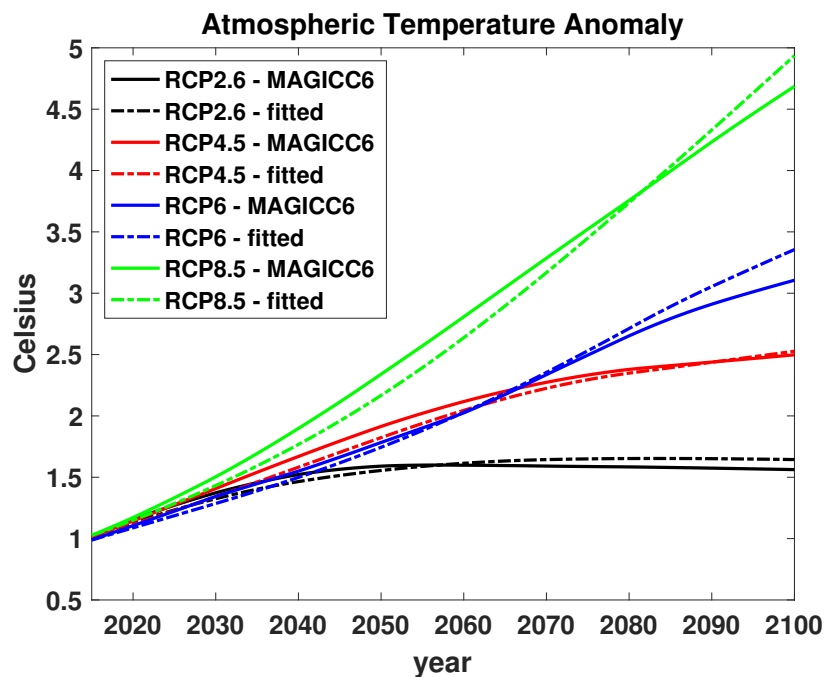


Figure A.1: Calibration of the TCRE climate system.

A.3.2 Calibration of Total Factor Productivity and Climate Damage

Figures A.2 and A.3 show that with our calibrated TFP and climate damage coefficients, the GDP per capita $y_{i,t}^{\text{NoCC}}$ or $y_{i,t}$ matches well with the projected data $y_{i,t}^{\text{BDD,NoCC}}$ or $y_{i,t}^{\text{BDD}}$ from Burke et al. (2018), respectively, for all regions.

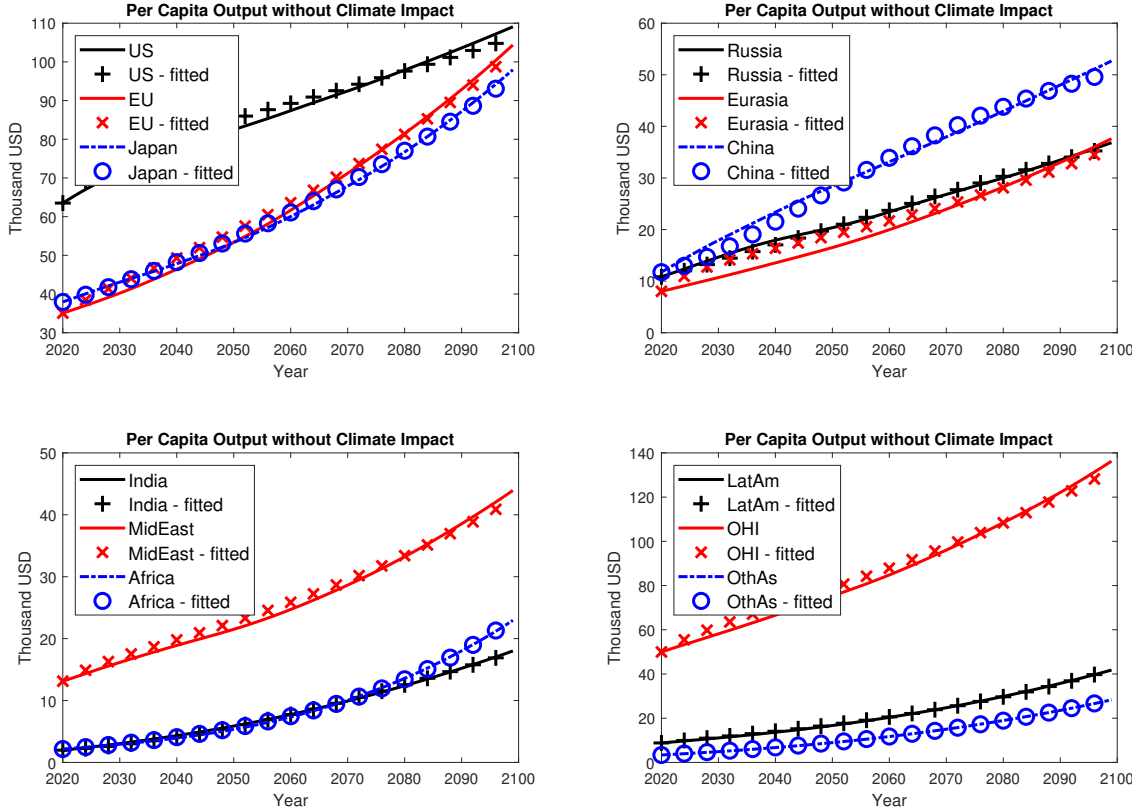


Figure A.2: Fitting GDP per capita under no climate impact. Lines represent GDP per capita under no climate impact from Burke et al. (2018); marks represent fitted GDP per capita.

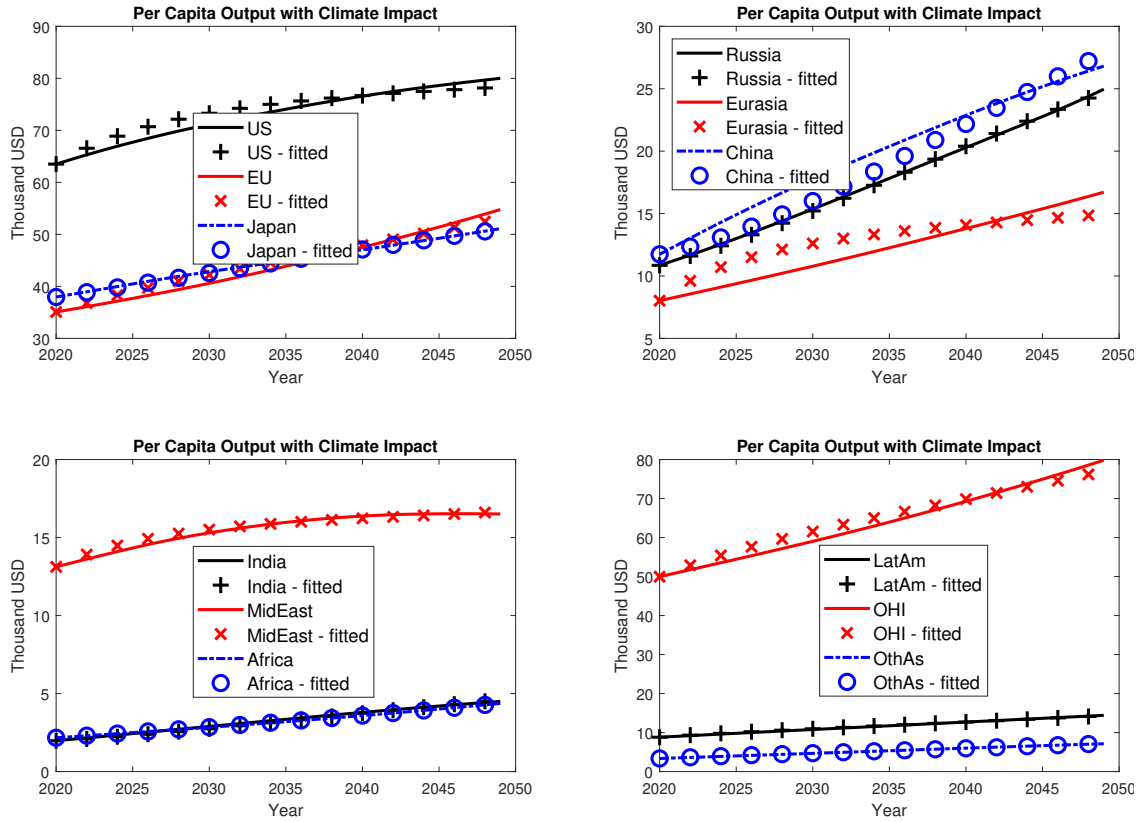


Figure A.3: Fitting GDP under climate impact. Lines represent the GDP per capita under the climate impact of RCP 4.5 from Burke et al. (2018); marks represent fitted values.

