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GLOBAL ECONOMIC AND ENVIRONMENTAL OUTCOMES OF THE PARIS AGREEMENT

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EXECUTIVE SUMMARY

The Paris Agreement, adopted by the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015, has now been signed by 197 countries. It entered into force in 2016. The agreement established a process for moving the world toward stabilizing greenhouse gas (GHG) concentrations at a level that would avoid dangerous climate change. The centerpiece of the agreement is a set of pledges made by participating countries, known as Nationally Determined Contributions (NDCs), to near-term GHG targets they plan to achieve. In this paper, we use a multi-region model of the world economy to analyze the economic and environmental outcomes that are likely to result from these NDCs. To construct the modeling scenario, we convert the disparate NDC formulations into estimated reductions in CO_2 emissions relative to a baseline scenario with no new climate policies. We then solve for the tax rate path on CO_2 in each region that achieves the NDC-consistent emissions reductions in the target year, 2030 for most regions.

We find that if all regions achieve their NDCs, the Paris Agreement significantly reduces CO_2 emissions relative to baseline. Projected reductions in CO_2 emissions growth rates across the regions in the model range from a low of one percent for OPEC to nearly six percent for Japan. Global CO_2 emissions would be lower than baseline by 13 billion metric tons by 2030. However, the Paris policy scenario suggests that global CO_2 emissions would not decline in absolute terms relative to 2015 levels, let alone follow a path consistent with a 2°C stabilization scenario.

Comparing projected 2030 CO_2 tax rates to the same year's percent emissions abatement relative to baseline, we find that declines in CO_2 emissions do not necessarily correlate with the CO_2 tax rate. For example, under Paris, Japan's emissions decline the most of all regions, but its CO_2 tax is the fourth lowest at about $US 16 per ton. India and the United States share a common goal for percent reduction of emissions relative to baseline, but India's tax rises to about $US44 per ton in 2030, about 70 percent higher than the $US 26 tax in the United States in its target year of 2025.

As with our earlier modeling study of the commitments in the Copenhagen Accord,[1] we find the NDCs result in significant macroeconomic spillovers across the global economy, meaning that macroeconomic outcomes across countries depend not only on their own commitments but also on those of the rest of the world. For example, GDP falls most relative to baseline for OPEC and Russia, which rely heavily on fossil fuels as both a domestic energy source and as exports.

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[1] McKibbin et al. (2011).

We also explore how outcomes could change if select countries unilaterally withdraw from the agreement and undertake no new climate policies. For example, in light of the Trump Administration's announcement that the United States will withdraw from the Paris Agreement by 2020, we run the scenarios with and without participation by the United States. We also run simulations with and without China, the world's largest GHG emitter, and Australia, an important fossil fuel exporter. We find that non-participation leads to economic gains (in terms of GDP) for these countries relative to participating, illustrating the challenge of forging an international agreement with participation by all major emitters and fossil fuel producers. However, we also find that if we account for the monetized climate and domestic co-benefits of emissions reductions, those countries, including Australia, are worse off if they unilaterally withdraw from the Paris Agreement than if they participate. Thus, although we find there are gross costs to participating, doing so generates net benefits for the individual country participants.

1. INTRODUCTION

The Paris Agreement, adopted by the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015, has now been signed by 197 countries, arguably making it the first truly global climate change agreement. It entered into force on November 4, 2016, after at least 55 Parties representing at least 55 percent of global greenhouse gas (GHG) emissions joined. The agreement aims to put the world on track to stabilize GHGs at a level that would avoid dangerous climate change, although the specific commitments made in 2015 are not enough to achieve that goal on their own.

Before and during the Paris conference, countries submitted to the UNFCCC national plans that explain what GHG or related targets they plan to achieve. Following through on these Nationally Determined Contributions (NDCs) will have direct and indirect implications for all countries, both environmentally and economically. This paper uses a global general equilibrium model to project the potential economic outcomes if countries meet their NDCs as promised. It also explores how those outcomes could change if select countries unilaterally withdraw from the agreement and undertake no new climate policies. For example, in light of the Trump Administration's announcement that the United States will withdraw from the Paris Agreement by 2020, we run the scenarios with and without participation by the United States. We also run simulations with and without China, the world's largest GHG emitter, and Australia, an important fossil fuel exporter.

This study investigates the environmental and economic implications of the Paris Agreement using G-Cubed, a multi-country, multi-sector model of the global economy. We simulate policies that would achieve the commitments of countries in each of the regions in our model and estimate how much global carbon dioxide emissions would fall relative to what would happen without those policies. We also estimate the economic results of the policies in each region, such as how they affect GDP growth, trade, and investment flows. The goal is to understand how environmentally, and economically, ambitious countries' pledges are in absolute terms and relative to each other.

The paper proceeds as follows. Section 2 outlines the NDCs of the regions in the model - converting them into comparable form. Section 3 summarizes other studies of the Paris Agreement with coverage divided into two sections: global studies and national studies of China and the United States. Section 4 presents an overview of the G-Cubed model, which is the basis of the simulation results. Section 4 also outlines the baseline (no new policy) scenario, which projects future economic and environmental outcomes without the Paris Agreement. Section 5 presents the policy scenario results in two parts. The first part presents detailed results for the case when all regions participate in the Paris Agreement. The second part considers the emissions and macroeconomic outcomes when individual regions withdraw from the Paris Agreement. Section 6 concludes.

2. REPRESENTING NDCS IN MODELING SCENARIOS

The formulation of the NDCs varies considerably across countries, including: the range of GHGs covered by the targets; the sectors of the economy to which targets apply; the base year used to establish targets; the year the targets are to be achieved; and the metrics of the targets themselves. To analyze these disparate targets, we first convert them into a common framework for comparison. We then aggregate them, where needed, so that they are suitable for use with the level of geographic detail available in G-Cubed, which is shown in Table 1. We follow the approach in McKibbin et al. (2011), which compared commitments in the Copenhagen Accord.

Table 1. Regions in the G-Cubed Model

Region	Region Description
Australia	Australia
China	China
Europe	Europe
India	India
Japan	Japan
OPEC	Oil-exporting developing countries
ROECD	Rest of the OECD, i.e. Canada, New Zealand and Iceland
ROW	Rest of the World
Russia	Russian Federation
USA	United States

Converting NDC targets into model-relevant emissions paths is a complex task. In some cases, the targets are straightforward emissions levels in a particular year relative to a historic base year, but we must still specify an emissions path for the years before the target date. In other cases, such as China and India, the targets are expressed as emission intensities (i.e. emissions per unit of GDP). This requires an estimate of projected output to calculate the implied level of emissions. Where the countries in G-Cubed are aggregated into regions, we must calculate a region-wide target. This is most difficult for the Rest of the World (ROW) region, which amalgamates countries with emission targets, intensity targets, and no targets.

One limitation of this study is that the only GHG sources G-Cubed includes are CO_2 emissions from fossil energy combustion, not other GHGs or CO_2 from industrial processes. Thus, to convert targets into the modeling simulations, we assume that NDC pledges to reduce broader CO_2-equivalent emissions will result in proportional reductions in CO_2 emissions from fossil fuels. For example, the United States' 26 percent reduction target applies to the full U.S. GHG inventory and we simulate a 26 percent reduction in U.S. energy-related CO_2. Thus, the results should be interpreted as approximate estimates of the economic adjustments under the Paris Agreement.

Table 2 summarizes the aggregated and approximated NDCs for each region in the model. For countries that offered alternative targets that would be more stringent under certain circumstances, such as assistance from developed countries, we model the target without such conditions (hence the term "unconditional reduction target" in column 7). For countries that offered a range of emissions targets, we chose the least stringent. Regions such as OPEC, ROECD and ROW involved significantly more analysis; we discuss them in the Appendix and omit them from Table 2 because it is difficult to explain their policies concisely. The reduction target shows the proposed decline in the applicable NDC's metric from the NDC's base year to the target year. For example, India committed to a 33 percent decline in all GHG emissions per unit GDP from 2005 to 2030.

Table 2. NDCs for the Regions in the G-Cubed Model

Region	GHG Coverage	Sectoral Coverage	Metric	NDC Base Year	NDC Target Year	Unconditional Reduction Target
Australia	All GHGs	All sectors	Emissions	2005	2030	-26%
China	CO_2	Energy	Emissions per unit GDP	2005	2030	-60%
Europe	All GHGs	All sectors	Emissions	1990	2030	-40%
India	All GHGs	All sectors	Emissions per unit GDP	2005	2030	-33%
Japan	All GHGs	All sectors excluding terrestrial carbon	Emissions	2013	2030	-26%
OPEC	See Appendix					
ROECD	See Appendix					
ROW	See Appendix					
Russia	All GHGs	All sectors	Emissions	1990	2030	-25%
USA	All GHGs	All sectors including terrestrial carbon	Emissions	2005	2025	-26%

Table 3 reports the CO_2 emissions targets for each region as we have approximated them for the modeling scenario.

Table 3. Targeted CO_2 Emissions from Energy Use for Regions

1	2	3	4	5	6	7
Region	**2015 Emissions (MMt)**	**Target Year**	**Baseline Emissions in Target Year (MMt)**	**Target (MMt)**	**Ratio of Baseline Emissions in Target Year to 2015 Emissions**	**Ratio of Target to Baseline Emissions in Target Year**
Australia	377	2030	457	297	1.21	0.65
China	9,610	2030	18,319	13,340	1.91	0.73
Europe	3,809	2030	4,086	2,540	1.07	0.62
India	1,982	2030	3,864	2,908	1.95	0.75
Japan	1,206	2030	1,526	876	1.27	0.57
OPEC	2,525	2030	3,550	3,212	1.41	0.90
ROECD	590	2030	742	456	1.26	0.61
ROW	5,894	2030	8,780	7,246	1.49	0.83
Russia	1,798	2030	1,933	1,541	1.08	0.80
USA	5,359	2025	5,921	4,440	1.10	0.75

The first column Table 3 lists the region of the model. The second column reports the 2015 level of CO_2 emissions in the region in millions of metric tons, as generated by the model. The third column is the target year of the NDC. The fourth column reports the model's projections of CO_2 emissions from energy use in the target year without policy intervention. This is the target year emissions in the baseline scenario, which we also refer to as the business as usual (BAU) or reference scenario. The fifth column contains the targeted level of emissions in the target year, as we have calculated it per the discussion in the Appendix. The sixth column contains the ratio of projected emissions in the baseline in the target year (2025 for the U.S. and 2030 for all others) relative to emissions in 2015. This reflects the projected growth in emissions without new policies. For example, without new climate policies, the model projects Chinese CO_2 emissions would grow by about 91 percent by the target year and European CO_2 emissions would grow by only 7 percent.

The seventh column contains the ratio of the target emissions relative to the baseline emissions in the target year. This puts in common terms the policy performance needed to hit the NDC targets. This change in emissions in the target year relative to the emissions that would have occurred without the policies to implement the NDCs provides one measure of the economic ambition of each target. The ratios of target to baseline emissions in column seven vary from 0.57 for Japan, reflecting the greatest percent emissions reduction relative to BAU, to 0.90 for oil exporting countries. By this standard, OPEC offers a significantly less ambitious pledge than other regions. The United States is on par with China and India, and Europe and the rest of the OECD are only slightly less ambitious than Japan. However, as the modeling results will show, this measure does not fully capture the relative macroeconomic impacts of the agreement on different countries.

In addition to the targets in Table 3, the modeling scenario must specify the policies that regions adopt to achieve their targets and the emissions paths they will follow from 2015 to the target in the target year. For simplicity, we model each G-Cubed region as achieving its emissions target using taxes on CO_2 emissions from fossil fuel use. Revenues from the taxes return to households in the region in an annual lump sum rebate. We impose linearly declining annual emissions targets and calculate the CO_2 taxes necessary in each year to achieve them.[2]

3. OTHER STUDIES OF THE PARIS AGREEMENT

The literature exploring the Paris Agreement is enormous and includes studies using a wide range of methodologies. In this section, we limit our review to studies that use large-scale computational models. Even so, the literature is large. It includes global studies, as well as studies of individual countries. Some studies were undertaken in the lead-up to the Paris negotiations to inform negotiators about proposed NDCs, but many have been undertaken since the agreement. These studies either use announced policies and measures or assume (as we do) illustrative policies implemented to hit a particular emissions target. The studies are not directly comparable because: (1) they assume different targets and different policies to reach those targets; (2) they take different modelling approaches with different assumptions and structures; (3) they focus on different aspects of the Paris Agreement, such as how the NDCs compare to policies that would be sufficient to keep warming below 2°C. This section does not aim to compare these studies, but to provide an overview on the existing literature on modeling the Paris Agreement.

3.1 Global Studies

From a modelling perspective, the global studies on the Paris Agreement fall into three main strands. The first strand uses dynamic computable general equilibrium (CGE) models, which often focus more on macroeconomic aspects of economies. An early study with the same approach as this paper, McKibbin (2015a, 2015b), uses the G-Cubed model to assess the

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[2] This approach does not minimize the intertemporal cost of the emissions reductions achieved. For that, the tax would need to start at a much higher value in 2020 than in our runs and then rise at the real rate of interest. Our taxes start lower but rise much more quickly: typically 15% to 20% per year. A cost-minimizing approach would thus have greater reductions in the near term and smaller reductions in the long term than our policies.

preliminary NDCs that countries proposed in the lead-up to the Paris climate negotiations. The study focuses on results for the United States, China, Japan, the European Union, Australia, and Canada and New Zealand, although all countries were included via the regional aggregations in the model. Under the assumption of continuation of policies in place in 2015, he finds that the Paris commitments have small negative impacts on GDP by 2030 with a loss of 0.1% for the United States, 0.02% for Japan, 0.2% for Europe, 0.8% for Canada, and 0.2 to1% for Australia.

Vandyck et al. (2016) use a global dynamic CGE model (JRC-GEM-E3), supplemented with a global partial-equilibrium energy model (JRC-POLES) for more disaggregation on energy sectors, to assess the implications of three scenarios: the baseline, the NDCs and the 2° scenario.[3] They find that the NDCs have little impact on global demand for oil and gas, and that energy demand reduction and decarbonization of power sectors are important contributors to overall emission reductions. The analysis shows that the NDC and 2°C scenarios both lead to small global GDP losses (-0.42% and -0.72% respectively). Their results also indicate that the Paris commitments of some regions are not ambitious such that their emissions targets are close to or even higher than their baseline levels in 2030. They also find that a substantial gap remains between the global emissions in the NDCs and 2°C scenarios in 2030.

Fujimori et al. (2016) assess the benefits of carbon emission trading on achieving the NDCs and the 2°C goal using a global dynamic CGE model (AIM, see Fujimori et al. 2012). They show that the global welfare loss of achieving NDCs, which is measured based on estimated household consumption change in 2030, is 0.47% without emissions trading, and falls significantly to 0.16% with emissions trading. Furthermore, achieving the 2°C target without emissions trading leads to a global welfare loss of 1.4 to 3.4 percent depending on the burden-sharing scheme, while implementing emissions trading reduces the loss to around 1.5 percent.

More recently, Kompas et al. (2018) develop an intertemporal version of the GTAP model, which allows forward-looking behavior in investment. They estimate economic impacts of different global warming scenarios in the range from 1 to 4°C for 139 countries. They follow van Vuuren et al. (2011) to translate temperature goals into emissions control policies, and conclude that while global mean temperatures could increase up to 4°C without any countervailing action to reduce emissions, implementation of the Paris Agreement would slow global warming to around 2°C by 2100. They then estimate the potential benefits of the Paris Agreement as the difference in losses between the 4°C and 2°C scenarios.

The second strand uses integrated assessment models (IAMs), which often include an environmental system in addition to economic and social components. For example, Fawcett et

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[3] See the CGE model JRC-GEM-E3 at https://ec.europa.eu/ jrc/en/gem-e3/ and the energy model JRC-POLES at https://ec. europa.eu/jrc/en/poles.

al. (2015) use a global integrated assessment model (GCAM)[4] to develop emissions pathways and then use a climate change model (MAGICC, see Meinshausen et al. 2011) to estimate probabilistic temperature outcomes. They find that the Paris scenario reduces the probability of temperature change exceeding 4°C in 2100 by 75% compared with the no-policy scenario, but it has only a chance of 8% to limit warming to 2°C in 2100.

Akimoto et al. (2016) analyze economic costs for achieving the NDCs using a global dynamic linear programming energy model (DNE21+, see Akimoto et al. 2010). They find that the marginal abatement costs of Japan and the European Union are high ($378 and $ 210 per ton CO_2 respectively) while marginal costs of China, India, South Africa and Russia are close to zero, with the United States in the middle ($85 per ton CO_2). The emissions in the NDC scenario is larger than the pathways consistent with the 2°C goal by 2100, and the size of the gap depends on the climate sensitivity.

Hof et al. (2017) estimate abatement costs of achieving the NDCs and the 2°C goal based on a bottom-up integrated assessment model (IMAGE, see Stehfest et al. 2014). They find that abatement costs are very sensitive to socio-economic assumptions. Of the ten major emitting economies, Brazil, Canada and the United States have the highest costs as a share of GDP to implement the conditional NDCs, while the costs for Japan, China, Russia and India are relatively low. They also find that allowing international emission trading could decrease global costs substantially, by more than half for the unconditional NDCs and almost by half for the conditional NDCs. The abatement costs of achieving 2030 emission levels consistent with 2°C pathways would be at least three times higher than the costs of achieving the conditional NDCs.

Kaya et al. (2015) examine the effect of uncertainty of climate sensitivity on achieving emission targets based on the energy model DEN21+ and the climate model MAGICC. They show that the global NDCs are not on track for the 2°C target with a climate sensitivity of 3°C but are compatible with the target with a climate sensitivity of 2.5°C.

The third strand uses partial-equilibrium or reduced-form energy models, which often have more detail in energy sectors. For example, Kitous and Keramidas (2015) use a global partial-equilibrium energy model (JRC-POLES) to explore the NDCs. They find that the implementation of the NDCs and prolonged efforts after 2030 result in global emissions peaking in 2035 (unconditional NDCs) or 2030 (unconditional and conditional NDCs). The emissions in the two NDC scenarios result in a global temperature increase of around 3°C by 2100.

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[4] See the GCAM model at http://www.globalchange.umd.edu/gcam/.

More recently, Parry et al. (2018) use a reduced-form energy model to project energy use and carbon emissions to 2030 for the G20 economies and then evaluate the impacts of various mitigation instruments. In their key scenario where the CO_2 tax rises in an annual increment of $5 per ton of CO_2 from 2017 onwards to reach $70 per ton by 2030, seven countries meet or exceed their NDCs, six countries would need further reductions of up to 10 percent, and another six would need further reductions of above 10 percent. This wide dispersion reflects both differences in countries' NDCs stringency and in the relative price responsiveness of emissions. Tax revenues are potentially large, typically around 1 to 2.5% of GDP. The economic welfare costs (losses in consumer surplus less government revenues) of CO_2 taxes are less than 0.8% of GDP in 2030 in all but three countries (China, India and South Africa) whose costs are 1-1.6% of GDP. Accounting for local environmental benefits (but not global warming), the net domestic welfare gains are quite large for some countries: 0.7% of GDP in Korea, 2.3% in India, 3.7% in Russia and 6.7% in China. These results suggest that many G20 countries can move ahead unilaterally with carbon pricing expecting positive net welfare gains.

To understand the implications of different modelling approaches and identify which results are robust and which are not, some authors have done comparison studies. For example, Aldy et al. (2016) use four integrated assessment models (DNE21+, GCAM, MERGE and WITCH) to assess and compare the NDCs across countries. They find that wealthier countries pledge to undertake greater emissions reductions with higher costs. They also find that marginal abatement costs vary across countries by two orders of magnitude, illustrating that large efficiency gains are available through joint mitigation efforts and carbon price coordination.

Rogelj et el. (2016) assess the implications of NDCs for global GHG emissions in 2030 based on a wide range of global NDC analyses.[5] Their comparison suggests that the studies reveal a wide range of estimates of future emissions, and they identify four key factors that contribute to the differences: incomplete coverage, uncertain projections, land-use-related emissions, and historical emissions and metrics. They conclude that the NDCs collectively lower emissions compared to current policies, but still imply a median warming of 2.6 to 3.1°C by 2100.

3.2 Single Country Studies

3.2.1 The United States

Vine (2016) draws on forecasts from the U.S. Energy Information Agency (EIA) and the U.S. Environmental Protection Agency (EPA), and estimates that GHG emissions in the United States would fall by 22% in 2025 relative to 2005. Larsen et al. (2017) model the impact of current policies on GHG emissions for the United States using the National Energy Modelling

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[5] These global NDC analyses include Climate Analytics, Ecofys, NewClimate Institute & PIK (2015), Admiraal, A. et al. (2015), IEA (2015), Boyd et al. (2015), Meinshausen (2015), DEA (2015), Climate Interactive (2015), Fawcett et al. (2015), UNFCCC (2015), Kitous and Keramidas (2015), den Elzen et al. (2015).

System developed by the EIA, and find that under current policy, the United States is on course for a 15-19% reduction in GHG emissions by 2025, which is considerably short of its 26-28% commitment in its NDC.

Chen et al. (2018) use GCAM and MAGICC models to assess the effect of the U.S. withdrawal in two scenarios: a temporary delay until 2025 and a complete stop after 2015 in mitigation actions. They find that the probability of achieving the 2°C goal would decrease by 6-9% even if the U.S. resumes mitigation efforts for achieving its NDC after 2025. Without U.S. participation, increased reduction efforts required for the rest of the world to achieve the 2 °C goal result in significantly higher global cumulative mitigation costs from 2015 to 2100.
The Energy Modelling Forum 32 examines the economic and environmental impacts of various carbon tax scenarios (tax pathways and revenue recycling options) for the United States. The results are summarized in McFarland et al. (2018). Although these exercises are not directly relevant to the Paris Agreement, they provide insights on the design of CO_2 taxes, the policy instrument we apply here. They find that CO_2 taxes must increase at a fairly high rate (5% every year) to sustain reductions in emissions as the U.S. economy grows. They also find that when the United States adopts a CO_2 tax unilaterally, international CO_2 leakage does not significantly undermine the emissions reducing objective.