A.3.3 Calibration of Climate Damage from Kahn et al. (2021)

For sensitivity analysis on climate damage parameters in Section 7.2, we calibrate the climate damage parameters $\pi_{1,i}$ and $\pi_{2,i}$ by considering projections on GDP loss across different climate scenarios in Kahn et al. (2021), which shows the percentage loss in GDP per capita by 2030, 2050, and 2100 under the RCP 2.6 and RCP 8.5 scenarios for China, EU, India, Russia, and the US. We use their method and data to project the percentage loss in GDP per capita ($\Delta_{i,t}^{\text{RCP26}}$ and $\Delta_{i,t}^{\text{RCP85}}$) every year from 2020 to 2114 under the RCP 2.6 and RCP 8.5 scenarios for each of our 12 regions, employing the baseline setup in Kahn et al. (2021). Specifically, $\Delta_{i,t}^{\text{RCP26}} = 1 - y_{i,t}^{\text{RCP26}}/y_{i,t}^{\text{base}}$ and $\Delta_{i,t}^{\text{RCP85}} = 1 - y_{i,t}^{\text{RCP85}}/y_{i,t}^{\text{base}}$, where $y_{i,t}^{\text{RCP26}}$, $y_{i,t}^{\text{RCP85}}$, and $y_{i,t}^{\text{base}}$ are GDP per capita under RCP 2.6, RCP 8.5, and the baseline scenario, respectively. Thus from equation (17) we obtain $(\pi_{1,i}, \pi_{2,i})$ by solving the following minimization problem for each region i :

$$\min_{\pi_{1,i}, \pi_{2,i}} \sum_{t=0}^{94} \left(\frac{1 + \pi_{1,i} T_t^{\text{RCP85}} + \pi_{2,i} (T_t^{\text{RCP85}})^2}{1 + \pi_{1,i} T_t^{\text{RCP26}} + \pi_{2,i} (T_t^{\text{RCP26}})^2} - \frac{1 - \Delta_{t,i}^{\text{RCP26}}}{1 - \Delta_{t,i}^{\text{RCP85}}} \right)^2. \quad (\text{A.1})$$

Here T_t^{RCP26} and T_t^{RCP85} are the global average temperature anomalies at time t (deviation from the pre-industrial temperature) under the RCP 2.6 and RCP 8.5 scenarios. Figure A.3 shows, with our calibrated climate damage coefficients, the ratios of GDP per capita between RCP 2.6 and RCP8.5 from our model, matches well with the ratios in Kahn et al. (2021).

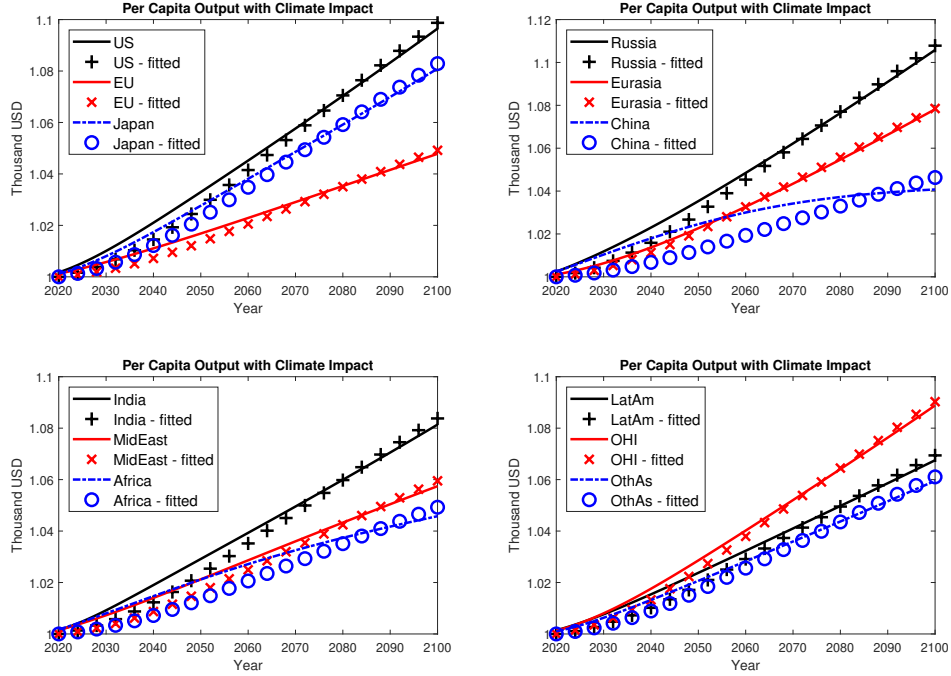


Figure A.4: Fitting climate damage parameters. Lines represent the ratios of GDP per capita between RCP 2.6 and RCP8.5 from Kahn et al. (2021); marks represent fitted ratios.

A.3.4 Regional Emission Cap Pathways

Figure A.5 displays the regional emission cap pathways, measured in Gigatonne of Carbon (GtC), for the baseline emission cap scenario, generated using the methodology described in Section 5.1.

Table A.6 lists the regional emission caps for every region in five-year time steps. The regional emission caps at annual time steps will be provided upon request.

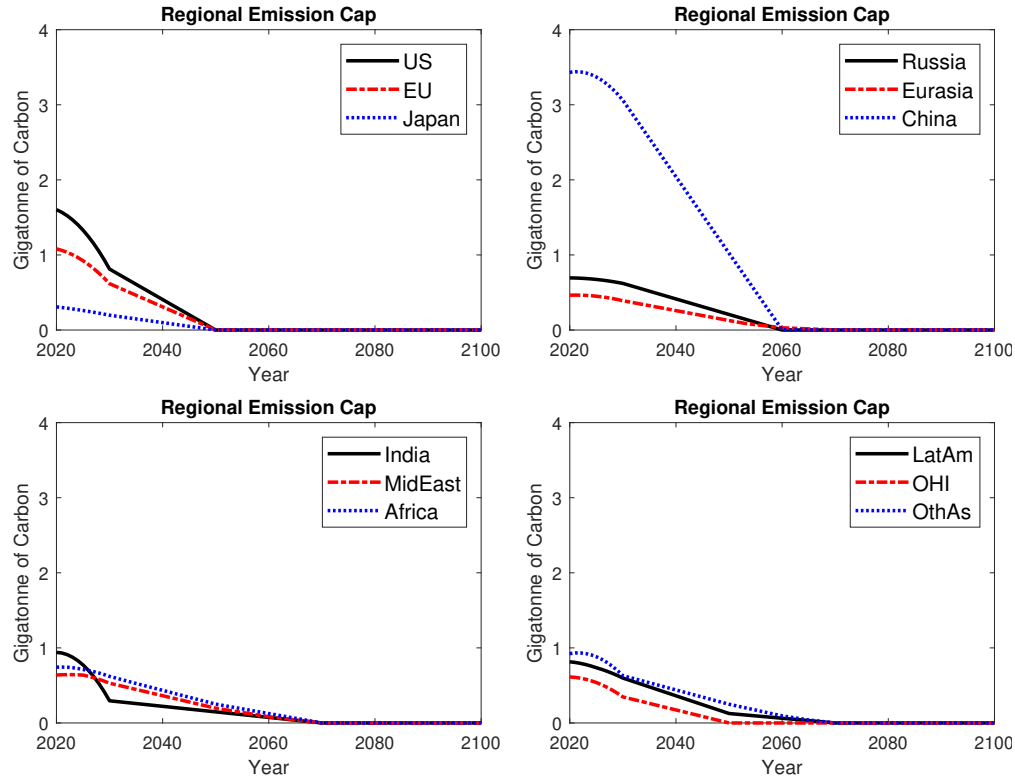


Figure A.5: Regional emission cap pathways under the baseline scenario.

Table A.6: Regional emission cap pathways under the baseline scenario (unit: GtC)

	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
US	1.603	1.330	0.812	0.609	0.406	0.203	0.000	0.000	0.000	0.000	0.000
EU	1.081	0.923	0.617	0.463	0.309	0.154	0.000	0.000	0.000	0.000	0.000
Japan	0.308	0.260	0.197	0.148	0.099	0.049	0.000	0.000	0.000	0.000	0.000
Russia	0.694	0.674	0.621	0.517	0.414	0.310	0.207	0.103	0.000	0.000	0.000
Eurasia	0.464	0.450	0.390	0.324	0.259	0.193	0.126	0.071	0.030	0.015	0.000
China	3.433	3.370	3.061	2.551	2.042	1.532	1.023	0.513	0.004	0.002	0.000
India	0.940	0.773	0.295	0.259	0.222	0.185	0.148	0.111	0.074	0.037	0.000
MidEast	0.638	0.638	0.530	0.446	0.363	0.280	0.196	0.140	0.083	0.041	0.000
Africa	0.743	0.712	0.621	0.526	0.434	0.342	0.251	0.188	0.125	0.063	0.000
LatAm	0.815	0.736	0.598	0.480	0.362	0.244	0.126	0.094	0.063	0.031	0.000
OHI	0.613	0.538	0.347	0.260	0.173	0.087	0.000	0.000	0.000	0.000	0.000
OthAs	0.924	0.882	0.630	0.535	0.440	0.345	0.249	0.172	0.094	0.040	0.000

Figure A.6 presents a comparison of global emission cap pathways under various scenarios: the baseline scenario, net-zero by 2050, net-zero by 2070, and net-zero by 2090. In the net-zero scenarios, it is assumed that all countries achieve net-zero emissions by the respective target years.

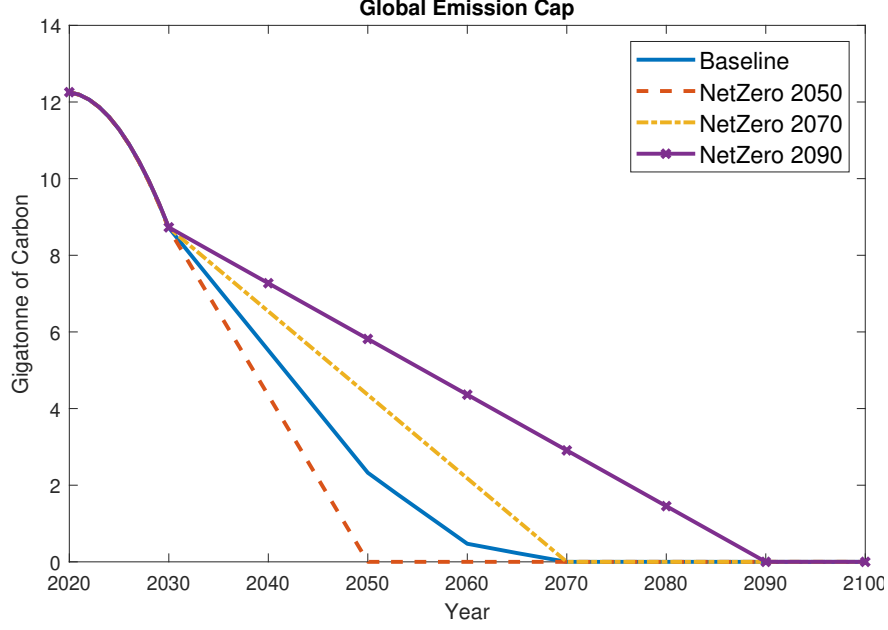


Figure A.6: Global emission cap pathways for the different net zero scenarios.

A.3.5 GDP Growth Rate beyond this Century

For the GDP growth rate beyond this century, we follow RICE to project $g_{t,i}$ for $t \geq 80$. We begin by assuming the long-run growth rate of TFP in the US is $g_{US,\infty} = 0.0033(1 - \alpha) = 0.00231$ with $\alpha = 0.3$. Next, we let $\tilde{y}_{i,79} = y_{i,79}^{\text{BDD}} y_{i,0} / y_{i,0}^{\text{BDD}}$ be our projected per capita output in 2099, where $y_{i,0}$ is the observed per capita output in 2020. We then assume that the TFP growth in the US is characterized by

$$g_{US,t} = g_{US,\infty} + (g_{US,79} - g_{US,\infty}) \exp(-0.01(t - 79)),$$

and let $\tilde{y}_{US,t+1} = \tilde{y}_{US,t} \exp(g_{US,t}/(1 - \alpha))$ for $t \geq 79$. For the regions other than the US, we assume their TFP growth can be expressed in relation to the TFP growth of the US. Specifically, we assume that, for $t \geq 79$,

$$\begin{cases} \tilde{y}_{i,t+1} = \tilde{y}_{i,t} \exp(g_{i,t}/(1 - \alpha)) \\ g_{i,t+1} = g_{US,t+1} + (1 - \alpha)\chi \ln(\tilde{y}_{US,t}/\tilde{y}_{i,t}) \end{cases}$$

where $\chi = 0.005$ is chosen such that $g_{i,t}$ gradually moves toward $g_{US,t}$ as $t \rightarrow \infty$.²⁴

²⁴Assume $\tilde{y}_{i,t} = A_{i,t} k_{i,t}^\alpha$ is GDP per capita where $k_{i,t}$ is capital per capita. We have

$$\ln \left(\frac{\tilde{y}_{i,t+1}}{\tilde{y}_{i,t}} \right) = g_{i,t} + \alpha \ln \left(\frac{k_{i,t+1}}{k_{i,t}} \right).$$

A.4 Additional Simulation Results

A.4.1 Benchmark Model: Regional Emissions

Figure A.7 displays the regional emissions under the noncooperative model with the ETS and the baseline emission cap scenario. Russia is the first to reach net zero emissions in 2050, followed by China and Latin America in 2056, MidEast in 2057, the US and Eurasia in 2058, and the OHI in 2059. Then, net zero emissions are achieved by EU in 2061, Japan and India in 2064. Finally, Africa and non-OECD Asia achieve net zero emissions in 2070.

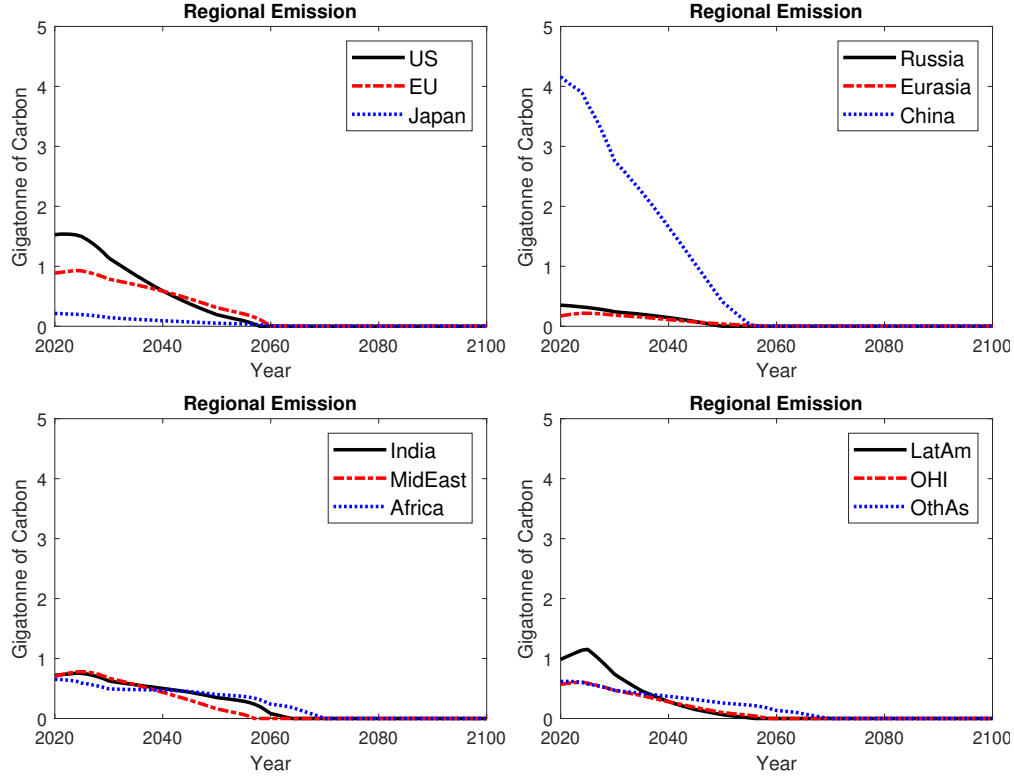


Figure A.7: Simulation results of regional emissions under the baseline emission caps.