3.2.2 China

Fu et al. (2015) analyze China's NDC based on a partial-equilibrium energy model for China (PECE, Renmin University and NCSC) and show that carbon intensity of GDP decreases quickly in the NDC scenario from an annual rate of 3.9% over 2005-2020 to 4.4% over 2020-2030, followed by 6.3% and 9.2% in the following two decades respectively. They point out that China faces several challenges in achieving its NDC targets, including the stage of economic and social development, the economic structure, the energy structure, technological capacity, institutional and policy constraints, etc.

McKibbin et al. (2015) assess two policies (economy-wide and electricity-only emissions trading systems) that China could adopt to achieve its NDC based on the G-Cubed model. They show that illustrative policies to achieve China's commitment of emissions peaking in 2030 imply a substantial departure from baseline emissions, even after accounting for large baseline reductions in China's emissions intensity. In their scenarios, China's real GDP would be about 1.5 percent lower than the baseline in 2030. Both policies operate mainly through reducing the use of coal. Under the economy-wide permit system, the reductions are spread throughout the economy while under the electricity-only policy they are concentrated in the electric sector. However, both policies have similar impacts on real GDP and its components. They also find that China's policies to control emissions have little effect on emissions elsewhere.

Qi et al. (2016) use a global CGE model (the China-in-Global-Energy Model) to analyze the combined impact of low-carbon energy policies and extending emissions intensity targets through 2050 implemented via a cap-and-trade program.[6] Although the policy reduces emissions significantly by 43% in 2050 relative to the no-policy reference, but China's emissions still increase by over 60% between 2010 and 2050. China's goal of peaking emissions by 2030 requires a CO_2 price higher than \$25. Weng et al. (2016) use the same model to simulate carbon price paths for achieving China's NDC in different uncertainty scenarios, which can serve as the floor prices for China's national carbon emissions trading system to ensure the achievement of its NDC.

Parry et al. (2016) develop a reduced-form energy model to project carbon emissions to 2030 with exogenous projections of energy prices and GDP as inputs, and evaluate a wide range of national level fiscal and regulatory policy options for reducing carbon emissions in China. They conclude that carbon and coal taxes are the most effective policies for meeting environmental and fiscal objectives as they comprehensively cover emissions and have the largest tax base.

Timilsina et al. (2018) use a dynamic CGE model of China to simulate various schemes of carbon taxes. They find that an increasing carbon tax that starts at a small rate in 2015 and rises to a level to meet the NDC target in 2030 would cause smaller GDP loss than the carbon tax with a constant rate would do. In addition, the GDP loss due to the carbon tax would be smaller when the tax revenue is utilized to cut existing distortionary taxes than when it is transferred to households as a lump-sum rebate.

Liu et al. (2017) survey a number of recent modeling scenarios that project China's economic growth, energy mix and carbon emissions until 2050 based on a wide range of models.[7] Their analysis suggests that China's emissions will continue to grow until 2040 or 2050 and will double their 2010 level without additional policy intervention. The emissions estimates by 2030 vary significantly across models with the growth rate ranging from 21% to 119% in 2030 relative to 2010, with the median value of 77%. Peaking emissions around 2030 requires the annual emissions growth rate to be reduced by 2% below the reference level, and the emissions reduction will be largely dependent on penetration of renewable energy.

The studies summarized here use a wide variety of modeling approaches and focus on a number of global and national issues related to the Paris Agreement. This paper fits into the first strand of global studies that use dynamic CGE models. Our contribution to the literature is three-fold. First, we apply a global macroeconomic model that uniquely incorporates financial markets, transitional responses of central banks, and international capital flows driven by

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[6] See the model at https://globalchange.mit.edu/publication/16001.

[7] These include six models mentioned before (AIM, DNE21+, GCAM, IMAGE, JRC-POLES, PECE), and another six models China-MARKAL, DDPP, ERI-3E, GEM-E3, MESSAGE and WEM. See more details in their paper.

intertemporal savings and investment decisions. Importantly, a proportion of firms and households have forward-looking expectations, and this anticipation of NDC policies significantly affects short run dynamic adjustments. Second, we consider the implication of selective withdrawal from the Paris Agreement by select countries, including the United States, China, and Australia. Third, we present a broader set of measures of the economic and environmental outcomes of the Paris Agreement. We calculate the economic outcomes and welfare effects of the NDC policies, as other studies have done. We also estimate the monetized domestic co-benefits of reductions in fossil energy use and the global climate benefits (through 2030) contributed by each participating region in the model. This allows us to calculate the net domestic benefits of the agreement to each region.

Several caveats apply to our modeling study, many of which would apply to any modeling study of this kind. The caveats primarily involve necessary simplifying assumptions. For example, owing to the structure of the model, we assumed that the NDC target reductions apply only to CO_2 from fossil energy use. To the extent that a country has significant baseline shifts in land use emissions, non-CO_2 GHGs, and the like, the stringency of the target we estimate could be higher or lower than would apply in practice. Likewise, countries may have abatement costs for other sources that are importantly higher or lower than those for energy-related CO_2. Also, for simplicity we assumed countries achieve their NDC targets with a stylized policy: a CO_2 tax that applies to all fossil fuels and the revenue of which is rebated to households in a lump sum fashion. If countries adopt much less efficient policies or use the tax revenue differently, the macroeconomic outcomes could be different. For a modeling study of how revenue use matters, see the Energy Modeling Forum 32 project described in McFarland et al. (2018).

To construct a policy scenario, we must assume what happens in the years other than those of the Paris Agreement targets. For each region, we solved for the annual CO_2 taxes, starting in 2020, that produce a linear decline in emissions levels from 2020 baseline levels to the NDC target in the target year. After the target year, we assumed CO_2 tax rates stay at their target year levels.

A key element of the Paris Agreement is the prospect of increasing the ambition of commitments every five years. Anticipation of these future more-stringent commitments could affect the emissions levels and economic outcomes we report here. Finally, in Article 6 the Paris Agreement allows for international transfer of “mitigation outcomes,” suggesting the potential for some kind of emissions trading that could lower overall costs. We assume each region achieves its target unilaterally.

4. MODELING APPROACH AND BASELINE PROJECTIONS

We extended the G-Cubed model to make it more suitable for analyzing the Paris Agreement.[8] The model version used here has new country coverage for India and the Russian Federation, as well as a revised regional aggregation for Europe, which now includes both Western and Eastern European economies consistent with the Paris Agreement groupings. The complete list of geographic regions in the model appears in Table 1.

The electricity sector in G-Cubed was also recently revised and now includes eight specific generation technologies: coal, natural gas, oil, nuclear, wind, solar, hydro and other (largely biomass and other renewables). A technical discussion of recent modeling improvements appears in McKibbin et al. (2015). The full list of sectors in the model is shown in Table 4.

Table 4. Sectors in the G-Cubed Model

Number	Sector Name	Notes
1	Electricity delivery	Energy Sectors Other than Generation
2	Gas utilities	
3	Petroleum refining	
4	Coal mining	
5	Crude oil extraction	
6	Natural gas extraction	
7	Other mining	Goods and Services
8	Agriculture and forestry	
9	Durable goods	
10	Nondurables	
11	Transportation	
12	Services	
13	Coal generation	Electricity Generation Sectors
14	Natural gas generation	
15	Petroleum generation	
16	Nuclear generation	
17	Wind generation	
18	Solar generation	
19	Hydroelectric generation	
20	Other generation	

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[8] See McKibbin and Wilcoxen (2009, 2013) for the details of the G-Cubed model.

The Baseline (Business as Usual) Scenario

We first solve the model from 2016 to 2100 for a baseline, or business as usual (BAU) scenario. This scenario assumes that regions continue policies they have already adopted, but do not undertake new policies to achieve their NDCs. Our approach to generating a baseline projection (which is complex in a model with rational expectations) is outlined in detail in McKibbin, Pearce and Stegman (2007). A comparison of the long-term projections with other global economic models in an earlier exercise appears in Stegman and McKibbin (2013).

The key inputs into the baseline are the initial dynamics leading into 2016 (that is, the evolution of the economy from 2015 to 2016) and subsequent projections from 2016 forward for labor force growth and productivity growth by sector and by country. We take the labor force growth from the United Nations Population Projections (2018). The productivity projections are generated following the approach of Barro (1991) and updated in Barro (2015). Over long periods of time, Barro estimates that the average catchup rate of individual countries to the world-wide productivity frontier is 2% per year. We use the Groningen Growth and Development database (2018) to estimate the initial level of productivity in each sector of each region in the model. Given this initial productivity, we then take the ratio of this to the equivalent sector in the United States, which we assume is the frontier. Given this initial gap in sectoral productivity, we then use the Barro catchup model to generate long term projections of the productivity growth rate of each sector within each country. In the case where we expect that regions will catch up more quickly to the frontier due to economic reforms (e.g. China) or more slowly to the frontier due to institutional rigidities (e.g. Russia), we vary the catchup rate over time.

The exogenous sectoral productivity growth rate, together with the economy wide growth in labor supply, are the exogenous drivers of sector growth for each country. The growth in the capital stock in each sector in each region is determined endogenously within the model.

Given assumptions about monetary policy rules, fiscal rules, and other institutional rigidities in the model, we then assume no further climate policies are adopted in the baseline beyond those that existed in 2015 prior to the Paris Agreement. When we do this exercise, we find that economic growth and energy-related CO_2 emissions for some regions may deviate from the EIA's Annual Energy Outlook (AEO, 2018) and other national official forecasts. To generate a BAU scenario that is closer to official projections, we then adjust sectoral productivity to more closely approximate the AEO and other official projections.

The GHG emissions included in G-Cubed comprise only CO_2 from fossil fuel consumption, including combustion of coal, natural gas, and oil. Figure 1 shows the model's BAU projections from 2015 to 2030 for global CO_2 emissions from energy use across the major regions in the model. These projections do not include the NDC pledges that countries made as part of the

Paris Agreement. Importantly, they also do not include any impacts on the global economy of climate disruption, and neither do the modeling results for the policy scenarios. G-Cubed does not include the economic impact of climate damages, but later in the paper we monetize the climate benefits from the policies we model using an estimate of the social benefit of reducing each ton of CO_2.

Figure 1. Global BAU CO_2 Emissions

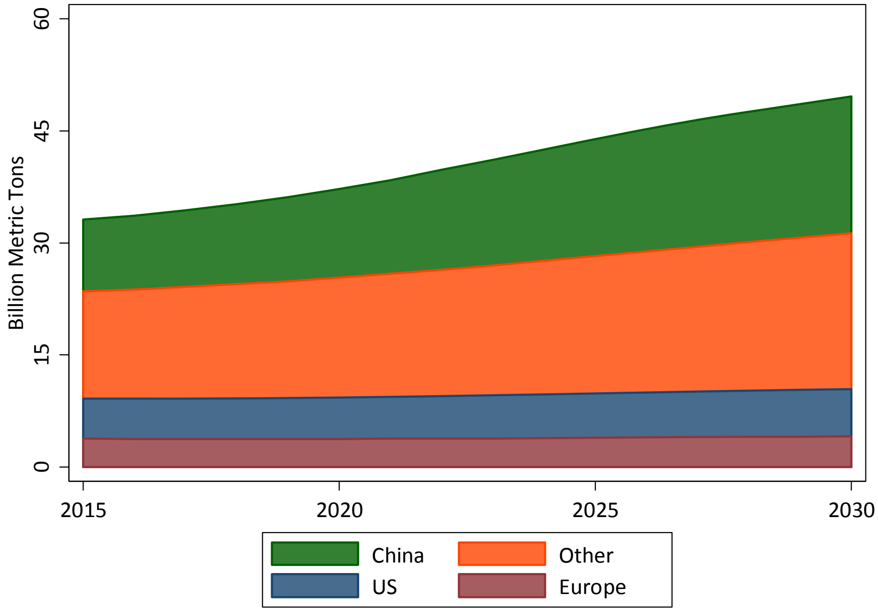


Figure 2 presents the BAU projections for the regions in the model labeled as "Other" in Figure 1, the wedge in orange. Figure 2 illustrates the rising levels of emissions from emerging economies included in ROW and the increasing importance of India in global emissions.

Figure 2. BAU CO_2 Emissions for Other Regions

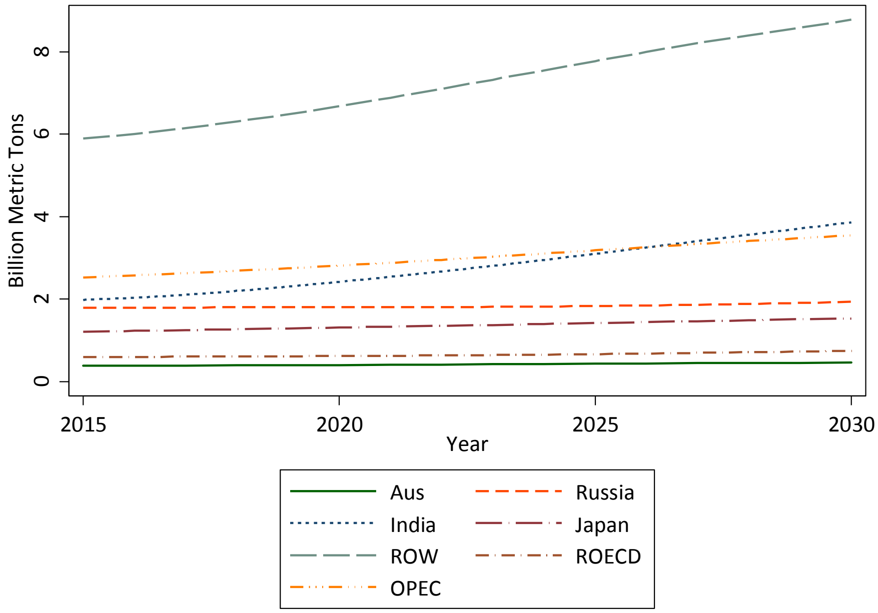
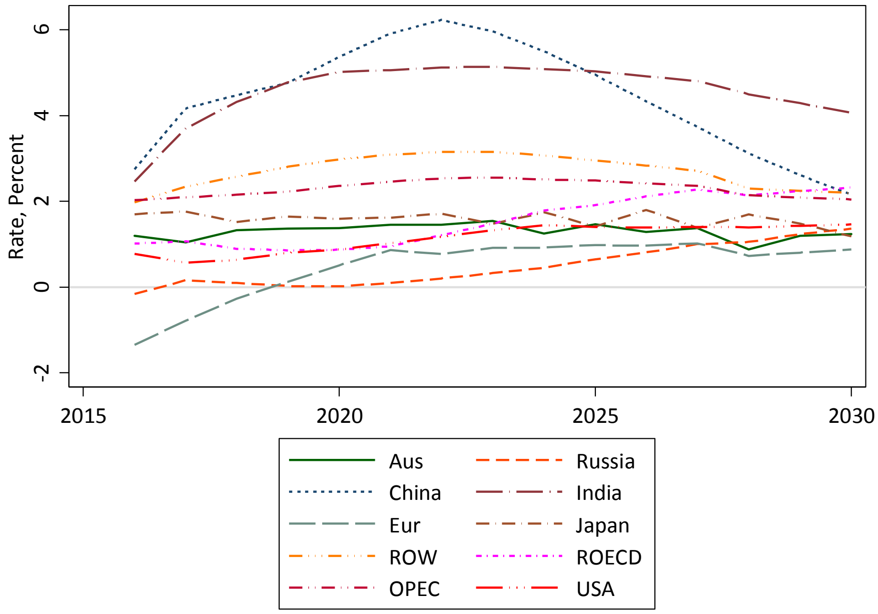


Figure 3 reports the emissions data from the previous figures as annual growth rates by region. The rates of growth in China and India, the two highest curves, stand out. While CO_2 emissions per capita are low in these regions, their annual growth rates are high compared to the others.

Figure 3. Annual BAU Emissions Growth Rate for Each Region



These results suggest that without the implementation of the Paris NDCs, growth in global CO_2 emissions from energy use would be large and clearly inconsistent with stabilizing atmospheric GHG concentrations. We also observe an increasingly large impact from emerging countries, particularly China and India.

It should be stressed that any economic projections out to 2100 are highly uncertain. In particular there is enormous uncertainty regarding technological innovations that may occur in end-use energy efficiency, renewable electricity generation, electricity storage and transmission, biofuels, and fossil fuel supplies. Some innovations, particularly in renewable electricity generation, could lower BAU emissions and reduce the cost of reaching any given climate target. Our results thus rely to a significant extent on the assumptions used in constructing the BAU scenario. As indicated in Table 5, our baseline includes a significant amount of renewable energy penetration over the coming decades, especially in Australia, India and the United States. These results are driven by the interaction between assumptions we make regarding the rate at which costs decline and endogenous price-driven responses by energy users in the model. If the costs of renewables fall faster than we have assumed, the Paris NDCs will be easier to achieve and the impacts of the agreement (both economic and environmental) will be smaller than we report. On the other hand, if our projections for renewables are too optimistic and costs fall more slowly, impacts of the agreement would be larger.

Table 5: BAU Renewable Electricity by Region, Percent of Total Generation

Region	Renewable Electricity in 2015	Renewable Electricity in 2030	Change in Renewable Electricity 2015-2030
Australia	9.8	30.4	20.6
China	12.8	18.1	5.3
Europe	44.8	48.9	4.1
India	12.6	23.1	10.5
Japan	24.5	25.8	1.3
OPEC	2.8	2.7	-0.1
ROECD	67.8	65.3	-2.5
ROW	21.4	21.6	0.2
Russia	5.3	5.5	0.2
USA	28.4	42.7	14.3

5. OUTCOMES OF THE PARIS AGREEMENT

We start by assuming that in 2016 — when the agreement entered into force — each region explicitly announced that starting in 2020 it will impose a policy sufficient to achieve its Paris pledge. Further, we assume that each region achieves its targets in Table 3 by reducing its emissions linearly from its baseline level in 2020 to its target level in the country's target year. Finally, we assume that regions achieve their year-by-year emissions targets by imposing a series of year-by-year taxes on CO_2 emissions with revenue from the taxes returned to households via lump-sum rebates[9]. We then solve for the taxes that will be needed, and examine the economic and emissions outcomes. This "Paris" scenario will be our central set of results in the figures and tables below.

Although in practice countries may use other policies to reach their NDC goals, we use CO_2 taxes with lump-sum recycling across the board for three reasons. First, by imposing a common approach, we are able to examine how differences in outcomes depend on differences between the economies of the regions rather than on differences in the policies used. Had we used different policies in different regions, it would not be possible to determine whether differences in outcomes arose from differences in the policies or differences in the underlying economies. Second, a tax on CO_2 is the most straightforward example of a wide range of carbon pricing policies that could be used, including taxes, emissions trading, or hybrid policies. There is broad agreement in the economics literature that carbon pricing would have the lowest economic costs among policies that would achieve any given emissions target. Third, using an emissions tax provides a direct and transparent way for us to measure the marginal cost of each region's target.

In addition to examining the full Paris Agreement, we explore the implications of unilateral non-participation by three regions: the United States, China and Australia. These illustrate interesting aspects of different regions in implementing the agreement. We choose the United States in light of its announced withdrawal from the Paris Agreement by 2020; China because of its role as the world's largest emitter, and because it has a high BAU path of emissions; and Australia because fossil fuels are one of its major exports. In all three cases, we assume that the regions remaining in the agreement adjust their policies as needed to continue to hit their Paris targets.

Importantly, our results for the non-participation cases are intended only to illustrate the economic impact of participating or not in the Agreement, all other things equal. They are not in any sense policy proposals or predictions. Moreover, they do not include international political consequences of any sort or any kind of economic retaliation against countries that withdraw, so in that sense they are likely to be overly optimistic about the benefits to non-participants of withdrawing .

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[9] There is a large literature on the importance of revenue recycling. See McKibbin et al. (2015) for a summary and an analysis with the G-Cubed model.

5.1 Global Action

Figure 4 shows the path of global CO_2 emissions from energy use under five scenarios: BAU, Paris, and the three scenarios with a single non-participant ("US out," "AUS out," and "CHI Out"). The Paris Agreement significantly reduces emissions relative to BAU; emissions are lower than baseline by 13 billion tons by 2030. However, emissions are still not declining in absolute terms, let alone following a path consistent with a 2°C stabilization scenario.

Figure 4. Global CO_2 Emissions Levels under Paris and Other Scenarios

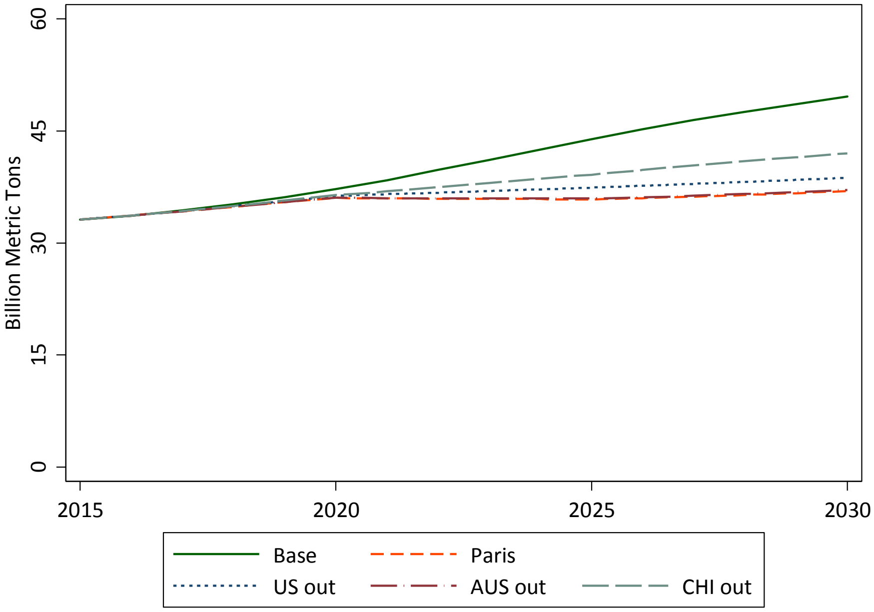
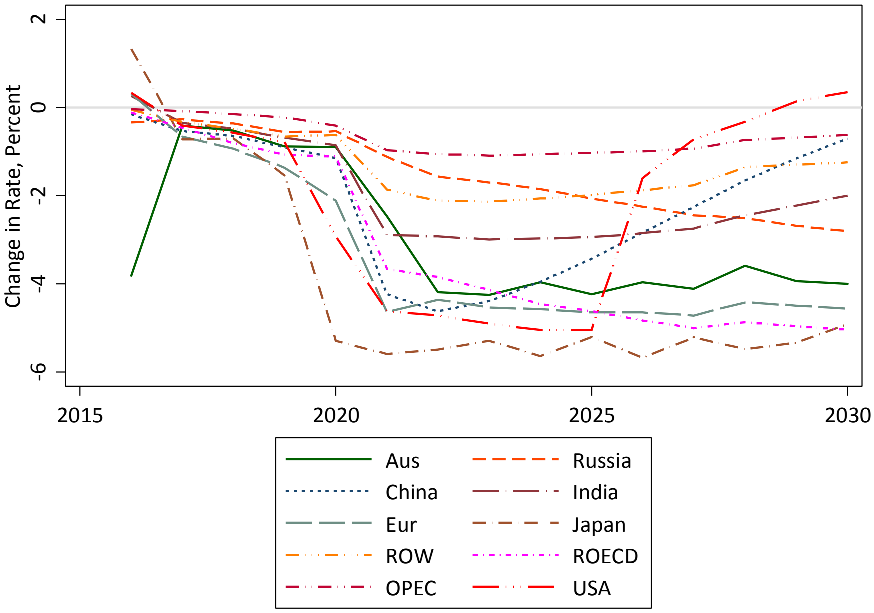


Figure 4 also shows that among the three opt-out scenarios, the biggest increase in emissions would result from the departure of China. Almost half of the reduction in global emissions comes from China's participation, so China's withdrawal would dramatically reduce the effectiveness of the agreement. Further implications of the opt-out scenarios are discussed in Section 5.2.

Figure 5 shows the change in the growth rate of emissions in each region under the Paris Agreement. Emissions begin to change in 2016 in anticipation of the CO_2 taxes that will take effect beginning in 2020. We assume the CO_2 taxes remain constant after the target year, which is 2025 for the United States and 2030 for all other regions. Once the taxes stabilize, economic growth causes each country's emissions growth to revert gradually to its baseline rate, although the level of emissions remains permanently below BAU. Two regions with unusual trajectories are the United States, which has an earlier target year than the others, and China, whose existing policies under BAU begin sharply reducing the growth of emissions after 2020 even without additional policies to hit its NDC target.

Figure 5. Change in CO_2 Emissions Growth Rate under Paris relative to BAU



The reduction in the growth rate in emissions ranges from a low of one percent for OPEC to nearly six percent for Japan. The absolute reduction in emissions differs enormously across regions because of the scale of each country's emissions, as shown in Figure 6. The biggest reduction in emissions is from China, followed by the United States.

Figure 6. Change in CO_2 Emissions under Paris Relative to BAU

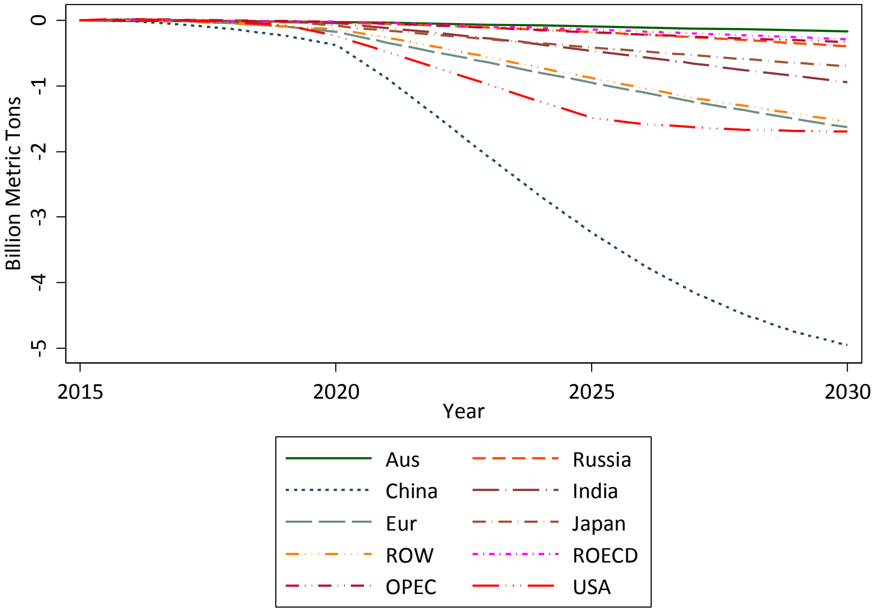


Figure 7 shows the percentage change in emissions under Paris relative to the BAU scenario. Note that this is not the change relative to a historical year's emissions (which is the formulation of many NDCs) but rather the percentage change relative to what emissions would have been without the emissions control policy. Anticipation of the taxes starting in 2020 cause declines in fossil fuel CO_2 between 2016 and 2020, particularly in Australia. By 2030, emissions reductions mirror the target-to-baseline figures in column seven of Table 3. For example, OPEC emissions fall by about 10 percent relative to BAU, and Japanese emissions fall by almost half. U.S. emissions are down by about 25 percent by its target year of 2025 and remain constant thereafter.

Figure 7. Percent Change in CO_2 Emissions under Paris Relative to BAU

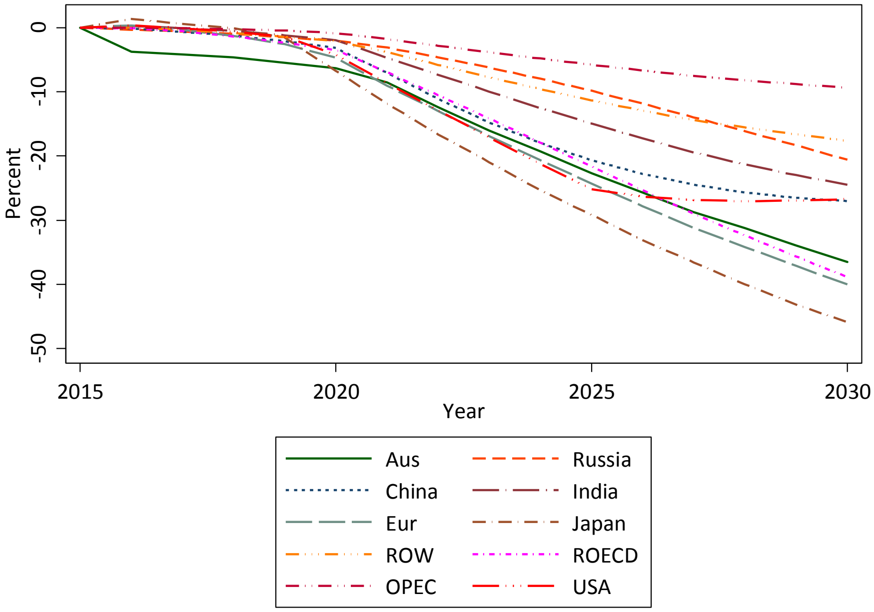


Figure 8 shows the CO_2 tax trajectory for each region. We express all dollar values in this paper in constant 2015 dollars. Owing to anticipation, by 2020 almost all regions' emissions are already below BAU, and therefore their initial CO_2 taxes in 2020 are zero. This is not the case for the United States, because financial capital flows into the United States at rates above BAU between 2016 and 2020 as returns on investment in the United States go up relative to other regions. The U.S. tax is therefore positive in 2020: $US 2. In all regions, the tax increases over time until the target year, at which point it levels off by design. By 2030, CO_2 taxes vary by an order of magnitude across regions, from $US 5 in Russia and Australia to $US 44 in India. With only five years of policy implementation before its 2025 target year, the U.S. tax is higher than in other regions, leveling off at $US 26 per ton.

Comparing the 2030 tax rates in Figure 8 to the 2030 percent emissions abatement in Figure 7, we see that the percent decline in emissions does not necessarily correlate with the tax rate.

For example, Japan's emissions decline by 46 percent relative to BAU, but its CO_2 tax is the fourth lowest at $US 16. India and the United States share a common goal for percent reduction of target emissions relative to baseline, but India's tax rises to about $US44 per ton in 2030, about 70 percent higher than the $US 26 tax in the United States in its target year of 2025.

Figure 8. Tax Rates on CO_2 under Paris

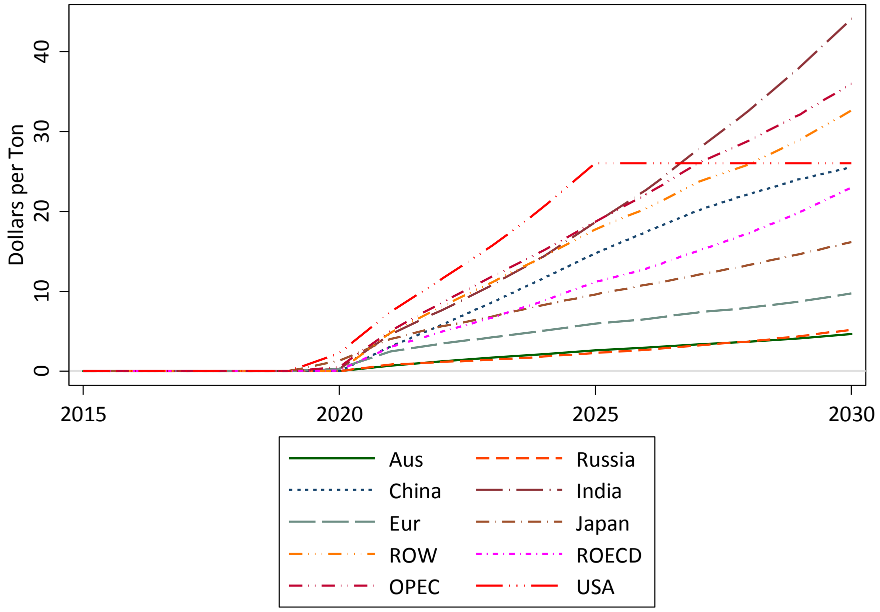
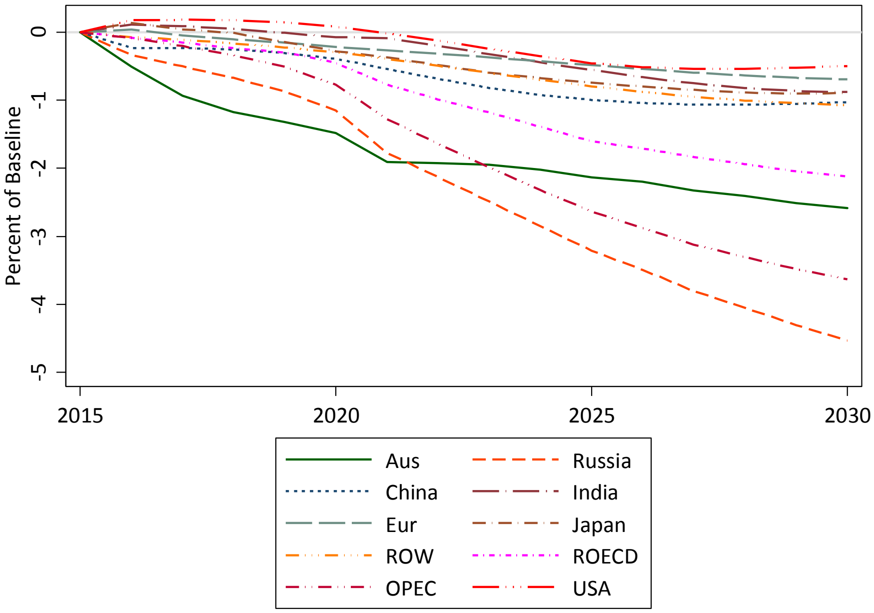


Figure 9 shows the change in GDP relative to BAU for all regions. Recall that in G-Cubed, neither the baseline nor the policy scenario account for the economic effects of climatic disruption. Owing to the anticipation of the policy, GDP falls for some regions beginning in 2016 even though the actual taxes do not take effect until 2020. GDP is below BAU for all regions between 2020 and 2030 and it falls most for OPEC and Russia, which rely heavily on fossil fuels as both a domestic energy source and as an export. In the period prior to 2020, Australia experiences relatively large GDP declines owing to anticipation of its own policies and those of the rest of the world. However, over time, the increased penetration of renewables and lower use of fossil fuels along Australia's baseline path reduce its losses relative to other regions (see Figure 3, where Australia's emissions growth is among the lowest of the regions during the years between about 2024 and 2030). The United States experiences a decline of about one half of one percent of GDP in its target year of 2025 relative to its baseline real GDP growth from 2015 to 2025 of over 20 percent.

Figure 9. Change in Real GDP under Paris Relative to BAU



We examine the change in the components of GDP across regions in the next few charts. Figure 10 shows the change in private consumption relative to BAU. Initially, consumption rises (except in Russia and Australia) and then gradually falls. Three main factors drive this path for consumption. First, revenue from the CO_2 tax goes back to households via lump sum rebates. In the model, only 30 percent of consumers are forward-looking (i.e. 70 percent are liquidity constrained), and therefore the additional household income from rebates raises consumption for a number of years (until the tax is high enough to slow the economy significantly). Second, the tax reduces investment because the after-tax return on capital in fossil fuel sectors falls. Even though investment in renewables rises, the investment decrease in fossil fuel sectors and fossil-fuel-intensive activities dominates that in the short run, so total investment falls. As investment declines, firms reduce retained earnings and hence provide relatively larger dividends to households, which helps to boost consumption further. Third, the fall in real interest rates causes forward-looking households to discount their future income at a lower rate, which tends to raise wealth, and thus consumption, in the near term.

Figure 10. Change in Private Consumption under Paris Relative to BAU

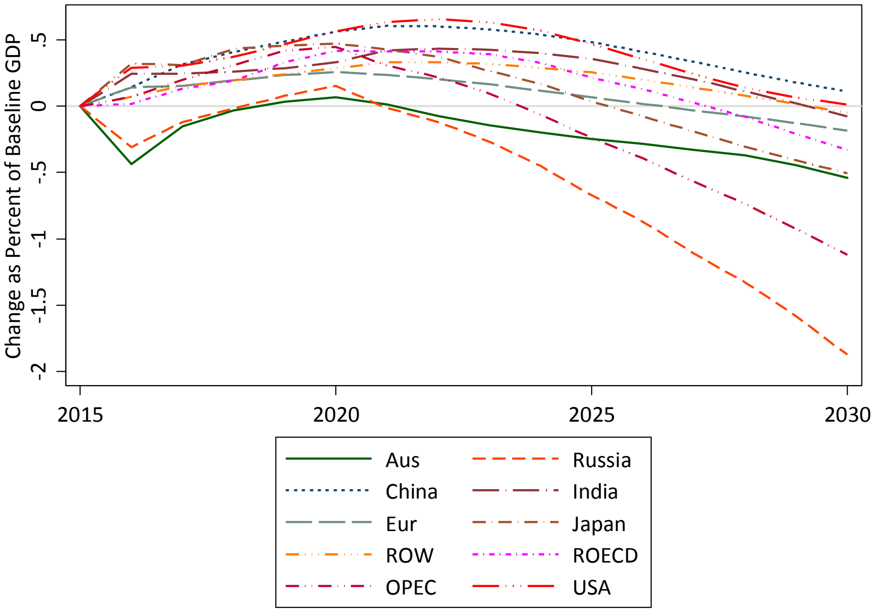


Figure 11 reports the change in total investment under Paris relative to BAU. For most regions investment falls immediately in 2016 in anticipation of the policy; the only exception is the United States where, as noted above, capital inflows raise total investment. Investment levels remain below BAU throughout the simulation, but start to recover after the target years.

Figure 11. Change in Total Investment under Paris Relative to BAU

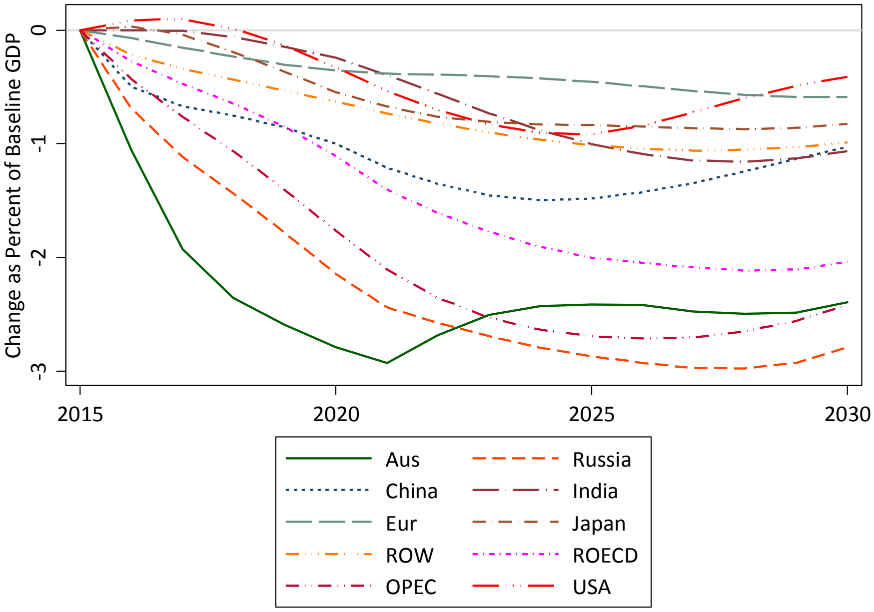


Figure 12 shows the change in each region's trade balance (exports minus imports). Regions that experience relatively large falls in investment experience outflows of financial capital, which depreciate their real exchange rates, increase exports, and decrease imports, thus strengthening their trade balances. Regions that attract foreign capital, such as the United States, experience the reverse: an appreciation of the real exchange rate and a decline in the trade balance. Because Australia relies heavily on fossil fuels for its own use and as a source of export revenue, it experiences a large fall in investment, a significant capital outflow, and the largest depreciation of the real exchange rate (see Figure 14).

Figure 12. Change in Trade Balance under Paris

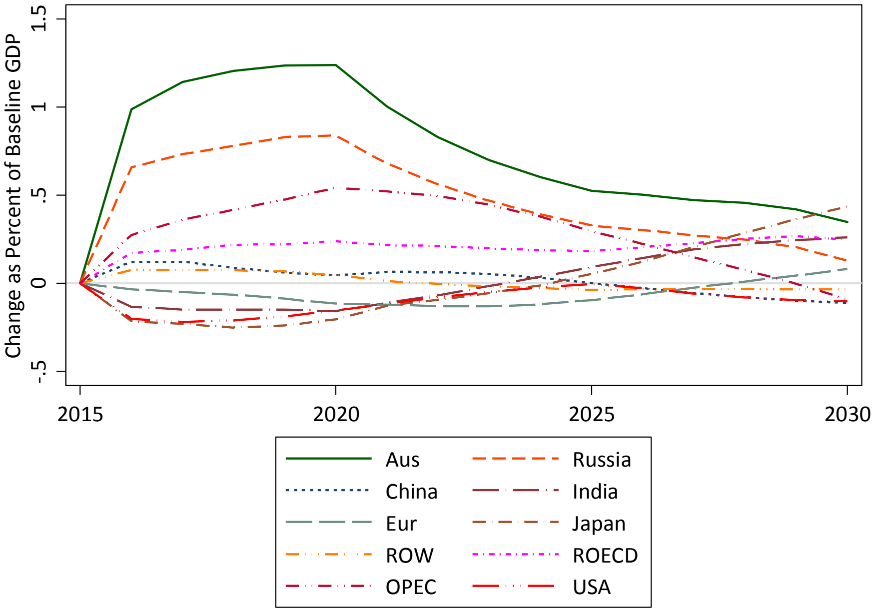


Figure 13 shows short run interest rates in each region. In the long term, the real interest rate is determined by the marginal product of capital in each region. In the short term, the real interest rate is the policy interest rate set by the central bank in each region minus the change in expected inflation. In the model, each region's central bank sets the policy rate by following a Henderson-McKibbin-Taylor Rule.[10] Interest rates will rise if either output growth or inflation are above the central bank's targets for these variables. The central banks in some regions also target the exchange rate (China, Russia, and ROW).

The CO_2 tax has two impacts on these monetary rules. First, it causes energy prices to rise, which increases inflation and, other things equal, would cause central banks to raise interest rates. Second, it slows economic growth which, other things equal, would cause central banks

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[10] See Henderson and McKibbin (1993) and Taylor (1993).

to reduce interest rates. The monetary rules embedded in the model involve explicit weightings of these factors, and the effects on interest rates play out differently in different countries depending on the relative magnitudes of the impacts on inflation and growth. In some cases, central banks tighten policy because the inflation effect dominates (the United States, Europe, India) or because they are partially pegging to the U.S. dollar (China). In other regions, they loosen monetary policy because the falling output dominates (Australia, Russia, and ROECD). Over time, however, the falling marginal product of capital causes all real interest rates to fall.