If we assume the growth of $k_{t,i}$ is equal to the growth of GDP per capita, then we have

$$\tilde{y}_{i,t+1} = \tilde{y}_{i,t} \exp(g_{i,t}/(1 - \alpha)).$$

A.4.2 Model Comparison of ETS Implementation

Figure A.8 compares regional emissions between two cases under noncooperation with the baseline emission caps: (i) with the ETS, (ii) without the ETS.

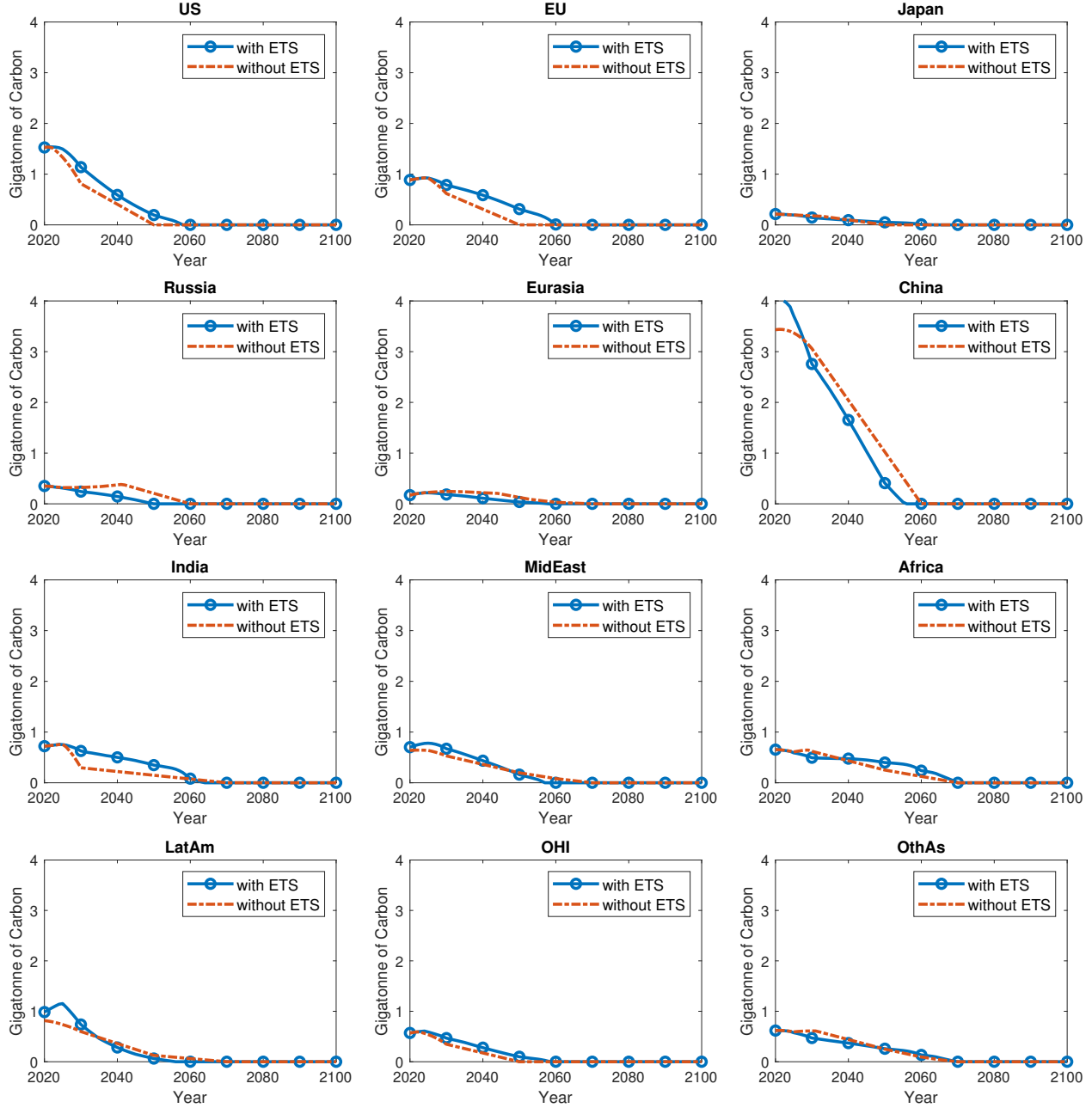


Figure A.8: Comparison of the ETS implementation: regional emissions.

Figure A.9 compares the regional MAC under noncooperation with the baseline emission caps. We compare two cases: (i) with the ETS, (ii) without the ETS.

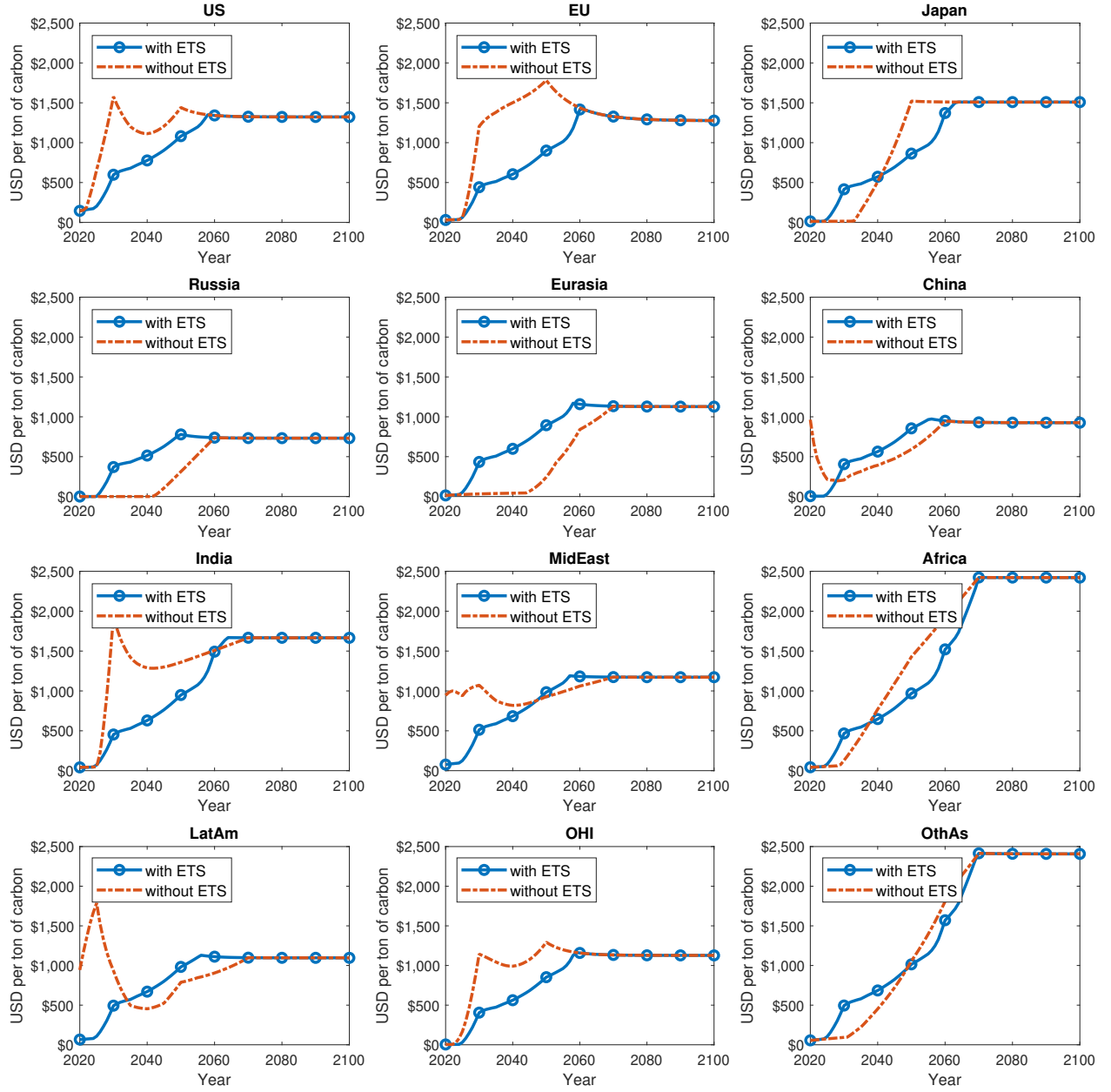


Figure A.9: Comparison of the ETS implementation: regional MAC.