Figure 13. Change in Short Term Real Interest Rate under Paris Relative to BAU

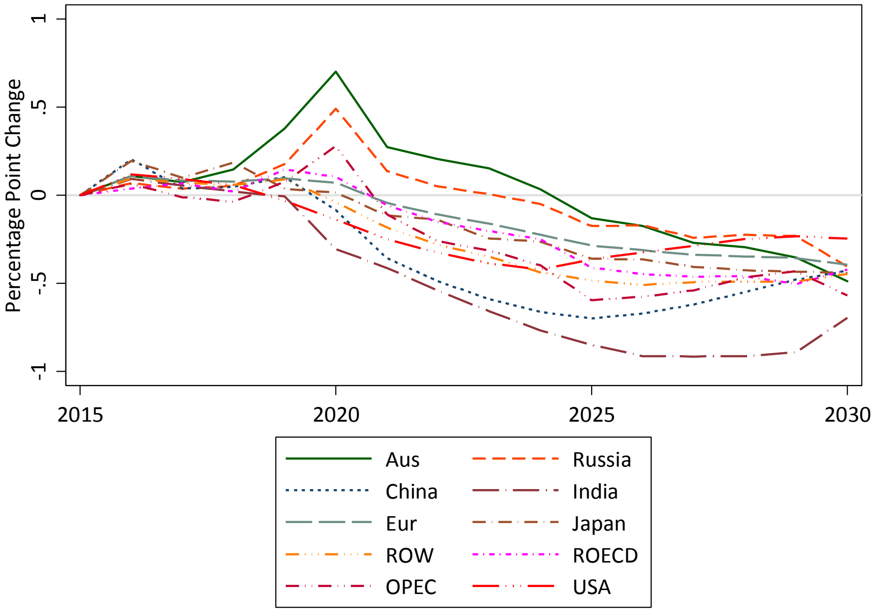


Figure 14 shows effects on real exchange rates. The real depreciation of the Australian currency is notable. Australia is a large exporter of coal and gas, and the implicit tax on Australia's exports through the CO_2 tax causes a substantial loss in the terms of trade in both the short and long run.

Figure 14. Change in Real Effective Exchange Rates under Paris Relative to BAU

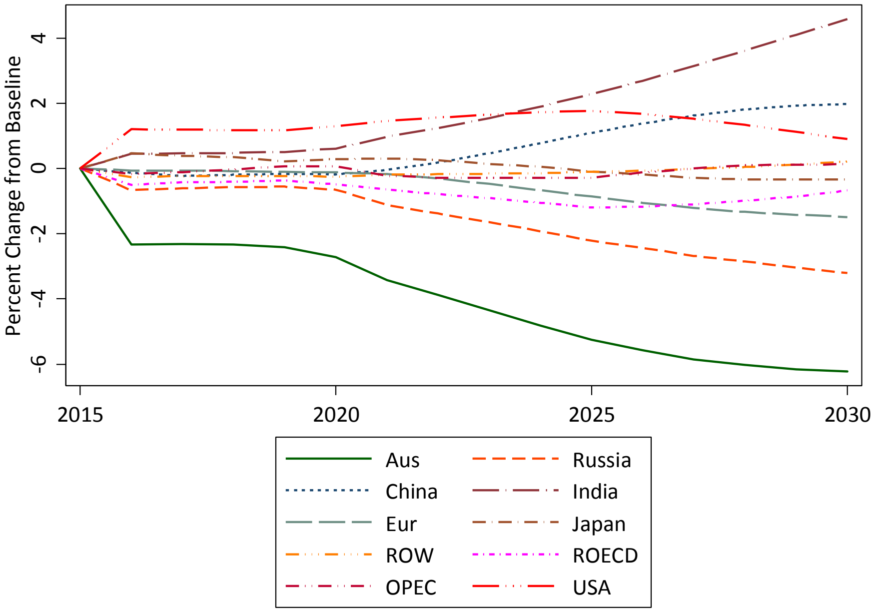
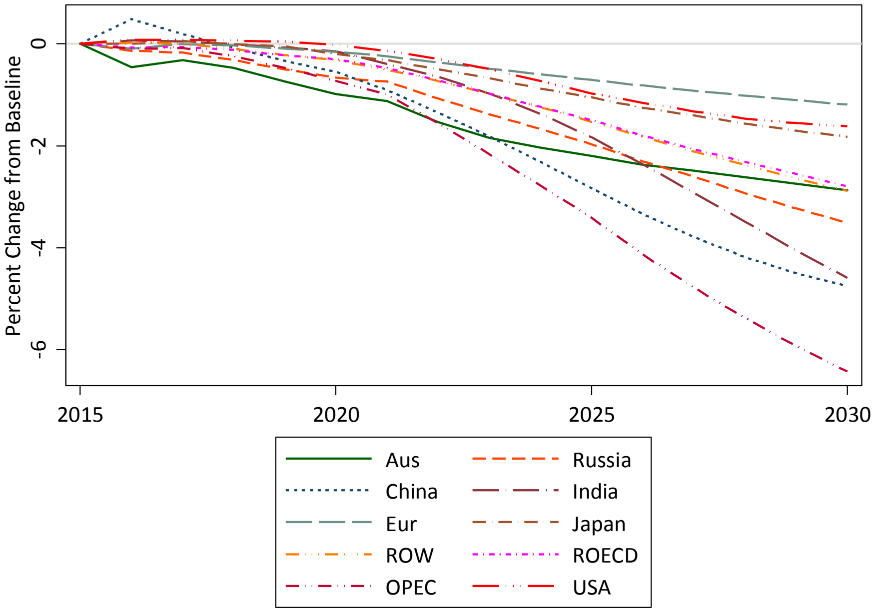


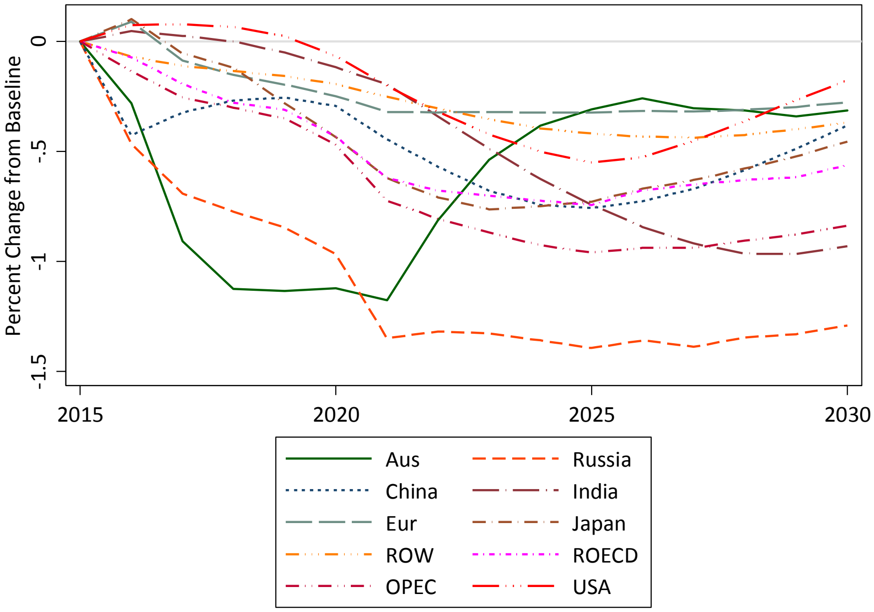
Figure 15 shows that real wages fall globally because of the CO_2 tax. As the capital stock falls in all regions, the marginal product of labor and the real wage fall as well.

Figure 15. Change in Real Wages under Paris Relative to BAU



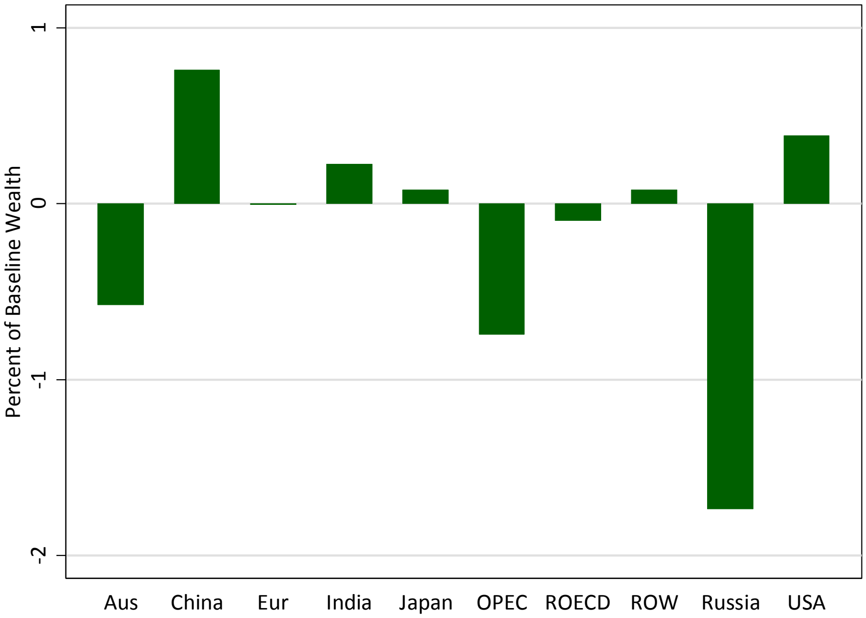
The change in employment is shown in Figure 16. The largest and longest-lasting employment loss relative to BAU is in Russia because global demand for its fossil fuels falls sharply. In contrast, Australia's employment drops during the period prior to the imposition of the policy and then rebounds quickly as workers shift from the fossil fuel industries into other sectors of the economy, including the expanding renewables industry. This structural adjustment is supplemented by a fall in the real wage, which gradually returns employment to its longer run path.

Figure 16. Change in Employment under Paris Relative to BAU



The welfare effects of the Paris policy scenario appear in Figure 17. We measure the effects by computing an intertemporal equivalent variation (EV) for each region: that is, the change in wealth, at baseline prices, that is equivalent to the policy's impact on households' intertemporal utility in each region. To put the EVs in context, we report each as a percent of baseline wealth. Figure 17 shows that participating in the Paris Agreement creates positive economic welfare benefits for China, India, Japan, ROW, and the United States, but negative economic welfare effects for Australia, OPEC, the rest of the OECD, and Russia. Europe is largely unaffected. The figure shows that the economic welfare effects range from -1.7 to +0.8 percent of baseline wealth.

Figure 17. Equivalent Variations as a Percent of Baseline Wealth under Paris



As with the other economic outcomes shown so far, the EVs in Figure 17 do not account for the benefits of reduced climatic disruption or local environmental and other benefits that result from the decline in fossil fuel combustion. These domestic ancillary effects, also known as co-benefits, vary by fuel. For coal and natural gas, they are primarily reductions in mortality risks from air pollution. For gasoline and road diesel, the benefits also include reduced road congestion, traffic accident risk, and road damage. These benefits may be more efficiently achieved by other policies, but to the extent they arise from the CO_2 tax, they are relevant constituents of the overall net effects of the tax.

Parry et al. (2015) enumerate the domestic non-climate external costs associated with fossil fuels in countries around the world. The authors estimate a price on CO_2 that would be in countries' own interest, i.e. the price that would internalize those external costs. They use country-level estimates of non-CO_2 damages by fossil fuel product and simple rules of thumb for the responsiveness of fuel use to CO_2 pricing. Table 6 provides the per-ton domestic co-benefit values we used, which in some cases are rough aggregations of the Parry et al. (2015) values to match the regions in the model.

Table 6. Values of Domestic Co-Benefits from Reduced Fossil Fuel Use*

Region	Co-Benefits, $ per Metric Ton of CO_2 abated	Notes
Australia	$11.50	Australia
China	$63	China
Europe	$52	Rough average of European countries
India	$30	India
Japan	$35	Japan
OPEC	$57.50	Average for large emitters
ROECD	$25	Based on Canada
ROW	$30	Rough average of developing countries
Russia	$85	Russia
USA	$36	United States

* After Parry et al. (2015), Figure 7.

We applied the per-ton dollar values in Table 6 to the reductions in CO_2 emissions in each year through 2030 to approximate the streams of co-benefits in each region or country.[11] We then took the present value of each region's stream to obtain co-benefit measures that we can add to the EVs in Figure 17. Figure 18 shows each of the following in billions of 2015 U.S. dollars: the EVs of the NDC policies; the present values of the domestic co-benefits; and the sum of the two (in blue). The figure shows that for most regions, the welfare effects of the emissions control policy are small (positive or negative) relative to the domestic co-benefits. All regions except Australia and OPEC experience positive net benefits from participating in the Paris Agreement.

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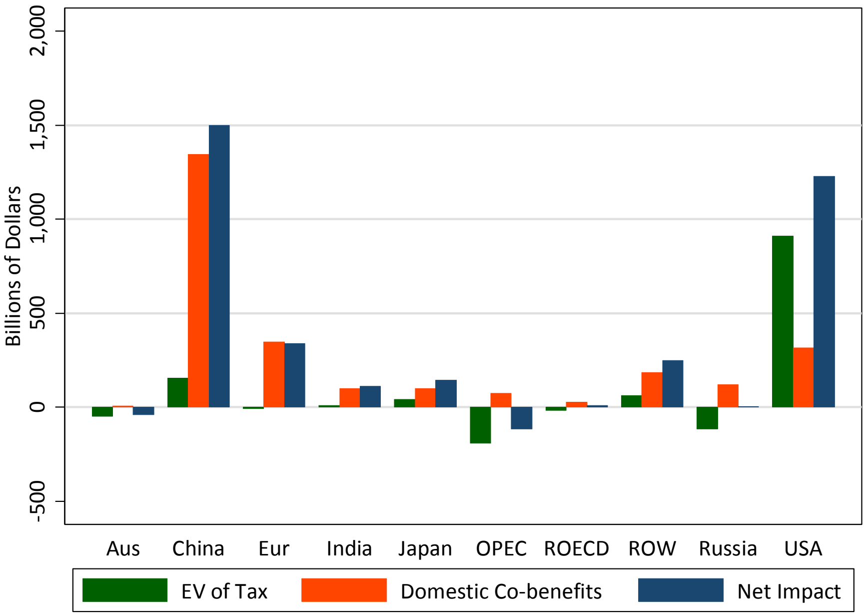
[11] As noted earlier, this calculation is a first-order approximation that does not account for interactions between changes in environmental conditions and decisions about production and consumption. Moreover, it is driven entirely by non-climate externalities, so it is a lower bound on the overall benefits from reducing emissions.

Figure 18. Economic and Ancillary Domestic Welfare Effects under Paris Relative to BAU through 2030



The domestic co-benefits shown in Figure 18 do not include the value of decreased climate change. Climate change benefits are captured in Figure 19, which shows the *global* benefits produced by each region's reduction in CO_2 emissions using an illustrative social cost of carbon equal to $US 42. To be clear, these are global benefits, not the benefits to individual regions: the value for the United States, for example, indicates that its emissions reductions contribute about $370 billion in benefits to the *global* community. The benefits produced by China's participation are the largest of all at $896 billion and account for about 40 percent of the total.

Figure 19. Global CO_2 Benefits Generated by Each Region under Paris

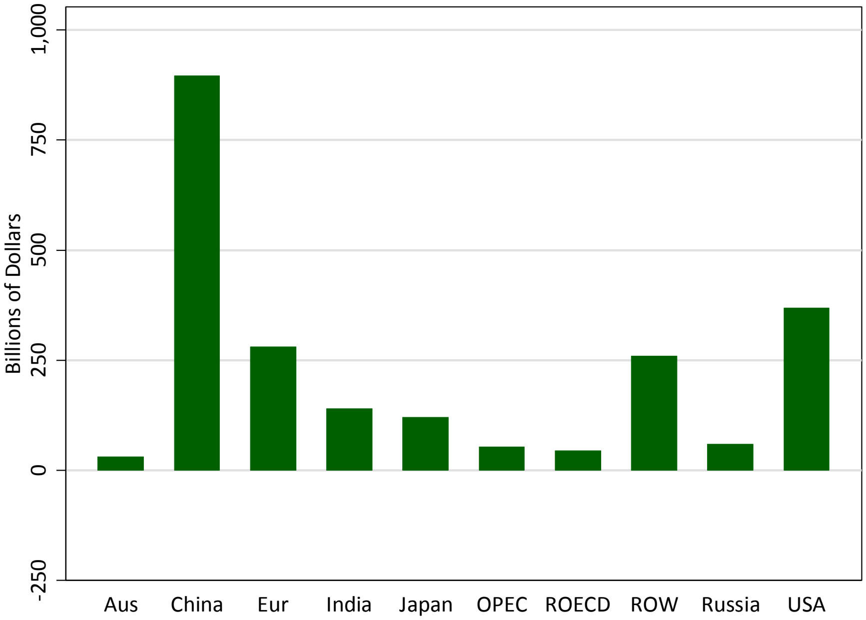


Table 7 presents several measures of the economic impact of the NDCs across regions: the tax rate in 2030, which reflects the marginal cost of the NDC; the percent reduction in emissions relative to BAU, which shows the proportional contribution to the overall goal of reducing emissions; the percent reduction in GDP relative to BAU, which is a rough measure of the average cost of the policy; the equivalent variation as a percent of baseline wealth, which indicates the welfare impact of the CO_2 tax alone; and the net impact, including domestic co-benefits, also expressed as a percent of baseline wealth. Bold figures indicate the most ambitious (or least favorable) row in each column.

Table 7. Alternative Measures of Stringency of the NDCs

Region	CO_2 Tax Rate in 2030, $US	Change in 2030 Emissions, %	Change in 2030 GDP, %	EV, % of Baseline Wealth	Net Impact, % of Baseline Wealth
Australia	5	-37	-2.6	-0.6	**-0.5**
China	26	-27	-1.0	0.8	7.3
Europe	10	-40	-0.7	0.0	0.2
India	**44**	-25	-0.9	0.2	2.2
Japan	17	**-46**	-0.9	0.1	0.3
OPEC	36	-9	-3.6	-0.7	**-0.5**
ROECD	23	-39	-2.1	-0.1	0.1
ROW	33	-18	-1.1	0.1	0.3
Russia	5	-21	**-4.5**	**-1.7**	0.1
USA	26	-27	-0.4	0.4	0.5

The relative ranking of regions from most to least stringent varies considerably with the measure used. This is not at all apparent from the NDCs in Table 2. India's CO_2 tax rate in 2030, for example, is the highest by far, but its reduction in GDP is toward the middle of the group. After accounting for domestic co-benefits, India has one of the best overall outcomes. In contrast, Russia experiences the largest reduction in GDP and has the worst EV outcome, but is still better off overall after accounting for co-benefits. The country gaining the most from the agreement is clearly China, which has a positive EV and, after accounting for domestic co-benefits, has the largest overall net gain by far. The only regions that experience an overall loss are Australia and OPEC, where co-benefits are relatively small and do not offset the negative EV associated with the Agreement.

5.2 The Impacts of Non-Participation

This section explores the impacts of selected regions withdrawing from the agreement. As described above, the regions that are the focus of this section are China, the Unites States, and Australia. Each region is assumed to withdraw unilaterally, with all other regions achieving their NDC targets.

Figure 4 indicates the effect each region's withdrawal on global emissions of CO_2. China has a major impact; its withdrawal reduces the impact of the agreement by about half. The United States also has a large impact, but it far smaller than that of China. Australia's domestic emissions, in contrast, are small relative to China and the United States. Since its exports of fossil fuels are taxed whether or not Australia itself participates in the agreement, Australia's withdrawal has little impact on global emissions.

Figure 20 shows the emissions outcomes from each region under the four different policy scenarios. Note that by assumption regions that stay in the Paris Agreement continue to meet their NDCs even when one region withdraws.

Figure 20. Change in CO_2 Emissions under Paris and Withdrawal Scenarios in 2030 Relative to BAU

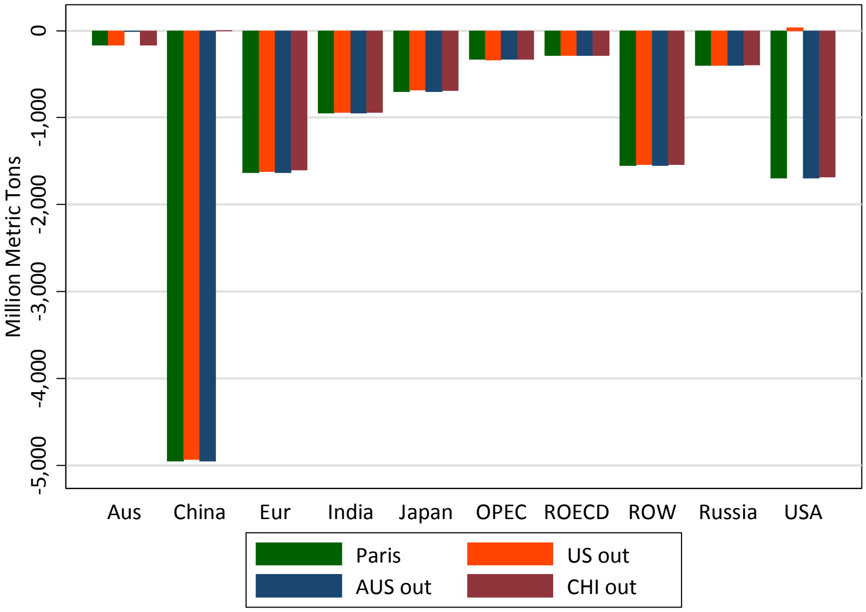
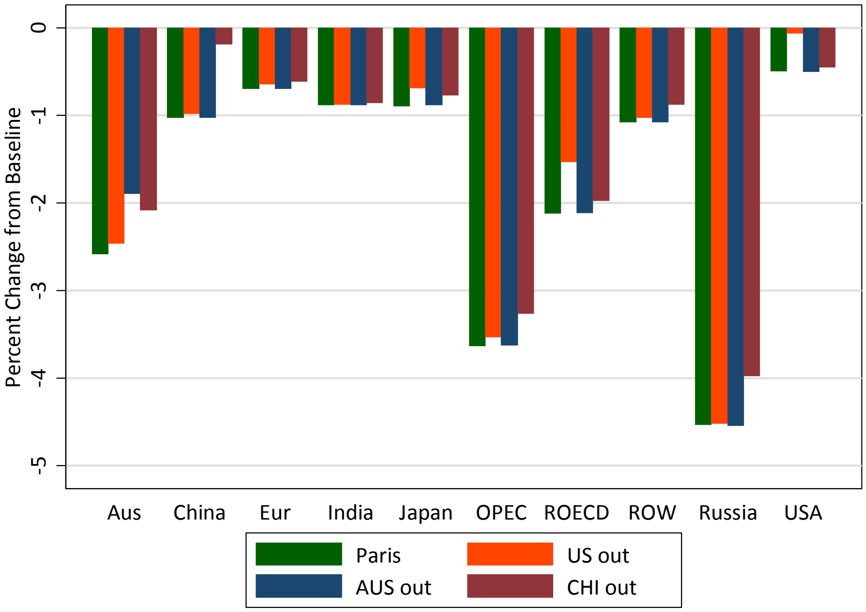


Figure 21 shows GDP impacts in 2030 by region under Paris and the three withdrawal scenarios. For both the all three countries, withdrawing from the agreement still results in lower GDP than baseline. For China and the United States, the resulting change is small: non-participation comes close to eliminating the GDP impact. For Australia, however, the Paris Agreement still has a significant impact on GDP even when Australia does not participate. These losses occur because Australia's exports of fossil fuels are still subject to the CO_2 tax in other regions, and the revenue is collected outside Australia.

Figure 21. Change in Real 2030 GDP relative to BAU under Policy Scenarios



Importantly, the values in Figure 21 are changes in the level of GDP relative to BAU more than a decade in the future (2030), and they are generally small: about a typical year's GDP growth or less. To put these values in perspective for our selected countries, Figure 22 shows their real GDP levels relative to 2015 under the BAU (Base), Paris, and withdrawal scenarios. The figure makes clear that the economic impacts of the agreement are small compared to the underlying growth in GDP in all three economies. There is little to be gained in terms of GDP for each region by withdrawing from the agreement. More importantly, we show below that a more complete accounting framework that includes environmental co-benefits indicates that participating in the Paris Agreement is in the self-interest of almost all regions—that is, that countries withdrawing from it make themselves worse off.

Figure 22. Real GDP Relative to 2015 Values for Selected Regions

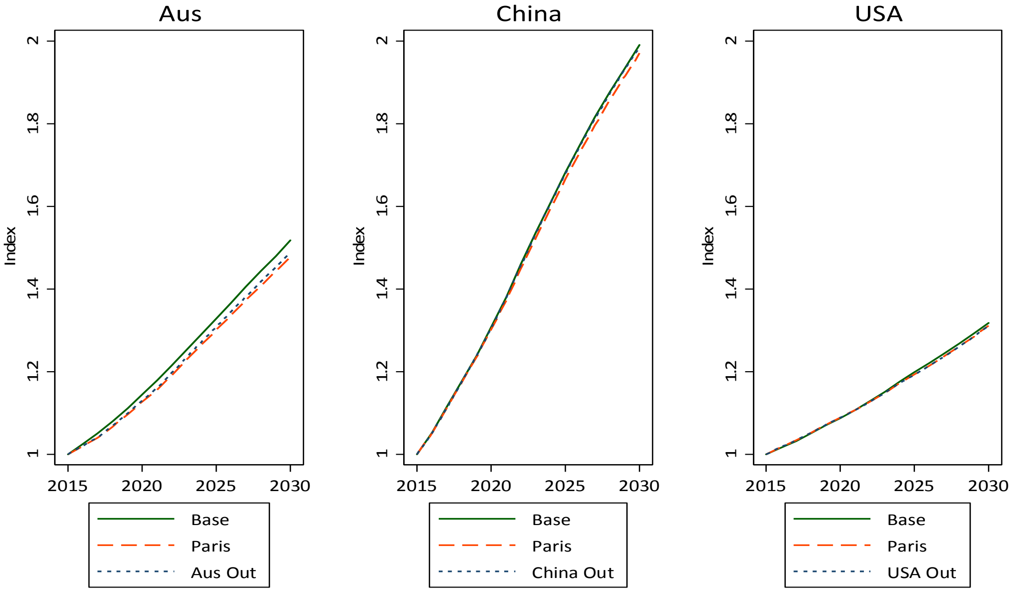


Figure 23 shows the equivalent variations by region through 2030 under the Paris Agreement and the alternative withdrawal scenarios. The results for the Paris Agreement scenario reframe the results shown in Figure 18 from billions of dollars to percent of baseline wealth. Figure 23 allows comparison of the relative welfare effects of the policy scenarios, not counting the domestic co-benefits shown in Figure 18 or global climate benefits. Even abstracting from those important benefits, all three countries are better off participating in the agreement than withdrawing. The welfare effects of the NDC policies lead to positive or negative outcomes for most regions of less than one half of one percent of baseline wealth.

Figure 23. Equivalent Variations Relative to Wealth under Policy Scenarios

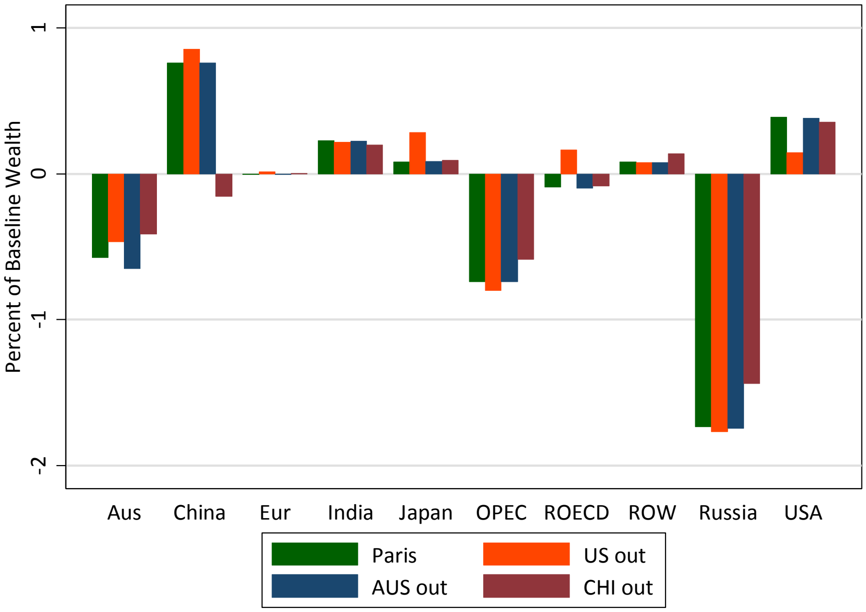


Figure 24 adds the present value (through 2030) of the domestic co-benefits of achieving the NDCs to the EV values in Figure 23. Once we add in the domestic co-benefits, nearly all of the policy outcomes are positive, with the exception of Australia and OPEC. Note the difference in the scales of the vertical axes of Figure 23 and Figure 24. Accounting for domestic co-benefits increases the estimated benefits of achieving the NDCs for some regions by one to two orders of magnitude, particularly for China, India, and Russia. Also, this addition does not change the result that none of the three regions is better off if it unilaterally withdraws.

Figure 24. EVs and Domestic Co-Benefits Relative to Wealth under Policy Scenarios

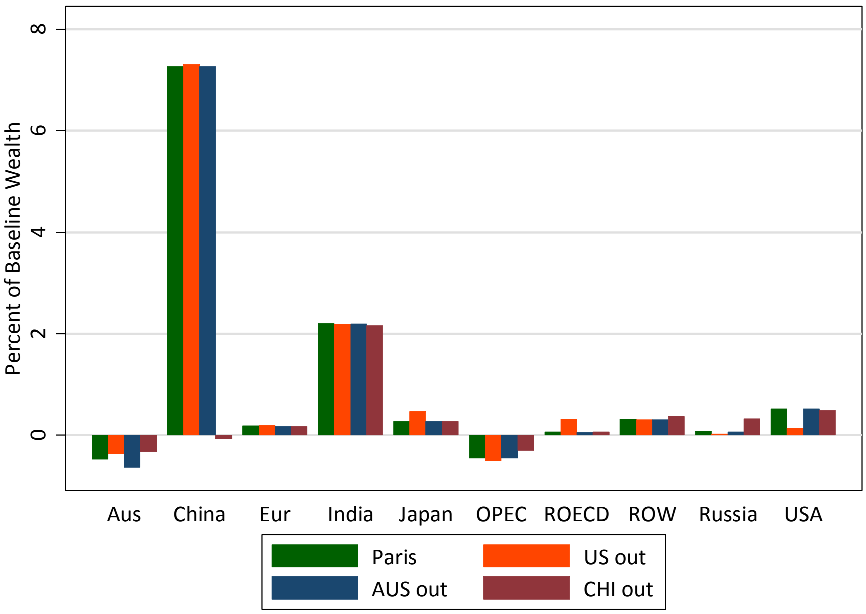
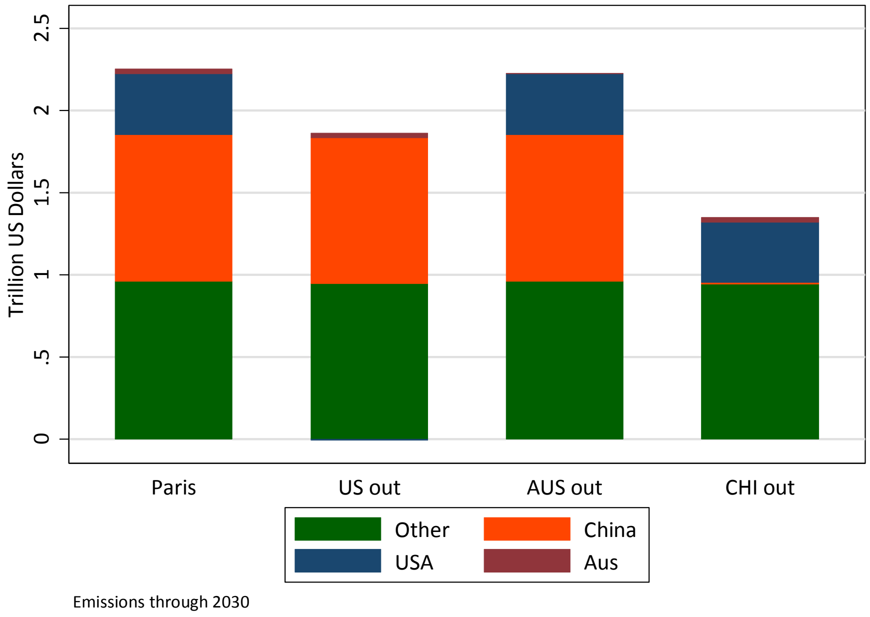


Figure 25 shows the present value of CO_2 benefits for the world under each policy scenario. The figure sums the benefits of emissions abatement through 2030 relative to the no-policy baseline. Under the Paris Agreement the present value of environmental benefits globally is around $US 2.25 trillion. The largest environmental gains come from the participation of China and the rest of the world (the green bars labeled "Other"). The unilateral withdrawal of the United States has a more significant environmental cost to the world than the economic gains to the United States of withdrawing. More importantly, the gain in GDP for the United States from withdrawal is smaller than the environmental benefits foregone by withdrawing.

Figure 25. Total PV of CO_2 Benefits through 2030 by Policy Scenario



6. CONCLUSION

This study explores the global economic and environmental implications of the NDCs that form the basis of the Paris Agreement on climate change. Although many scientists argue that the targets in the Paris Agreement are not sufficient to reach the stated goal of limiting global warming to 2°C, we find that the targets in the NDCs have significant implications for global outcomes and for individual regions. In particular, we find that the differential targets across regions correspond to very different levels of impact, whether measured by the emissions taxes required, or the effects on GDP and welfare that result.

In addition, we observe that co-benefits from reductions in conventional pollutants are sufficiently large that even without accounting for reductions in climate change, every region receives a net benefit from participating in the agreement. Second, we note that the globe's two largest CO_2 emitters, China and the United States, are both better off participating in the agreement than withdrawing from it; in both countries, the equivalent variation of participating is larger than that of withdrawing. Finally, we end by observing that the climate benefits produced by the Paris Agreement are very large even though it does not stabilize emissions. Assuming the social value of a metric ton of CO_2 abated is $42 US, the global climate benefit of the Paris Agreement through 2030 is $2.25 trillion in present value.

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APPENDIX: NDC AGGREGATION FOR G-CUBED

Table 2 contains the targets calculated for each region in the G-Cubed model. The targets for OPEC and ROW depend on the G-Cubed baseline because most of OPEC countries and some of ROW countries set their NDCs relative to 2030 BAU and thus we assume the G-Cubed baseline as their BAU emissions (see more details below).

We calculate the NDC targets by making a number of assumptions. We start with the NDCs each country submitted to the UNFCCC. For each NDC,

(1) We assume that all countries targeting GHGs will reduce their energy-related CO_2 proportionally to the overall scope of emissions pertinent to their targets. We do not adjust for expected changes in other GHG sources and gases, so our estimated targets may be more or less stringent than they will be in practice owing to baseline trends in non-energy sectors.
(2) We source all emissions data over the period from 1990 to 2015 from the U.S. Energy Information Administration.
(3) We target the unconditional NDCs or the least ambitious target in a range of proposed targets. If any country does not have an unconditional NDC, we assume the conditional NDC as the target.

For individual countries in the G-Cubed model, Table 3 in the text reports the NDC we calculate. Estimated targets for Australia, Japan, and the United States require only the above three assumptions. Other countries and regions involve more complicated or subjective analysis.

(1) Russia expresses its NDC target relative to 1990, but Russian emissions data starts from 1992, so we substitute its 1992 data for 1990.
(2) China has a target in terms of emissions intensity of GDP, and we calculate its emissions target as follows:
    (a) China aims to double its real GDP by 2020 from 2010, and the National Energy Administration of China assumes for energy consumption forecasting that Chinese GDP will grow at 5.5% each year from 2021 to 2030.
    (b) China targets to reduce its carbon intensity by 60% by 2030 relative to 2005.
    (c) Given China's GDP and total CO_2 emissions in 2005, we calculate China's emissions intensity in 2005 and then the target emissions intensity in 2030.
    (d) Given China's GDP target, we calculate the implied emissions target in 2030.
(3) India also has a target in terms of emissions intensity of GDP, but we don't have official forecasts for GDP, so we solve in the G-Cubed model for the CO_2 tax rates required to

achieve the targeted emissions intensity in 2030 and obtain the projected emissions level in 2030.

(4) Europe consists of all countries in the European Union, and Norway and Switzerland. The European Union submits its NDC target as a whole. We calculate its emissions target as follows:
   (a) For eight countries without emissions data in the reference year (1990) including Croatia, Estonia, Germany, Latvia, Lithuania, Slovakia, Slovenia and Switzerland, we use their earliest data for their 1990 emissions. As the earliest data for those countries are available in either 1991, 1992 or 1993, so this approximation would not have much bias.
   (b) We calculate the emissions target for the European Union, Norway and Switzerland respectively, and add them up to get the target for the region.

(5) ROECD consists of three countries and each has a straightforward NDC target relative to a historical year, so we calculate the emissions target for each country and then add them up to get the target for the region.

(6) OPEC countries fall into two groups: one group has NDCs, and the other has no NDCs.
   (a) All countries with NDCs set their targets relative to 2030 BAU, so we use the G-Cubed baseline emissions as their BAU emissions.
   (b) We disaggregate the aggregate OPEC BAU emissions in 2030 across all countries based on their emissions shares in 2015.
   (c) We calculate each country's target given their BAU emissions in 2030, and keep unchanged the emissions of those countries without NDCs, and then added them up.

(7) ROW consists of all countries that are not included in the above regions, and its target calculation is complicated.
   (a) We first categorize all ROW countries into three groups:
      - Type 1 - Countries that set their NDCs relative to 2030 BAU;
      - Type 2 - Countries that set their NDCs in levels relative to historic years;
      - Type 3 - Countries that set their NDCs in terms of emissions intensity of GDP relative to historic years;
      - Type 4 - Countries without NDCs.
   (b) We use actual emissions in 2015 to calculate the share of each above group in total ROW emissions.
   (c) We disaggregate the total 2030 emissions of ROW in the G-Cubed baseline for the four groups based on their shares in 2015.
   (d) For Type 1 countries, we calculate their targets based on their 2030 BAU emissions.
   (e) For Type 2 countries, we calculate their targets given the historical data,
   (f) For Type 3 countries (Chile, Malaysia and Singapore), we have different treatments. We directly obtain an estimate of emissions for Chile from Climate Action Tracker. For Malaysia, we assume a constant growth rate of GDP (4%) over the period from 2016-2030 based on its recently historical growth rates, to give an estimate for GDP in 2030,

and then calculate emissions given the intensity target. We exclude Singapore from ROW because its official emissions data is not consistent with the EIA data.

(g) For Type 4 countries, we assume the BAU emissions to be their target emissions.

(h) We add up emissions targets of the four types of countries to get the target for the region.

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The role of border carbon adjustments in a US carbon tax

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Abstract

This paper examines carbon tax design options in the United States using an intertemporal computable general equilibrium model of the world economy called G-Cubed. Four policy scenarios explore two overarching issues: (1) the effects of a carbon tax under alternative assumptions about the use of the resulting revenue, and (2) the effects of a system of import charges on carbon-intensive goods ("border carbon adjustments").

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THE ROLE OF BORDER CARBON ADJUSTMENTS IN A U.S. CARBON TAX

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EXECUTIVE SUMMARY

This paper examines carbon tax design options in the United States using an intertemporal computable general equilibrium model of the world economy called G-Cubed. Four policy scenarios explore two overarching issues: (1) the effects of a carbon tax under alternative assumptions about the use of the resulting revenue, and (2) the effects of a system of import charges on carbon-intensive goods ("border carbon adjustments").

We first establish a baseline scenario in which the United States does not adopt a climate policy other than policies in place in early 2017. Then we model a simple excise tax on the carbon content of fossil fuels in the U.S. energy sector starting in 2020 at $27 per metric ton of carbon dioxide (CO_2) and rising at 5 percent above inflation each year through 2050. We investigate two approaches to using the revenue: one that rebates the revenue to households in annual lump sum transfers (LS below) and one that applies the revenue to reduce the marginal tax rate on capital income (KT below). For each revenue policy, we run scenarios with and without a border carbon adjustment (BCA) on imports. The BCAs vary by country and good and account for the carbon emitted throughout the full production chain of the good in the country where it is produced.

Consistent with earlier studies, we find that the carbon tax raises considerable revenue and reduces CO_2 emissions significantly relative to baseline, no matter how the revenue is used. Gross annual revenue from the carbon tax with lump sum rebating and no BCA begins at $110 billion in 2020 and rises gradually to $170 billion in 2040. By 2040, annual CO_2 emissions fall from 5.5 billion metric tons (BMT) under the baseline to 2.4 BMT, a decline of 3.1 BMT, or 57 percent. Cumulative emissions over 2020 to 2040 fall by 48 BMT.

Also consistent with earlier studies, we find that the carbon tax has very small overall impacts on GDP, wages, employment, and consumption. Different uses of the revenue from the carbon tax result in slightly different levels and compositions of GDP across consumption, investment and net exports. Overall, using carbon tax revenue to reduce the capital income tax rate results in better macroeconomic outcomes than using the revenue for lump sum transfers. Indeed, even while achieving remarkable emissions reductions, the policy results in the U.S. economy reaching the output projections in 2040 only about three months later than it would without the carbon tax. With the rebates, consumption rises in the short run and then returns close to baseline in the medium to longer run. Investment falls sharply in the short to medium run and recovers somewhat in the long run, but remains about one percentage point below baseline. In contrast, the capital tax reduction has little effect on consumption in the short run and causes investment to rise briefly relative to baseline before it settles within a half percentage point from baseline in the long run.

Counter to their purported purpose of protecting U.S. trade strength, for a given revenue policy, BCAs tend to produce lower net exports than the carbon taxes alone. This is generally because the BCAs result in higher value of the dollar relative to other currencies, thus lowering exports more than they lower imports. This is consistent with standard results in the international trade literature on the effects of import tariffs and export subsidies on real exchange rates, a result that is often ignored in the discussion of domestic carbon policy.

In a finding new to the literature, our results show that BCAs can have strikingly different effects depending on the use of the revenue. The BCAs in the lump sum rebate scenario result in slightly lower domestic output than the same scenario without the BCAs, thus doing more harm than good -- including in the relatively energy-intensive sectors like durable goods manufacturing. In contrast, BCAs tend to result in higher output than the carbon tax alone when the revenue is used to reduce other distortions in the economy.

1. INTRODUCTION

Two important design choices for a U.S. carbon tax policy are the use of the revenue and whether and how to include measures to address the competitiveness concerns of American businesses. Both of these policy design choices affect the political appeal and overall performance of the policy, and their effects can be interdependent. For example, a carbon tax that funds reductions in corporate income tax rates could make U.S. firms more competitive overall than they otherwise might have been. Using a model of the global economy, this paper explores the effect of an illustrative carbon tax on U.S. macroeconomic outcomes with special attention to these trade-related policy design options.

Because climate policies and effective carbon prices vary widely across countries, a unilateral carbon tax instituted in the United States could in principle promote the relocation of economic activity from the United States to regions with less ambitious climate policy, resulting in an offset to the environmental gains achieved by the United States. This is known as emissions leakage.[1] Unilateral carbon pricing would be particularly likely to lower output and employment in American energy-intensive trade-exposed (EITE) sectors by hurting their global competitiveness.

On the other hand, if the United States adopts a carbon tax that slows its economic growth, that in turn may lower growth in other countries and thereby reduce their carbon emissions relative to baseline. We call this phenomenon "negative leakage." So the question arises whether, where, and in which sectors emissions leakage is positive or negative, and what the overall effect would be on global emissions. To decompose the various forces that drive leakage, this study simulates a unilateral U.S. carbon tax with a computable general equilibrium model of the global economy called G-Cubed.

The second question we address here is the effect of measures that could counteract the potential for positive leakage and ameliorate the concerns of domestic EITE industries.[2] A number of options appear in the literature, each of which comes with important tradeoffs,[3]

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[1] Here we refer to the leakage that occurs through shifts in emissions-intensive industry locations. Price-based leakage occurs when fossil fuel consumption in countries without carbon constraints increases as a result of a decrease in demand and prices of traded fossil fuels. This leakage channel cannot be addressed by a border carbon adjustment or similar policy.

[2] Fischer and Fox, 2012a; Condon and Ignaciuk, 2013.