Figure A.10 compares the regional SCC under noncooperation with the baseline emission caps, comparing two cases: (i) with the ETS, (ii) without the ETS.

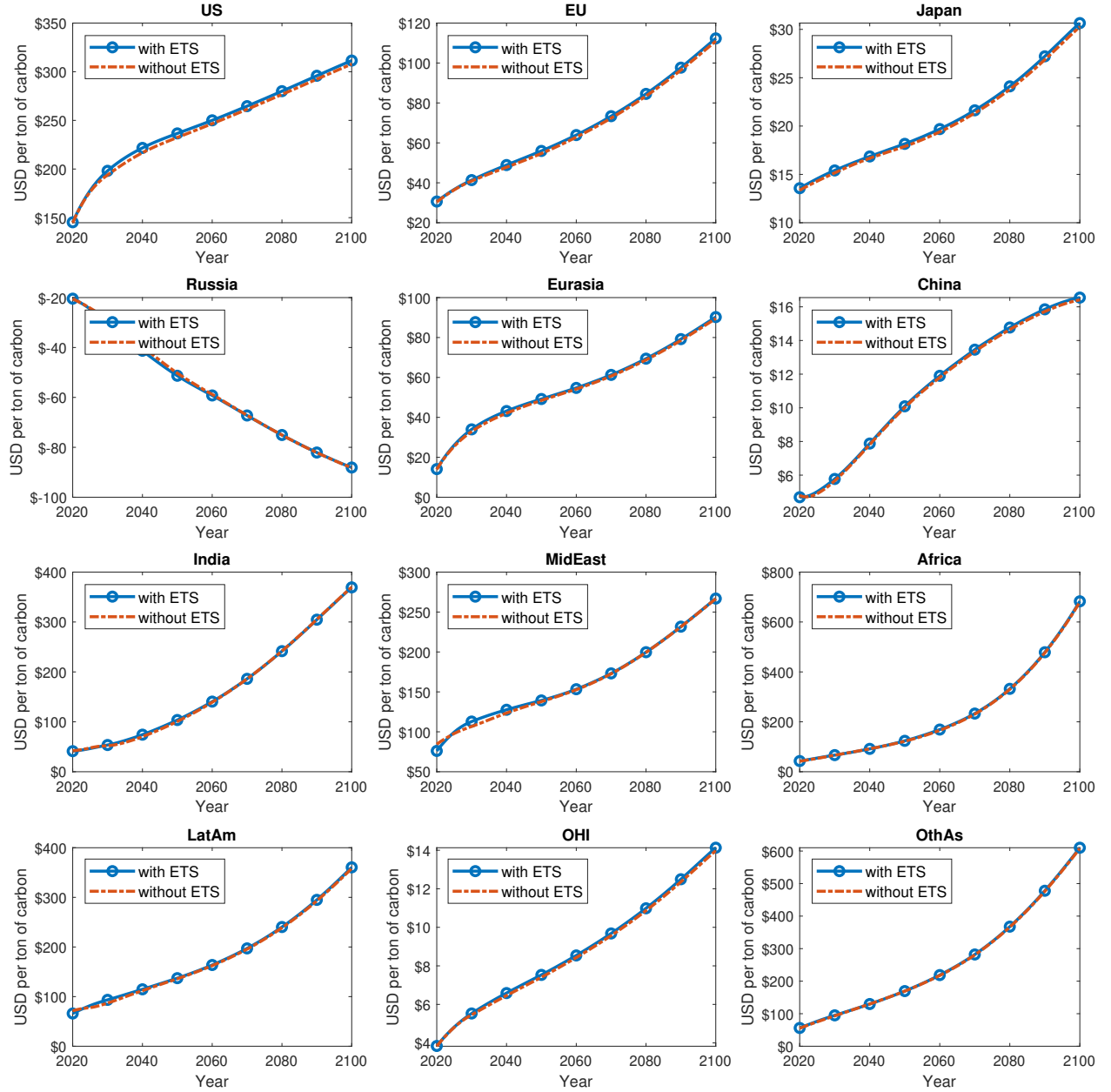


Figure A.10: Comparison of the ETS implementation: regional SCC.

A.4.3 Sensitivity Analysis over Emission Caps

In Figure A.11, we compare the MAC for the noncooperative model with the ETS across alternative emission cap scenarios.

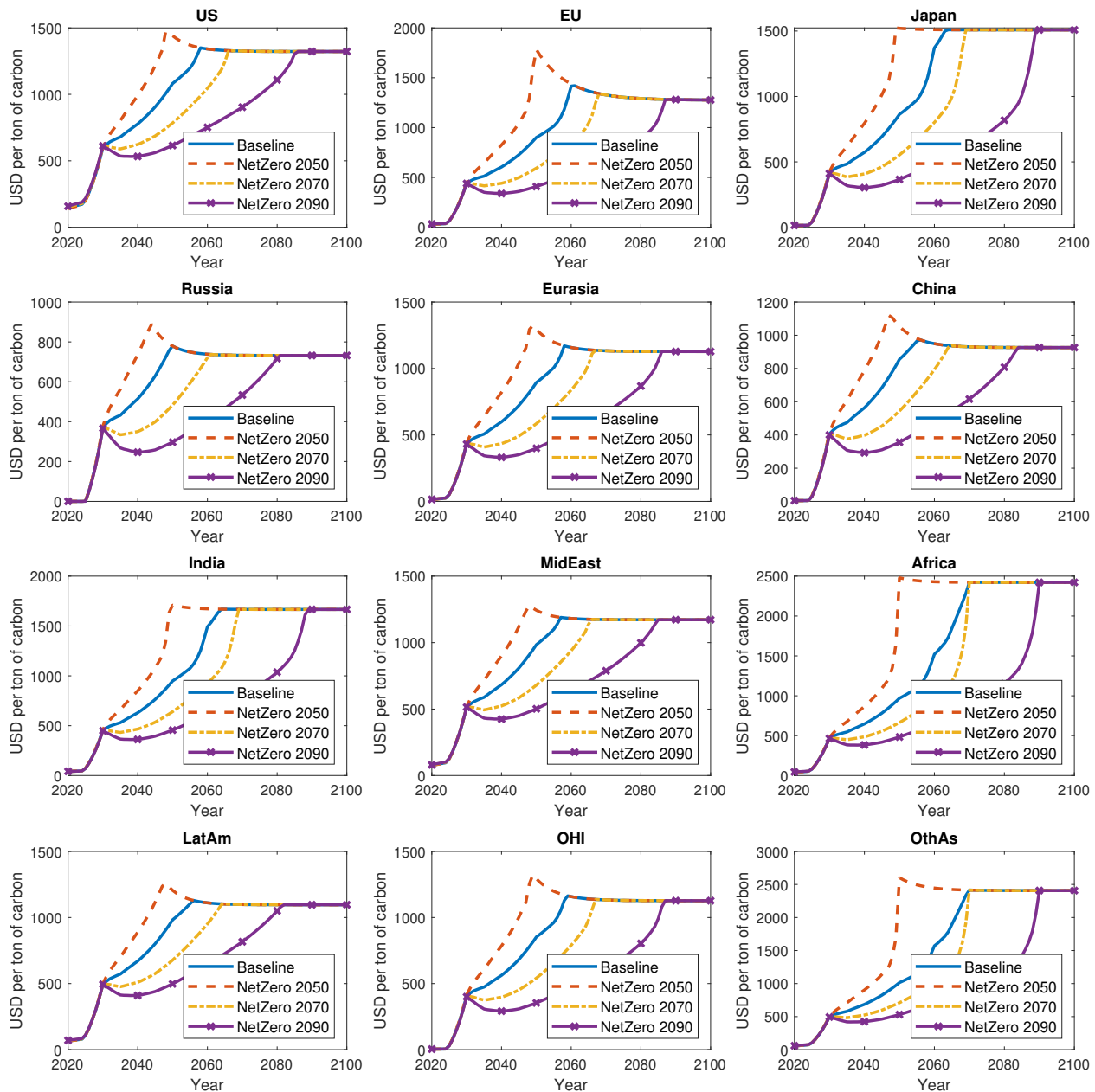


Figure A.11: Comparison of regional MAC under different emission caps.