[3] For a succinct summary of these pros and cons, see Fischer et al. (2015)

design challenges,[4] and questions of consistency with current World Trade Organization (WTO) law.[5] For example, policymakers could partially or fully exempt EITE sectors from the carbon tax or give rebates to EITE firms based on their output levels. Arguably the most prominent option is a border carbon adjustment (BCA). The carbon tax itself would apply to the carbon content of imported fossil fuels, whereas a BCA would apply to goods other than fossil fuels. In practice, a BCA would apply to goods imported from countries that do not price carbon at a level at least as high as the carbon price in the United States.[6] In principle, this would help ensure that the U.S. carbon tax does not disadvantage emission-intensive goods produced in the United States relative to emission-intensive goods produced in foreign countries without a similar climate policy.

A BCA on imports (which we model here) could vary by country and good, based on the average carbon intensity of production. For example, if the carbon tax in the United States is \$30 per metric ton of CO_2, and steel produced in Country X involves emissions of five metric tons of CO_2 per unit in its supply chain, the BCA would impose a charge of \$150 for every unit of steel the United States imports from Country X. The idea is that this charge would prevent unfair competition to steelmakers in the United States as a result of lower environmental standards abroad, and in principle such a charge could incentivize the exporting country to reduce its emissions. To be sure, a host of details arise, such as exactly how to calculate CO_2 emissions for steel in Country X (for example by firm, region, production process, or using an industry average), how to differentiate across different kinds of steel, and whether and how to account for differences between County X's policies and those of the United States.

An export BCA would rebate the carbon tax liability producers incur in making goods they export from the United States. This would help U.S. exports of emission-intensive goods remain competitive in countries without similarly-stringent climate policies. Analysts generally agree that a BCA on imports would likely satisfy the requirements for an environmental exception under WTO law as long as the adjustment is no greater than the domestic carbon tax. An export BCA may more difficult to justify in the case of a WTO dispute because its justification is trade competitiveness, not environmental protection.[7] We restrict our focus here to a border carbon adjustment on imports, and in our conclusions we speculate as to how our results might differ with a BCA on exports as well.

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[4] See, for example, Kortum and Wesibach (2016); CBO (2013); Sakai and Barrett (2016); Cosbey (2008); Branger and Quirion (2014); Böhringer et al. (2012)

[5] For a full discussion of WTO law constraints on BCAs and similar policies, see Trachtman (2016)

[6] A question arises about how a BCA should apply to goods from countries that apply a carbon price at a level below that of the United States, but at a rate above zero. We abstract from that in our modeling by assuming countries either have analogous policies or no climate policy.

[7] Trachtman (2016)

A number of studies have explored leakage and competitiveness and policy options to address them. For example, Böhringer et al. (2012) find that overall leakage rates in the range of 5 to 20 percent. McKibbin et al. (2012a), in contrast, find no evidence of energy-related emissions leakage.

The estimated magnitudes of the effects vary by industry as well, with EITE industries disproportionately affected (Fischer and Fox, 2012b). Aldy and Pizer (2009) estimate that vulnerable EITE industries with energy costs that exceed ten percent of shipment value would expect at most a one percent shift in production overseas.

A large literature demonstrates how carbon taxes can both lower emissions and raise a substantial amount of revenue (CBO, 2011; McKibbin et al., 2012b; Rausch and Reilly, 2015). Previous literature finds that the macroeconomic impact of a carbon tax depends significantly on the use of revenue. If the revenue is used to fund reductions in other distortionary taxes, the tax reductions can offset the macroeconomic drag of the carbon tax (i.e., a weak double dividend).[8] Generally, research shows that using the revenue to reduce the marginal rates of distortionary taxes such as those on capital and labor income produces better aggregate welfare than using it for lump sum rebates, although the lump sum rebates can produce more progressive distributional outcomes.[9]

In this paper, we examine a simple excise tax on the carbon content of fossil fuels in the U.S. energy sector starting in 2020 at $27 per metric ton of carbon dioxide (CO_2) and rising at 5 percent above inflation each year through 2050 and remaining constant thereafter. The tax revenue either returns to households in rebates or funds reductions in the marginal tax rate on capital income, and we model both approaches with and without a BCA on imports. We do this using the G-Cubed model, a global intertemporal computable general equilibrium (CGE) model, which allows us to explore the possible effects of emissions control policies on: the U.S. macroeconomy; individual industrial sectors within the United States; and other outcomes, such as trade flows, currency values, emissions levels, and economic activity.

Our baseline and policy scenarios do not account for the economic damages that would result from a disrupted climate. These unaccounted-for damages and the benefits of emissions mitigation are likely to be particularly important in the later years of our modeling time horizon. Since our analytical approach does not quantify the economic effects of climate change, this study does not elucidate the potential net benefits of a carbon tax. Indeed, the benefits of

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[8] Goulder, 1995; Jorgenson et al., 2013

[9] McKibbin et al 2015; Tuladhar et al., 2015; Jorgenson et al., 2015; Elmendorf, 2009.

avoided damages may be well in excess of the costs we report for emissions control. Rather, our focus here is on the relative economic outcomes of the different policy designs with equivalent environmental outcomes, consistent with the very similar cumulative emissions in our policy scenarios.

The paper is structured as follows. Section 2 describes the model, the baseline (no policy) scenario, and four policy scenarios. Section 3 reviews the results. Section 4 concludes.

2. MODELING APPROACH AND SCENARIOS

In this section we present a brief overview of the G-Cubed model and its features that are most relevant for our analysis. An extended technical discussion of G-Cubed appears in McKibbin and Wilcoxen (2013) and a more detailed description of the theory behind the model can be found in McKibbin and Wilcoxen (1999).[10]

The version of G-Cubed we use in this study includes the nine geographical regions listed in Table 1 below. The United States, Japan, Australia, and China are each represented by a separately modeled region. The model aggregates the rest of the world into five composite regions: Western Europe, the rest of the OECD (not including Mexico and Korea); Eastern Europe and the former Soviet Union; OPEC oil exporting economies; and all other developing countries.

Table 1: Regions in the G-Cubed Model

Region Code	Region Description
US	United States
Japan	Japan
Aus	Australia
Eur	Western Europe
ROECD	Rest of the OECD, i.e. Canada and New Zealand
China	China
EEFSU	Eastern Europe and the former Soviet Union
LDC	Other Developing Countries
OPEC	Oil Exporting Developing Countries

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[10] The type of CGE model represented by G-Cubed, with macroeconomic dynamics and various nominal rigidities, is closely related to the dynamic stochastic general equilibrium models that appear in the macroeconomic and central banking literatures.

The full list of sectors in the model is shown in Table 2. The "code" column provides short names for the sectors that will appear in tables and graphs of results. G-Cubed's electricity sector includes specific technologies: coal, natural gas, oil, nuclear, wind, solar, hydro and other (largely biomass and other renewables). A technical discussion of modeling improvements to the electricity sector appears in McKibbin et al. (2015).

Table 2: Sectors in the G-Cubed Model

Num	Sector Name	Code	Notes
1	Electricity delivery	ElecU	Primary Energy
2	Gas utilities	GasU	
3	Petroleum refining	Ref	
4	Coal mining	CoalEx	
5	Crude oil extraction	CrOil	
6	Natural gas extraction	GasEx	
7	Other mining	Mine	Nonenergy Traded Goods
8	Agriculture and forestry	Ag	
9	Durable goods	Dur	
10	Nondurables	NonD	
11	Transportation	Trans	
12	Services	Serv	
13	Coal generation	Coa	Electricity Generation
14	Natural gas generation	Gas	
15	Petroleum generation	Oil	
16	Nuclear generation	Nuc	
17	Wind generation	Win	
18	Solar generation	Sun	
19	Hydroelectric generation	Hyd	
20	Other generation	Oth	

The Baseline Scenario

The model's projections of future emissions and economic activity in the absence of new climate policy is our business-as-usual (baseline) scenario. A detailed discussion of the baseline construction process for G-Cubed appears in McKibbin, Pearce and Stegman (2009). The baseline in this study is broadly consistent with the emissions and GDP growth in the Energy Information Administration's *Annual Energy Outlook Early Release*, No Clean Power Plan case from May 2016.[11] However, our projected productivity growth rates cause the model's baseline to be slightly higher for both variables. We assume that annual federal deficits will start to be reined in when the Federal debt reaches 100 percent of GDP. Accordingly, we impose lump sum taxes annually such that ratio of debt to GDP is no higher than one.

Along with the baseline for the United States, we construct a baseline scenario for the other regions in the world that reflects our best estimate of the likely evolution of each region's economy without concerted climate policy measures beyond those announced by the end of 2015. To generate this scenario, we begin by calibrating the model to reproduce approximately the relationship between economic growth and emissions growth in the United States and other regions over the past decade and then impose carbon policies that were already implemented as of mid-2016. In the baseline, neither the United States nor other countries adopt climate policies that are any more restrictive than is reflected in existing policies.

The greenhouse gas emissions included in G-Cubed comprise only CO_2 from energy-related fossil fuel consumption, including combustion of coal, natural gas, and oil. Figure 1 shows the model's projections from 2015 to 2040 for global CO_2 emissions from energy use across four major regions: China, the United States, Europe, and the rest of the world (ROW). These projections do not include countries' Nationally Determined Contribution pledges in the 2015 Paris Agreement.[12]

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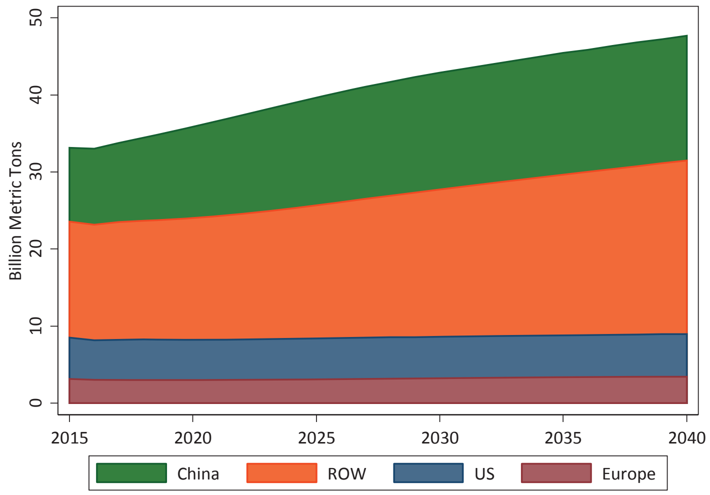
[11] The report appears at the DOE's Energy Information Administration website: https://www.eia.gov/forecasts/aeo/er/

[12] In December 2015, the Parties to the United Nations Framework Convention on Climate Change met in Paris. They struck an agreement in which 195 countries made climate-related pledges. The agreement went to force in March 2017, having been ratified by 141 nations. http://www.un.org/apps/news/story.asp?NewsID=56477#.WScXEE0zWgz

Figure 1: Global Baseline Carbon Dioxide Emissions



The Policy Scenarios

In this study, we examine an illustrative carbon tax imposed in the United States but not in other countries. The tax applies economy-wide to all sources of CO_2 emissions from fossil energy use. To the extent that trade and investment may be distorted by climate policy, those outcomes are most likely to be apparent in such a unilateral context. Thus, in our scenarios without border measures, we are likely estimating the upper bound on competitiveness effects.

As shown in Figure 2,[13] we impose the tax beginning in 2020, starting at $27 per metric ton of CO_2, and we increase the tax rate annually by 5 percent over inflation. By 2040, the final year we report for our simulations in this paper, the tax is $72 per metric ton. In years after 2050, which are relevant for agents in the model with forward-looking expectations, we hold the carbon tax rate constant at its 2050 level of $117. We assume the carbon tax is anticipated, not a surprise.

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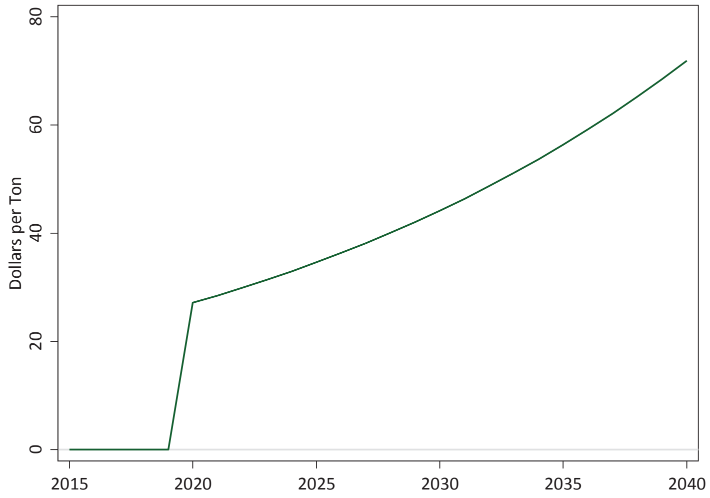
[13] Unless otherwise indicated, all dollar values are in 2015 dollars.

Figure 2: U.S. Tax Rate on Carbon Dioxide



We model two different assumptions about how the carbon tax revenue is used. The first, denoted LS in figures and tables, assumes the revenue is returned to households each year as a lump sum rebate. The second, denoted KT, applies the revenue to reduce the marginal tax rate on capital income. In both cases the revenue is processed such that total government spending is constant relative to baseline.

In the lump sum rebate scenarios, general equilibrium effects of the carbon tax lower the revenue from other taxes, so the total rebates in each year are a little smaller than the gross receipts of the carbon tax. In the tax swap scenarios, we calculate the change in the capital income tax rate (in percentage points) achievable in each period, using the recycled revenue to hold the deficit constant relative to baseline.

We also run a variation on each policy that imposes import BCAs in proportion to the carbon content of non-fuel imported goods (denoted LS bca and KT bca). We exempt European goods from the BCA on the grounds that European carbon policies are very roughly comparable to the tax being imposed in the US.

A BCA is a unit tax, meaning for each unit it is the carbon emissions associated with the production of a unit of the good times the relevant carbon tax rate. The BCA does not depend on the market value of the good, so it is not, strictly speaking, a tariff, but as we shall see it produces some of the same effects as a tariff might. The appendix explains how we calculate the emission intensity of each good and compute the revenue associated with the BCA. We add the revenue from the border adjustments to the direct revenue stemming from the carbon tax policy and use it in the same way, either incorporated in the lump sum rebate or as part of the revenue recycled via a reduction in the capital tax rate.

We stress that there are considerable uncertainties involved in how a BCA would play in out practice. The carbon intensity of imports from different countries could evolve very differently from what we assume here if market conditions change or the countries adopt new policies. For example, the volume of trade from each region to the United States is very uncertain as it depends on overall economic growth, the evolution of comparative advantages in each country, terms of trade, and a host of other factors. In addition, other countries may respond to the U.S. BCA in a variety of ways, including by obviating the U.S. BCA by taxing the carbon content of their exports. In addition, U.S. authorities may be required by trade law to allow individual firms to petition for a lower BCA if they can prove their production is lower in carbon than the national average.[14] Thus we offer these scenarios as illustrative of one possible future rather than an actual forecast. Our focus is primarily on the contrast between different policy options, particularly on how the impact of a BCA varies with how the revenue is used.

Table 3 below summarizes the key features of the five scenarios.

Table 3: Summary of Baseline and Policy Scenarios

Scenario	**Carbon Tax**	**Lump Sum Rebate**	**Capital Tax Reduction**	**Border Adjustment**
Baseline	No	No	No	No
LS	Yes	Yes	No	No
KT	Yes	No	Yes	No
LS bca	Yes	Yes	No	Yes
KT bca	Yes	No	Yes	Yes

The comparative general equilibrium effects of these scenarios are of particular interest. For example, the tax swap scenarios (KT and KT bca) use the carbon tax revenue to reduce other distortions in the economy. This raises the question of whether the net effect of these fiscal reforms on employment, consumption, and GDP will be positive or negative.

Because a carbon tax policy can change wages and thus change the burden of government, as noted above we hold government total real spending on *everything* (including interest payments) to baseline levels. We also hold the federal deficit unchanged relative to baseline levels. Together, these restrictions determine the overall level of government revenue required. After accounting for the revenue raised by the carbon tax, by the BCA if applicable, and by other taxes (such as from labor income), we adjust the lump sum rebate or the capital tax rate as

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[14] Cosbey (2008), pp. 24-26.

needed to achieve the target level of revenue. This approach is imposed for analytical clarity and is not necessarily a practical way to implement a carbon tax.

3. RESULTS

As shown in Figure 3, the carbon tax would have an immediate and substantial impact on U.S. carbon dioxide emissions no matter the details of the tax policy. Under the lump sum policy (LS) emissions fall relative to baseline by 1.14 BMT when the tax is imposed in 2020 and are 3.17 BMT lower by 2040. Emissions fall slightly less under the capital tax reduction (KT): 1.08 BMT in 2020 and 3.07 BMT in 2040. The addition of border adjustments (LS bca and KT bca) has almost no impact on domestic emissions. By 2040, cumulative reductions under all four of the policies are very close to each other: the results range from a low of 45 BMT under KT bca to a high of 48 BMT under LS bca.

Figure 3: Level of U.S. Emissions of CO_2 in Billion Metric Tons

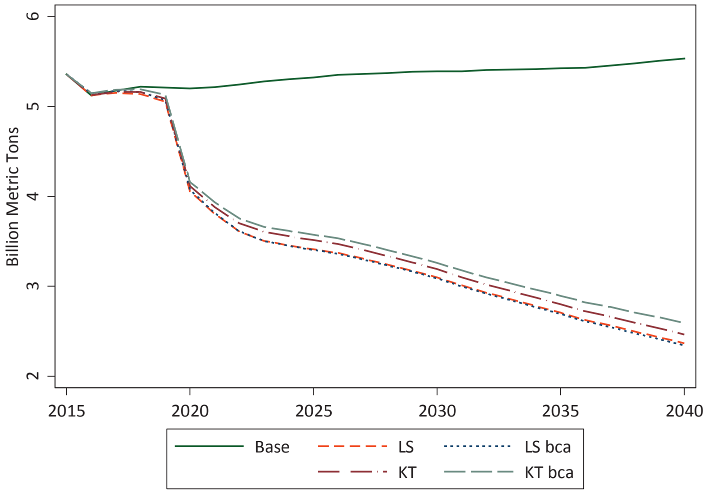


Figure 4 shows the impact of each policy as a percent reduction in baseline emissions. The initial impact in 2020 is a drop of about 20 to 21 percent and by 2040 the reduction is around 53 to 57 percent depending on the policy.

Figure 4: Changes in U.S. CO_2 Emissions Relative to Baseline

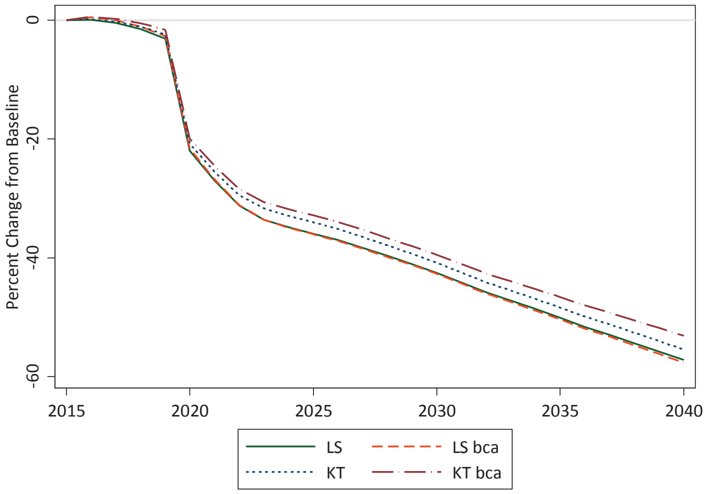
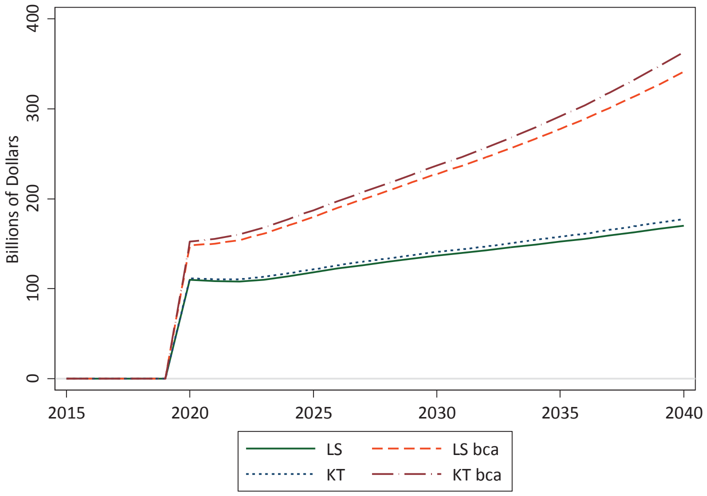


Figure 5 shows the gross receipts of the carbon tax and the BCA in each scenario. The tax policies without BCAs generate roughly $110 billion in the first year and rises to $170-$177 billion by 2040. The carbon tax policies with BCAs bring in substantially more revenue, starting at about $150 billion in 2020 and more than doubling to about $350 billion in 2040. Revenue is slightly higher under the capital tax cases since emissions don't fall quite as much.

Figure 5: Gross Revenue in Billions of $2015 Dollars



To put these figures in perspective, the revenues are shown as a percent of baseline GDP in Figure 6. In 2020, the carbon taxes without BCAs raise revenue equivalent to about 0.5 percent of GDP, which is roughly similar to the total for all U.S. federal excises taxes today.[15] Through 2040, the increase in the carbon tax rate approximately balances out the decline in emissions. Revenue from BCAs adds about 0.25 percent of GDP in 2020 and grows to about 0.6 percent of GDP by 2040.

Figure 6: Gross Revenue as a Percent of Baseline GDP

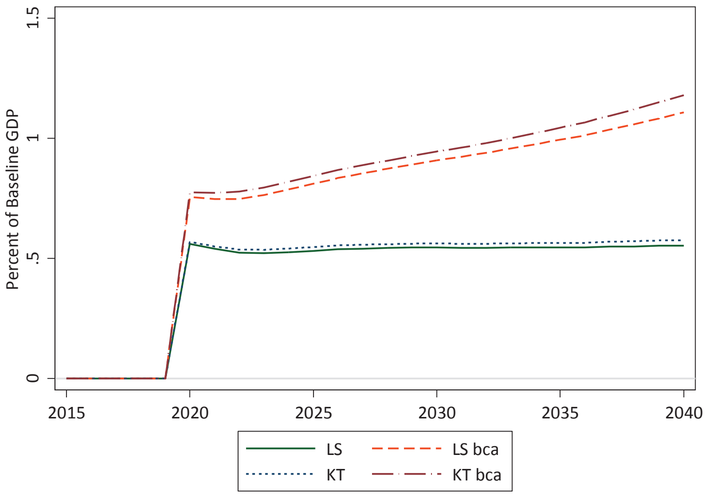


Figure 7 below displays the composition of the border carbon adjustments by the regions from which goods are imported into the United States. The preponderance of the BCA revenue comes from China and LDCs, reflecting both the carbon intensity and volume of trade with those regions. Revenue from BCAs on goods from LDCs rises relatively rapidly because our baseline assumes relatively little reduction in energy intensity in that region.

Figure 7: Border Carbon Revenue by Region of Origin

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[15] Peter G. Peterson Foundation, *Revenue*: http://www.pgpf.org/finding-solutions/understanding-the-budget/revenue

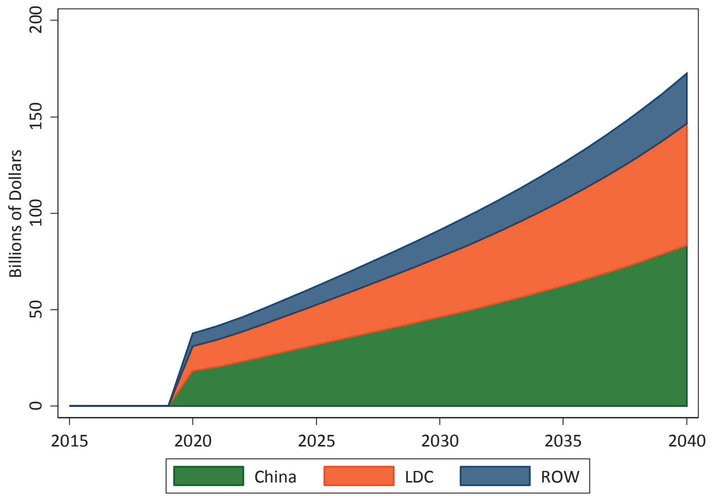


Figure 8 shows the border adjustments used in the LS bca and KT bca simulations. Each bar indicates the border adjustment for a particular good category from a particular country of origin in cents per model unit in 2035. The model's prices are normalized to one in 2015, so roughly speaking the adjustments range from about 1 to 8 cents. Figure 8 shows the adjustments grouped first by country and then by good, while Figure 9 shows them grouped by good and then country. As noted above, border adjustments are only applied on the six non-fuel goods (sectors 7-12 in Table 2). Europe does not appear in either figure because no border adjustments are applied against it. In general, the border adjustments tend to be relatively higher from China, the rest of the OECD, and Eastern Europe and the former Soviet Union, reflecting their relatively high 2035 projected carbon intensity. For reference, the U.S. carbon tax is approximately $56 per ton of carbon dioxide in 2035. At that rate, a border adjustment of 8 cents, such as that on durables from China, indicates that there is approximately 1.4 kg of carbon dioxide per dollar of imports.

Figure 8: Border Carbon Adjustments in 2035

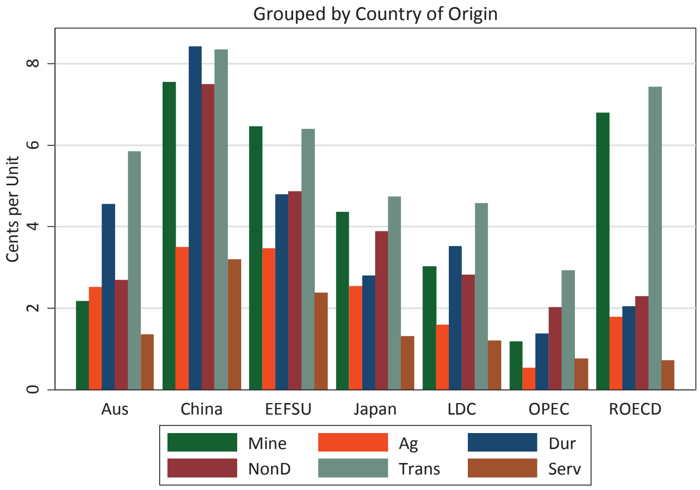
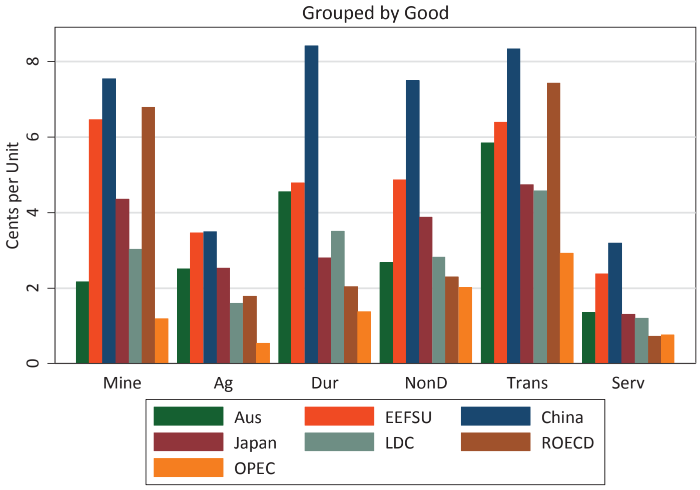


Figure 9: Border Carbon Adjustments in 2035



Before we turn to the macroeconomic outcomes of the different policy scenarios, it is worth noting the fiscal effects of the revenue uses. Figure 10 shows the trajectory of the tax rate on capital income in the KT and KTb scenarios. In the baseline, the tax rate stays constant at 6.47 percent.[16] In the KT scenario, the capital income tax rate falls by roughly two percentage points in 2020 and remains close to that through 2040. In the KT bca case, the BCA revenue allows an additional one percentage point drop in the capital income tax rate at the outset of the policy,

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[16] The model has a single tax on capital. In the baseline it is set to the overall average rate of taxation on capital income in the economy. As a result, it is considerably lower than the statutory corporate tax rate.

and by 2040 the capital income tax rate is down to a little less than one percent, a 5.6 percentage point drop from its baseline level.

Figure 10: Capital Income Tax Rate

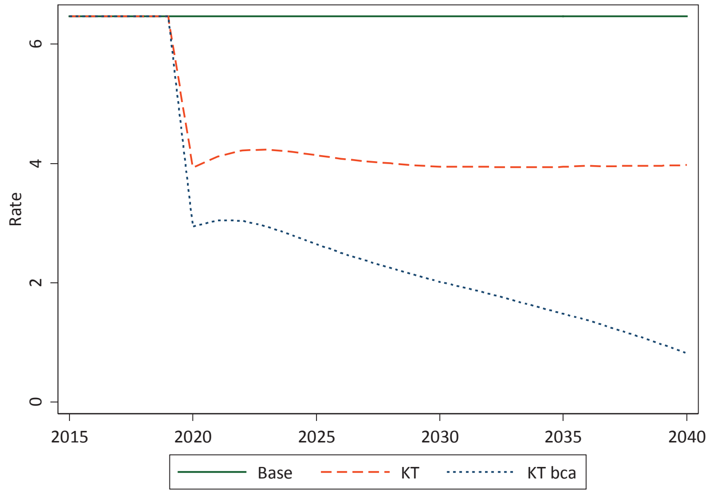
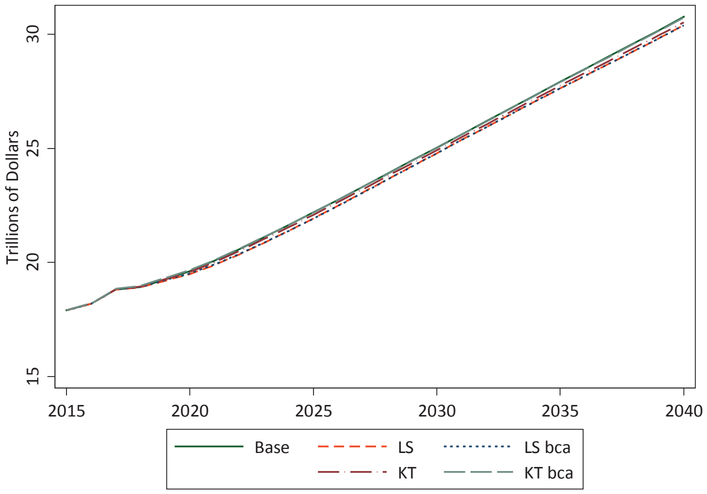


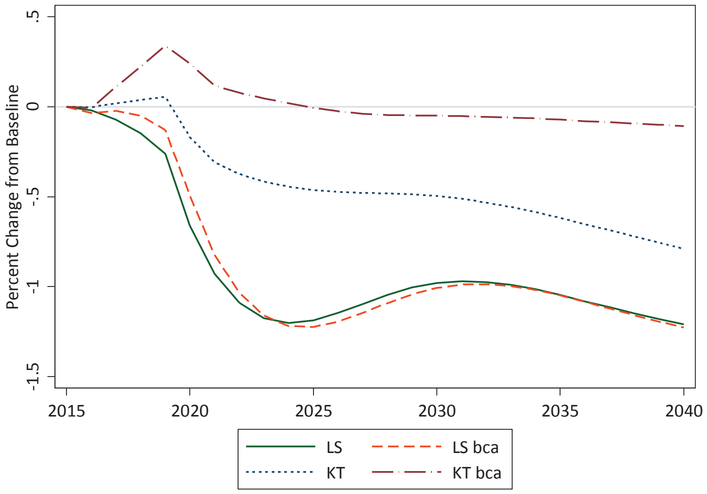
Figure 11 shows levels of real U.S. GDP for all the scenarios. We see that none of the carbon tax policies cause GDP to fall in absolute terms; rather, they cause a very slight slowing in GDP growth. Indeed, generally the United States achieves the same level of GDP in the policy scenarios only a few months after it does in the no-policy baseline. We emphasize this point here, because in other figures below we report changes *relative to baseline*. While the differences may look dramatic, a careful reading of the vertical axes indicates that many policy effects are less than a percentage point or two of those same outcomes in the baseline case. Recall as well that we are not accounting for the potential economic benefits of the climatic damages avoided.

Figure 11: Real U.S. GDP (Level)



The impact of each policy on U.S. real GDP in percentage terms relative to baseline is shown in Figure 12. Under both LS and LS bca, GDP falls slightly during the period preceding imposition of the tax in 2020 while under both KT policies it rises slightly. Once the tax is in place, under the rebate policies, GDP falls by about 1.2 percent of its baseline value by 2025 and remains roughly at that level. The BCA makes little difference. Under the capital income tax swaps, the long run impact of the climate policy is less negative, with GDP falling by only about 0.5 percent of its baseline by 2030 in the KT scenario and by about 0.1 percent in the same year with BCAs. This suggests that from a GDP standpoint, consistent with other modeling studies of carbon taxes in the United States, capital income tax swaps tend to be more pro-growth than lump sum rebates, and here we find that adding the BCA is even better. But again, we are talking about a difference of around a half of one percent of GDP, or a few months of GDP growth, after 20 years of the policy.

Figure 12: Changes in Real U.S. GDP ($2015)



The next few graphs show the components of GDP relative to their levels in the baseline. Figure 13 shows the impact of each policy on real consumption. All four policy variants cause an increase in consumption in anticipation of the tax, but the effect is far more pronounced in the LS scenarios. Once the tax is in place, consumption falls back toward its baseline trajectory and then falls below it.

The consumption results for the LS scenarios are driven by a couple of factors. In the LS scenarios, households experience an initial rise in cash income (Figure 14). This derives in part from a decline in investment (Figure 15) in those same scenarios during the period before the policy takes effect. Lower investment means lower retained earnings on the part of firms. Because investment falls earlier than revenues drop, dividends rise for a time and household cash income increases. Higher income and consumption in the LS and LS bca scenarios is also due to the increase in income to credit-constrained households from the lump sum transfer of the revenue from the carbon tax. The border tax generates additional revenue, which is also transferred to households in the LS and LS bca scenarios, reinforcing the early increase in income and consumption. The border adjustments primarily tend to amplify the effects of the LS revenue recycling policy.

Figure 13: Changes in Real U.S. Consumption

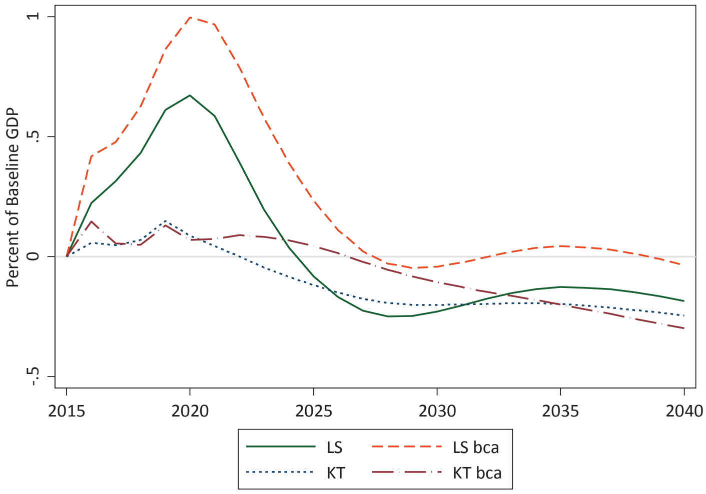
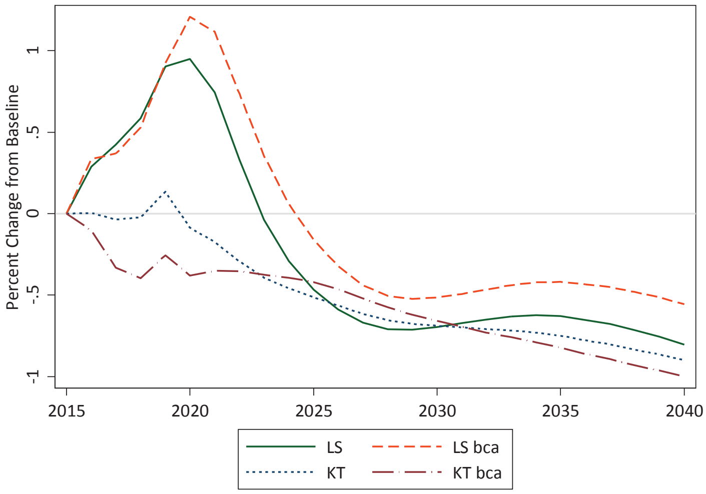


Figure 14: Changes in Real U.S. Household Income



The impact of the LS and KT policies on investment is sharply different from the results for income and consumption. As shown in Figure 15, the LS and LSb policies cause investment to fall during the anticipation period up to 2020 and then to continue falling immediately after that. By 2030, investment rebounds somewhat but is still about one percent of GDP below its baseline. Under KT and KT bca, however, investment rises during the anticipation period and then essentially tends to return to its baseline quickly after the tax is implemented. Investment rises because the revenue in KT and KT bca funds a reduction in the tax on capital income, and the KT bca funds a bigger one. This, together with the short term rise in GDP, provides an incentive for firms to increase their capital stocks in the short run, leading to a period of stronger investment. For all but the KT bca policy, over time, the overall slowdown in economic activity is reflected in a fall in investment relative to baseline but the KT policy produces more investment relative to the case where the revenue was given the households.

Figure 15: Changes in Real U.S. Investment

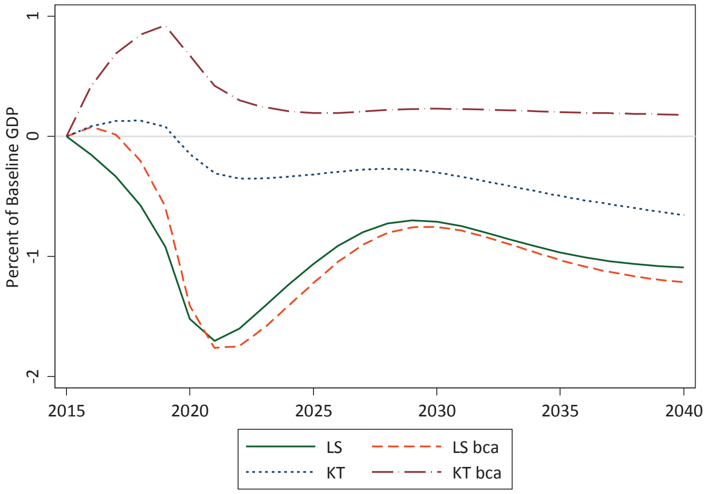


Figure 16 shows the effects of the policies on net exports. This is decomposed into aggregate exports in Figure 17 and aggregate imports in Figure 18. While the carbon tax has only a slight impact on net exports, the decomposition of this into exports and imports is interesting. The carbon tax makes U.S. goods less competitive in world markets because of higher energy costs. This reduces exports (Figure 17). It also slows the U.S. economy which reduces demand for imports. When an import BCA is imposed in the LS case, imports become more expensive, and the demand for imports falls further. As we will see in Figure 20, the BCA also leads to an appreciation of the U.S. dollar. This is a conventional result for an increase in tariffs in the international trade literature. A tariff generally causes an appreciation of a country's currency because it makes imports more expensive, lowering the demand for imports and thereby reducing the demand for foreign currency and causing the home currency to appreciate relative to the foreign currency. The appreciation of the U.S. dollar also makes U.S. goods more expensive in world market so the demand for U.S. exports falls. Thus although a BCA doesn't affect the net trade position much (Figure 16), the BCA reduces both imports and exports of U.S. goods. The sectoral composition of this result will be explored further below.

Figure 16: Changes in Real U.S. Net Exports

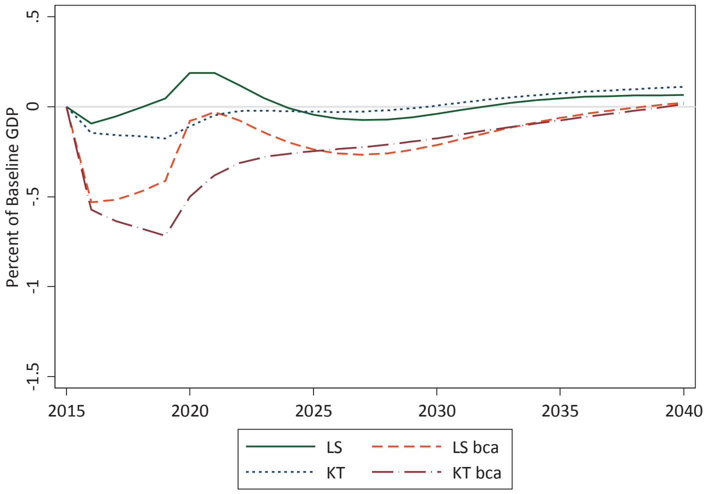


Figure 17: Changes in Real U.S. Exports

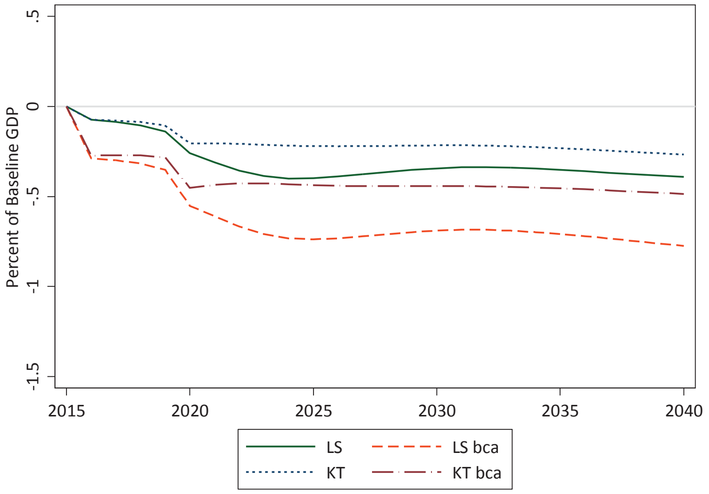
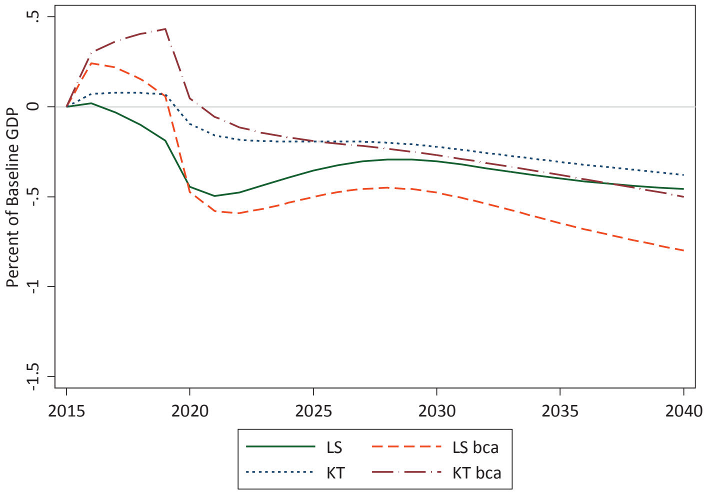


Figure 18: Changes in Real U.S. Imports



The changes in real interest rates and the real exchange rate appear in Figure 19 and Figure 20, respectively. The policies have little effect on U.S. interest rates. All four of the policies tend to appreciate the U.S. real exchange rate modestly right away, in anticipation of the policy, and then appreciate it further in the longer run. The appreciation reflects the assumption in the model that goods from different countries are imperfect substitutes. With a permanent fall in U.S. production, and the assumption that consumers demand goods from all countries, there is a rise in the relative price of U.S. goods in the global economy. To the extent that U.S. goods are more substitutable for goods from other countries, this effect will be smaller. The BCA reduces the relative price of U.S. goods in world markets which leads to a rise in demand for these goods and therefore in the demand for U.S. dollars to pay for them. Therefore, in equilibrium the U.S. real exchange rate has to appreciate further to clear the market. The LS policy causes a larger appreciation of the real exchange rate than the KT policy because the transfer raises household income, and therefore the demand for U.S. goods, which drives up prices. The KT policy, although also increasing demand for U.S. goods, increases the supply of U.S. goods over time through greater investment. Thus the price of U.S. goods relative to foreign goods (the real exchange rate) rises by more under the LS policy than the KT policy.