Similarly, Figure A.12 displays the SCC of the noncooperative model with the ETS across different emission cap scenarios.

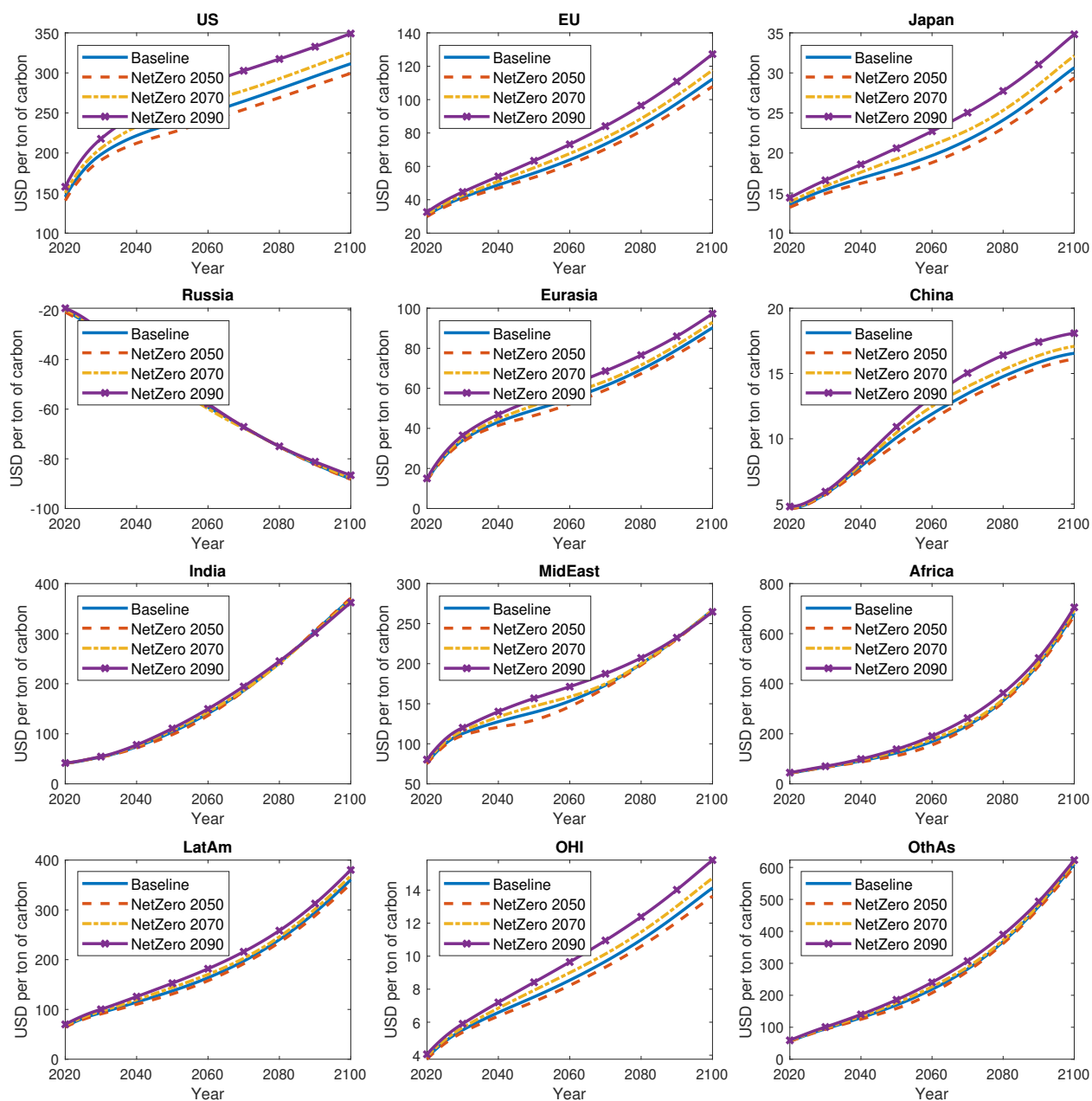


Figure A.12: Comparison of regional SCC under different.

A.4.4 Sensitivity Analysis over Climate Damage Parameters

In Figure A.13, we compare the MAC for the noncooperative model with the ETS under alternative values of the climate damage parameters ($\pi_{1,i}$, $\pi_{2,i}$), based on climate damage projections from Kahn et al. (2021) and Nordhaus (2010a) alongside the baseline climate damage projection from Burke et al. (2018).

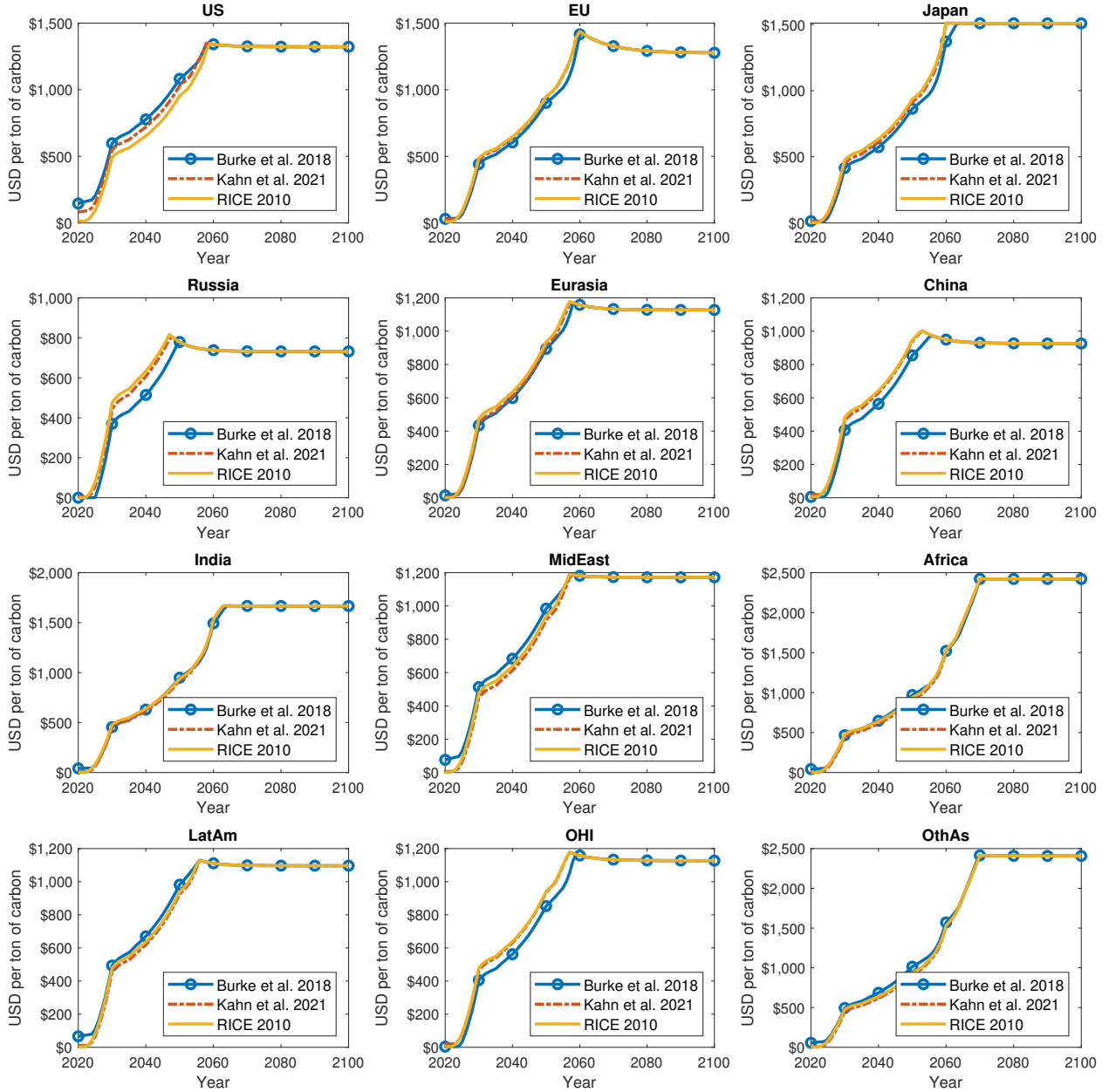


Figure A.13: Comparison of regional MAC under different estimates of climate damages.

Similarly, Figure A.14 displays the SCC of the noncooperative model with the ETS under different values of the climate damage parameters.

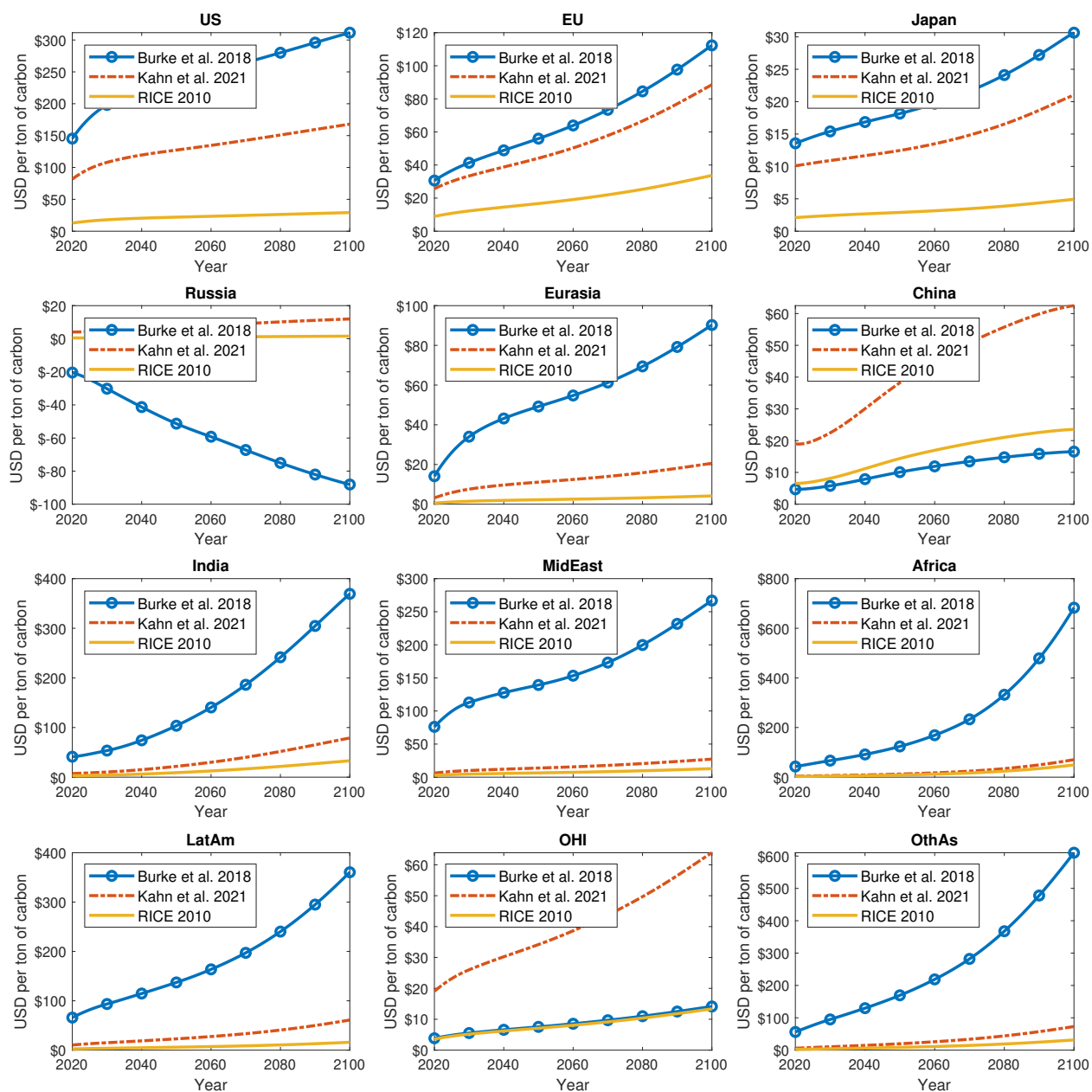


Figure A.14: Comparison of regional SCC under different estimates of climate damages.

A.4.5 Sensitivity Analysis over Abatement Cost Parameters

In Figure A.15, we compare the MAC for the noncooperative model with the ETS under alternative estimates of the emissions abatement parameters ($b_{1,i}$, $b_{2,i}$, $b_{3,i}$, $b_{4,i}$), calibrated from Ueckerdt et al. (2019) and Nordhaus (2010a).

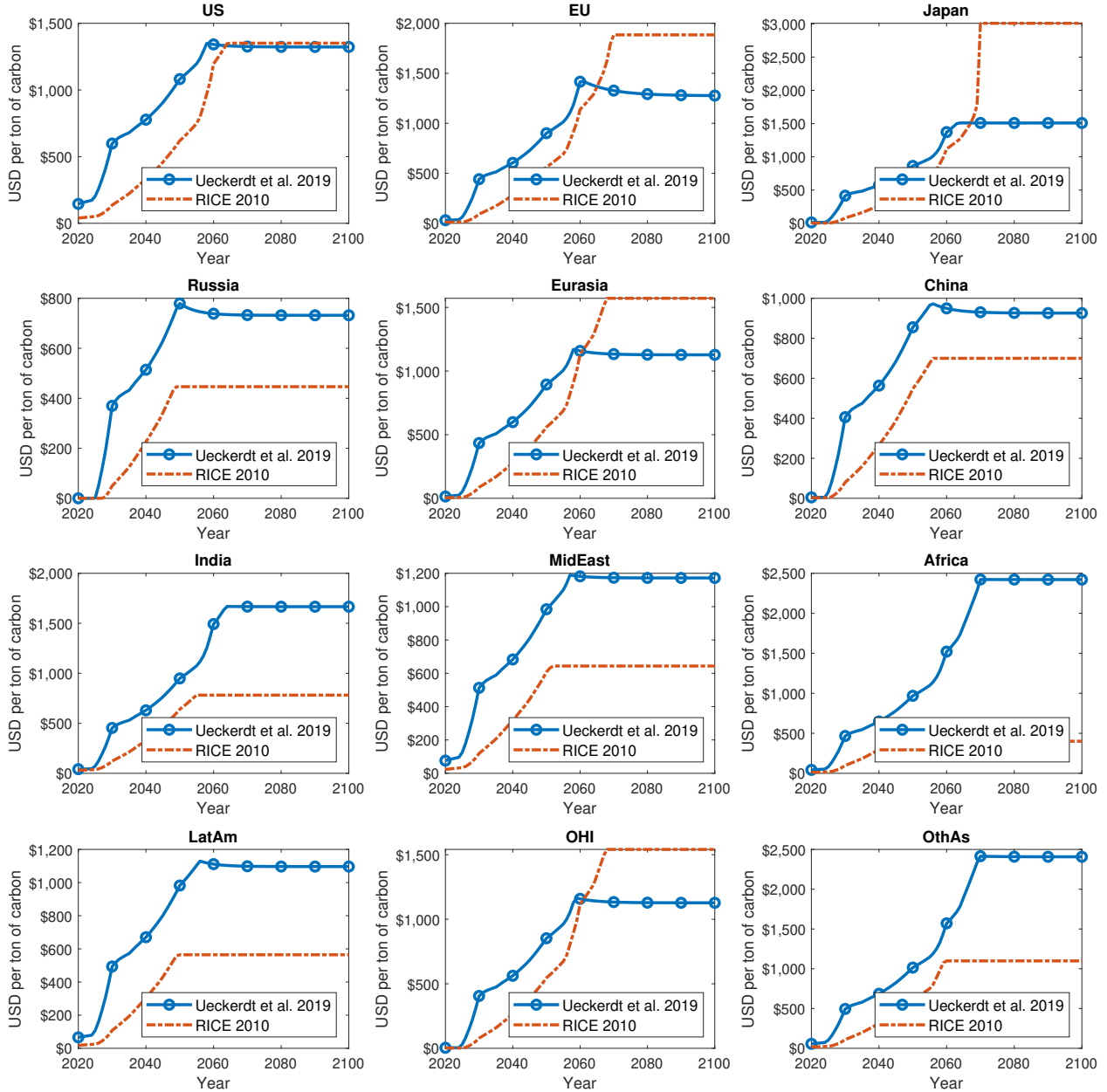


Figure A.15: Comparison of regional MAC under different estimates of emissions abatement cost.

Similarly, Figure A.16 displays the SCC of the noncooperative model with the ETS under different emissions abatement cost estimates.

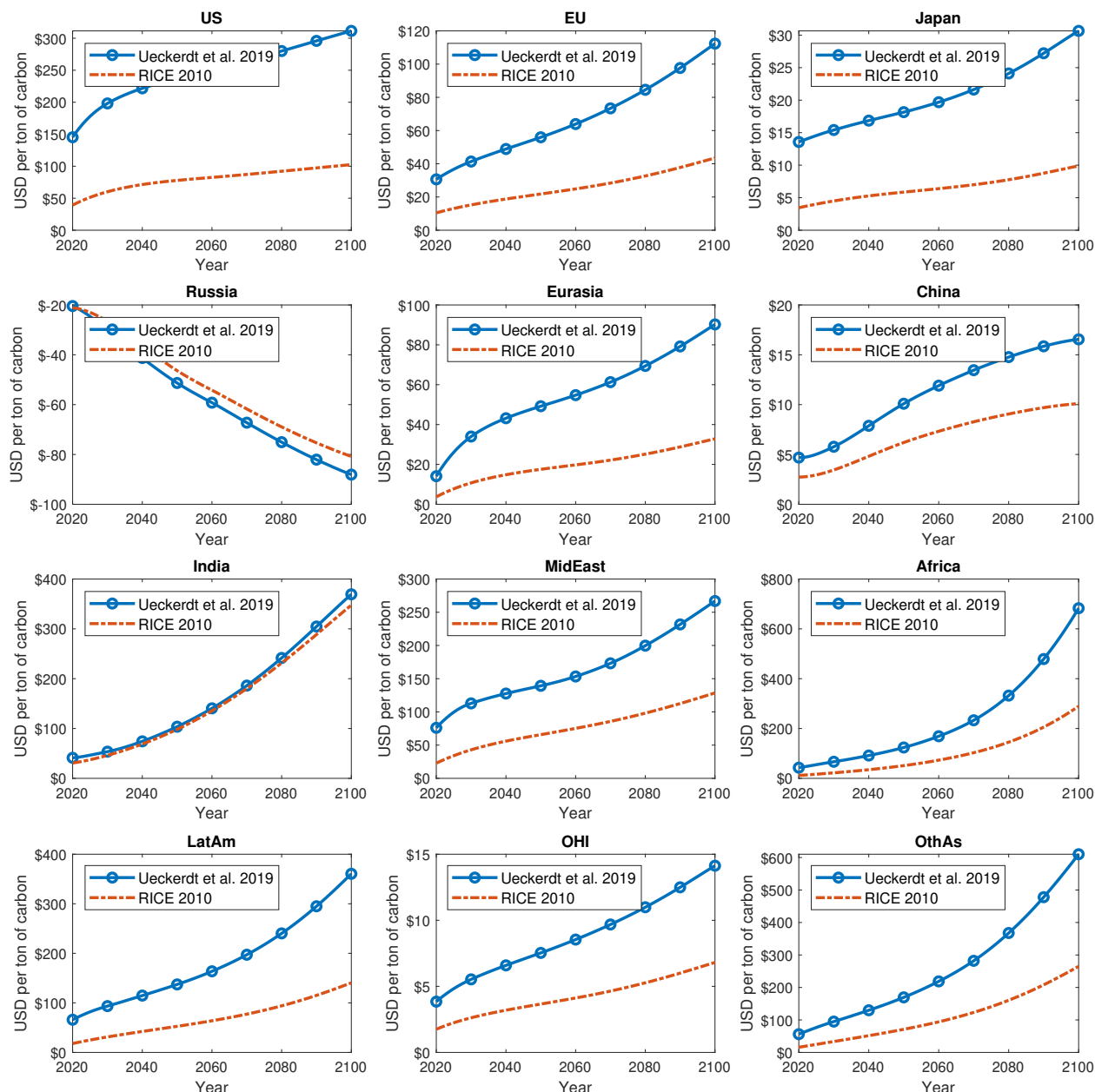


Figure A.16: Comparison of regional SCC under different estimates of emissions abatement cost.

A.4.6 Sensitivity over TFP Growth Rates

Figure A.17 compares key model outcomes under different TFP growth rates: the baseline TFP growth rates derived from Burke et al. (2018) and the alternative rates based on Nordhaus (2010a).

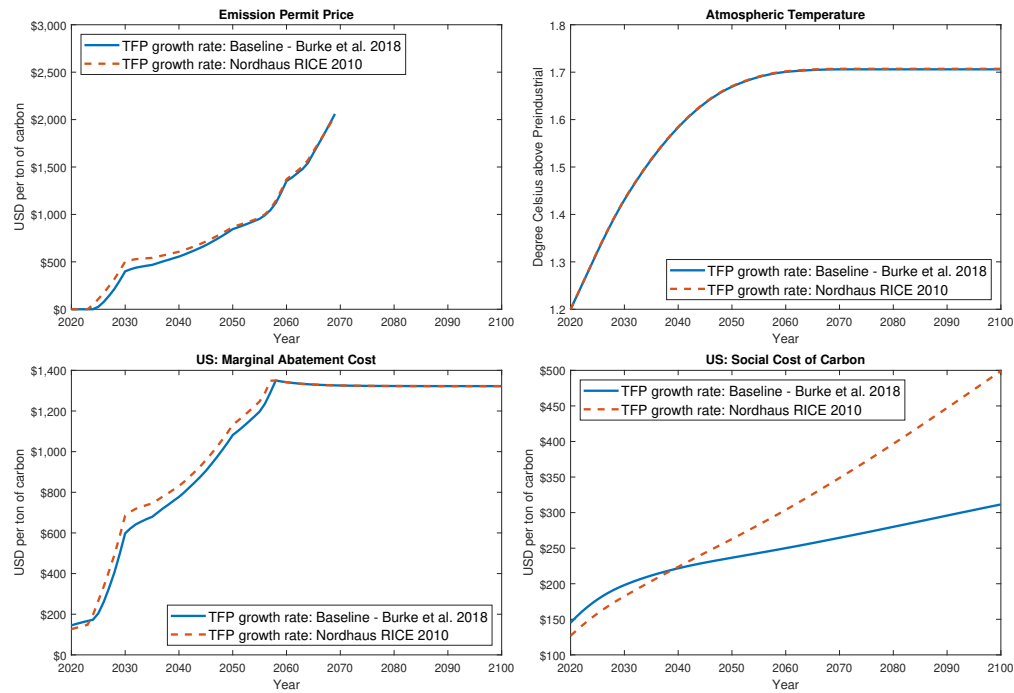


Figure A.17: Comparison of simulation results under different TFP growth rates.