Figure 19: Levels of the Real U.S. Interest Rate

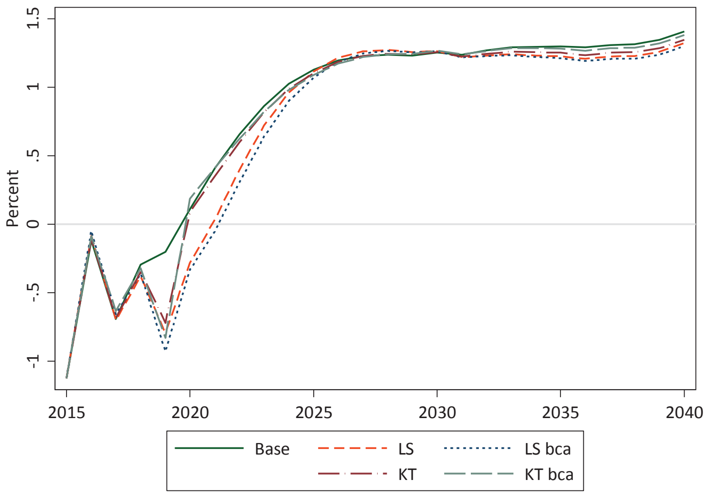
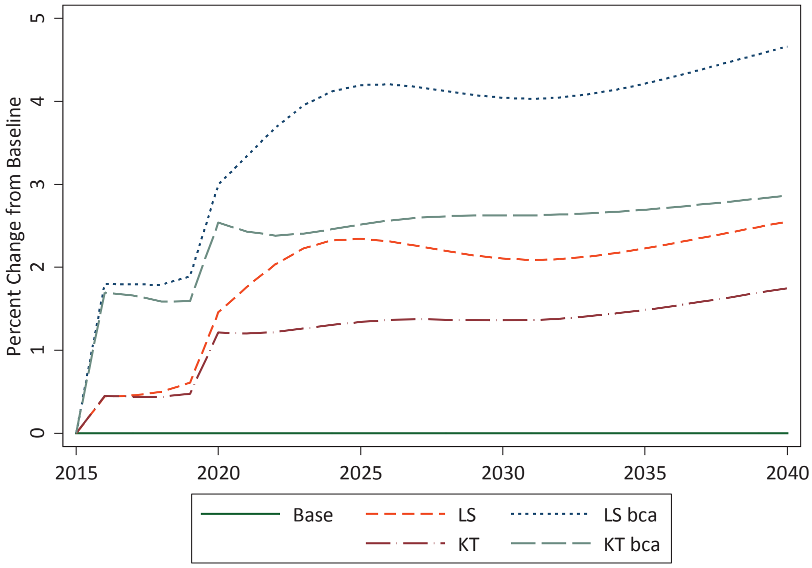


Figure 20: Changes in Real Effective Exchange Rate of U.S. Dollar



The effect of the two policies on real wages is shown in Figure 21. Real wages fall relative to the baseline (although the baseline itself is rising) under each carbon tax scenario except KT bca. The carbon tax reduces the marginal product of capital, which drives down real wages. We find that only in the KS case does the BCA protect U.S. workers from the effects of a carbon tax.

Figure 21: Changes in Real U.S. Wage

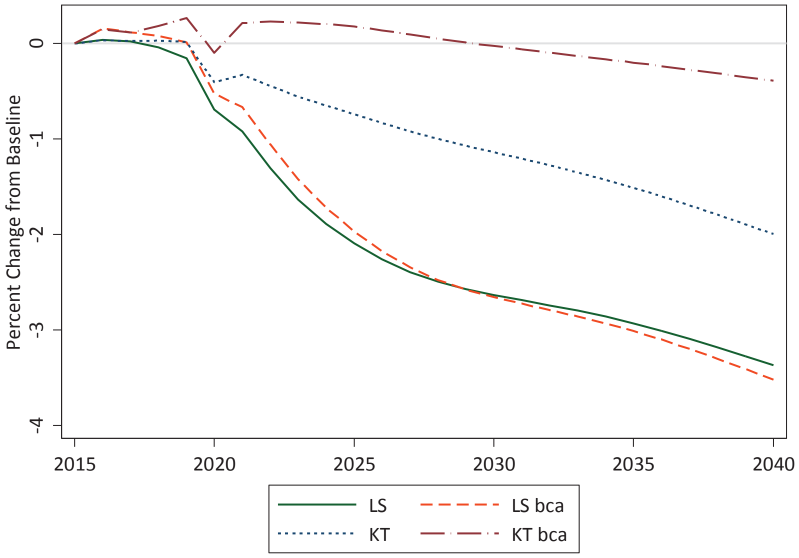
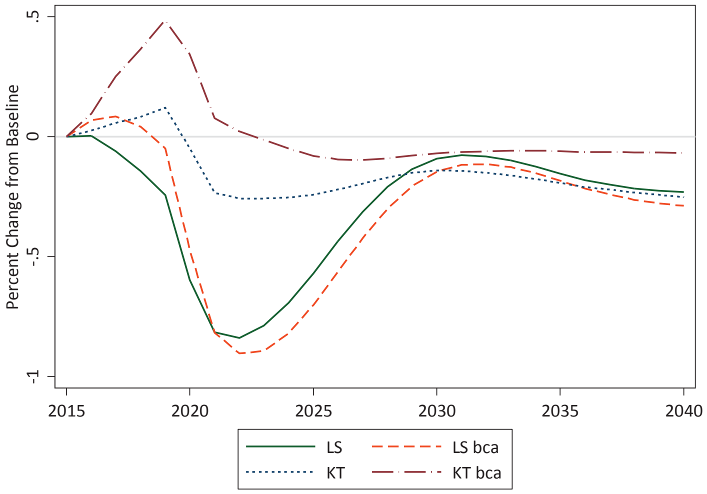


Figure 22 shows the impact on employment under each policy. Note that in the long run G-Cubed imposes the assumption that the economy eventually returns to full employment. This is achieved through an economy-wide adjustment in the real wage. In the short run, however, real wages are assumed to be slow to adjust and there can be an extended period of employment that is above or below its long term level as a result of a policy change. Figure 22 shows that the two LS policies reduce aggregate employment in the 5-7 years immediately following the introduction of the policy; it takes time for the structural adjustment to occur and for aggregate real wages to adjust enough for employers to soak up workers who have lost their jobs, especially in fossil fuel intensive industries. Adding the BCA to a lump sum rebated carbon tax very slightly exacerbates the overall loss in employment. In contrast, the employment impact is much smaller under the KT policy and employment actually rises in the short to medium term when the BCA is added.

Figure 22: Changes in Aggregate U.S. Employment



Results by sector

We will now turn to the sector-specific results behind the macroeconomic outcomes discussed above. Figure 23 shows the change relative to baseline in 2035 of producer prices for each non-energy sector (as shown in Table 2) under the policies. The graph shows the change in broad prices charged to all buyers of each non-fuel good. Not surprisingly, the extractive and direct energy sectors are hit hardest; the BCA makes little difference.

Figure 23: Changes in U.S. Producer Prices in 2035

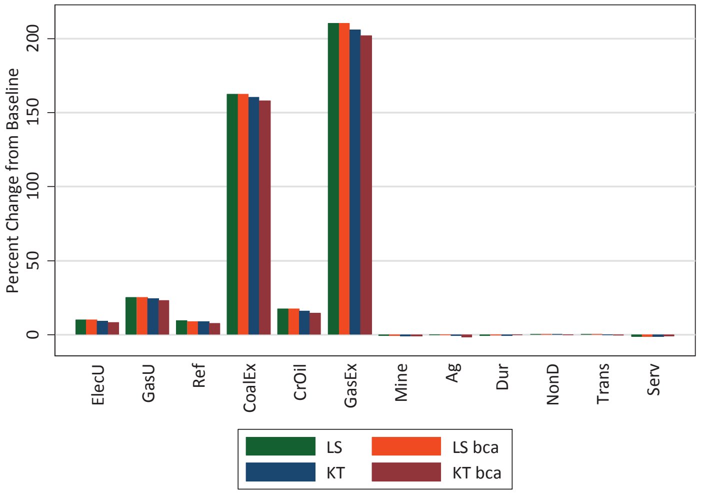
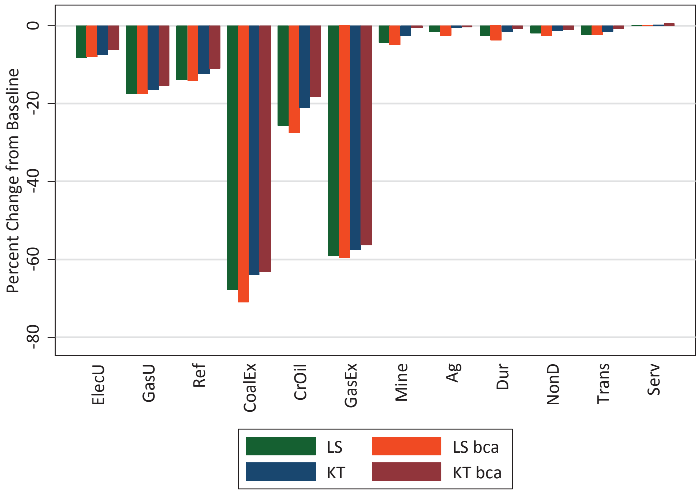


Figure 24 shows the impact of the carbon tax policies on output from the twelve core sectors in the model in 2035. Not surprisingly, the largest reductions in output arise in the coal sector, followed by the gas sector and then oil sector.

Figure 24: Changes in Output of Each Sector in 2035



Because the primary goal of this study is to examine the incremental effects of BCAs, in the next few figures we focus on the results for the non-energy sectors to which they apply. As is clear from the previous two figures, the carbon tax effects are much larger in percentage terms in the energy sectors, so showing all sectors on the same scale would make it hard to see the subtle impact of BCAs on the non-energy sectors. The detailed impacts of carbon taxes on energy sectors are explored in other papers using the G-Cubed model.[17]

To lay the groundwork for understanding the results of the carbon tax and BCAs on trade, we first consider the baseline composition of domestic output, imports, and exports in the United States in 2035, as shown in the next figure. The model projects that in 2035 imports and exports will be small relative to domestic output for nearly all sectors, with the important exceptions of durable goods manufacturing and, to a lesser extent, non-durable manufacturing. The figure also shows how significant the services sector is relative to everything else.

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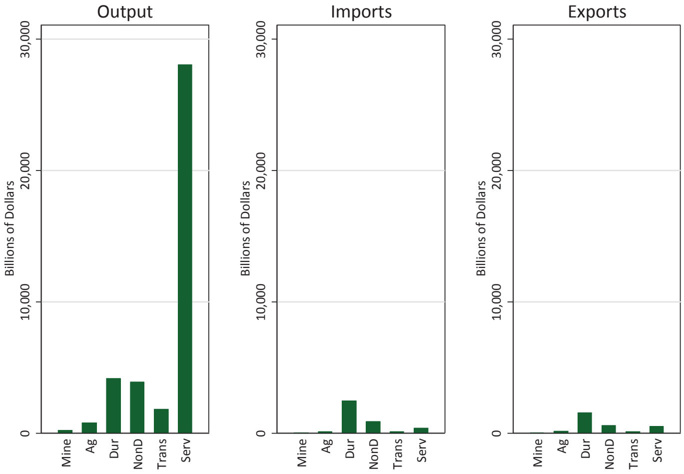
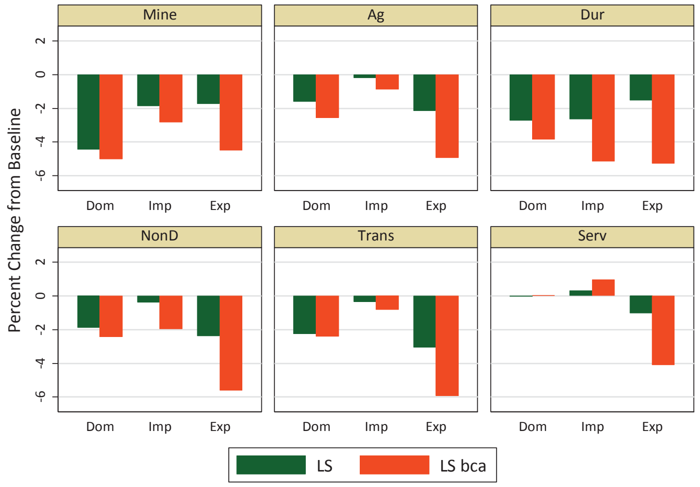
[17] See McKibbin and Wilcoxen (2013) and McKibbin, Morris, Wilcoxen and Cai (2015)

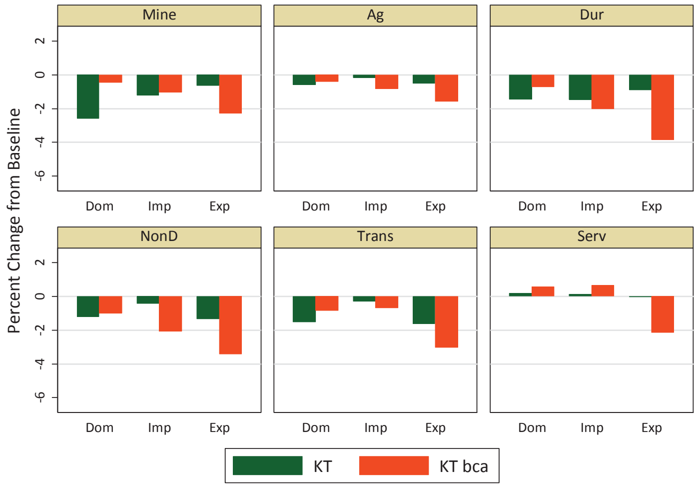
Figure 25: Baseline U.S. Output, Imports, and Exports for Non-Energy Sectors, 2035



Now consider the industry-specific effects in 2035 of the carbon tax on domestic output, imports, and exports for the six non-energy sectors. Figure 26 shows changes in these variables in 2035 relative to baseline. Bars labeled “Dom” show changes in domestic output. Bars labeled “Imp” and “Exp” are changes in imports and exports, respectively. To compare the relative impacts across sectors and scenarios, all of the figures appear on the same vertical scale in percentage point changes from baseline. The green bars show the results for the carbon tax policies without BCAs, and the orange bars show the results with the BCAs.

Figure 26: Changes in U.S. Domestic Output, Imports, and Exports in 2035 by Sector





Comparing domestic output across the results in Figure 26, we see that the carbon tax reduces output in all of the sectors except for services. The two most affected sectors are mining and durable manufacturing, where output declines up to four percent relative to baseline. In general, output falls significantly more in the LS scenario than the KT scenario. For example, the output decrease is about twice or more in the LS scenarios than the KT scenario for mining and agriculture. Stronger results under KT are consistent with the efficiency gains from the capital income tax swap.

We also see in Figure 26 that the BCAs have strikingly different effects in the LS and KT contexts. The BCAs in the LS scenario result in slightly lower domestic output than the LS scenario without the BCAs, thus doing more harm than good. In contrast, BCAs tend to result in higher output in the KT scenarios. For example, the decline in output for durables falls from about 1.5 percent to less than half that by imposing BCAs. This results in part from the role of the additional revenue from the BCAs in further reducing the tax rate on capital income, as shown in Figure 10.

Recall that Figure 18 showed no evidence of an economy-wide surge in imports upon the imposition of the carbon tax. Figure 26 shows that the same is true in all of individual sectors. Thus, at the level of the broad categories of economic activity in the model, we see no evidence of a broad competitiveness problem. Of course, trade in individual subsectors (that is, in narrower segments of the economy than the sectors in the model) may be far more sensitive.

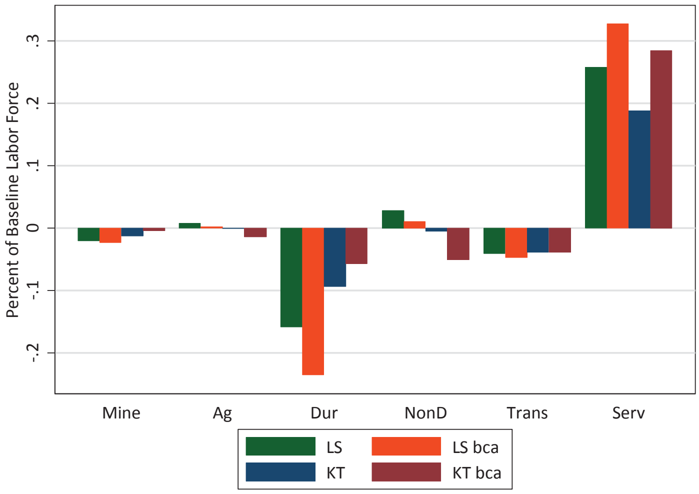
We saw in Figure 16 that overall net exports across the U.S. economy are lower than baseline in the carbon tax scenarios. Consistent with that, we see in Figure 26 that in most sectors in percentage terms exports fall by more than imports, particularly in the scenarios with the BCAs and particularly for the LS scenarios. Thus, if policymakers are concerned about net exports from the United States, it may be preferable to impose a carbon tax with no border adjustments than a carbon tax with BCAs only on imports.

Next consider the politically-important durable goods manufacturing sector in more detail. In the LS and KT scenarios, the carbon tax lowers domestic production by roughly the same proportion as it lowers imports. That means that to the extent that the carbon tax reduces the market for durables, it doesn't not disproportionately disadvantage domestic durables relative to imported durables. In both the LS and KT scenarios without BCAs, imports fall a little more than exports, but both fall more in the LS scenario. With BCAs, the capital income tax swap scenario reduces exports far more than imports, whereas with rebates the two percentage changes are about the same.

These outcomes are an amalgam of several competing factors, in addition to the shift in the relative costs of production in the United States and abroad that results from the carbon tax. First, as we saw in Figure 20, in general equilibrium the carbon tax induces a stronger U.S. dollar. That has a tendency to increase imports and lower exports. At the same time, in the LS scenarios the carbon tax drives overall economic activity in the United States, particularly investment (Figure 15), slightly below baseline, and that would tend to lower both imports and domestic output, all else equal. Finally, the carbon tax shifts the composition of goods and services produced and consumed in the U.S. economy, and that can affect domestic output and imports and exports. For example, the carbon tax shifts consumption towards relatively low-emissions-intensive services, which are disproportionately domestically produced. Overall, our results show that if policymakers want to minimize the impact on domestic output, it is more important to focus on choosing an efficient use of the revenue than on addressing trade competition.

Figure 27 shows how the domestic output effects in Figure 26 translate into employment in the United States in the six non-energy sectors. Each bar is the change in employment in 2035 as a share of *total* baseline employment in that year. Thus bars with the same height have represent the same number of workers, even though the sector sizes vary significantly. We see that overall, the U.S. labor market effects of all of the policies are modest, with no sector losing more than about one quarter of one percentage point of total baseline employment in 2035. The carbon tax produces the largest employment losses in the durable manufacturing sector, and that is the sector in which the BCAs do the most harm in the LS scenarios, resulting in about quadruple the employment loss relative to the capital income tax swap. The BCAs improve labor market outcomes in the service sector, however.

Figure 27: U.S Employment by Sector in 2035



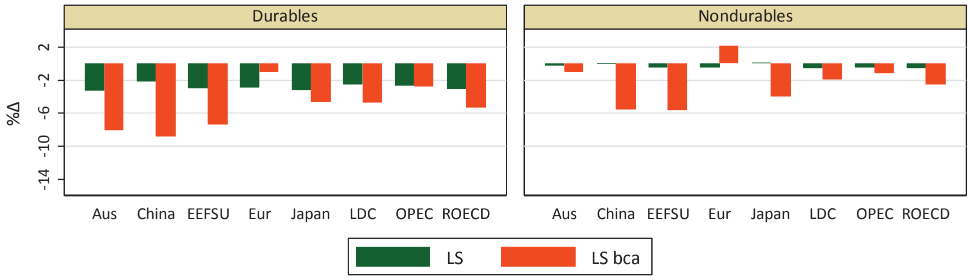
Results by region

Because the carbon intensity of products from different countries varies considerably, the BCAs cause different changes in imports across sources. Figure 28 shows percentage changes relative to baseline in U.S. imports and exports of durables and nondurables in 2035 for each U.S. trade partner and for each of the policies. As expected, BCAs cause greater reductions in imports from countries with larger BCAs. For durables, the impacts are largest for Australia, China and EEFSU, while for nondurables they are largest for EEFSU and Japan. Because Europe is not subject to a BCA, U.S. imports from Europe are stronger under the BCA policy for both goods. Thus, there is some redirection of imports from other countries of origin to Europe. Also as expected, since the exchange rate is a key mechanism, exports to all trade partners fall more when BCAs are imposed.

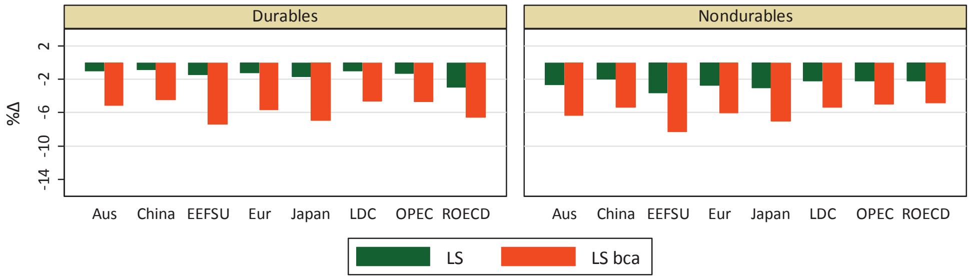
Several factors are at work in the durables sector. The BCAs reduce global investment through transmission of the macroeconomic impact of the tax to non-U.S. economies. The BCAs reduce employment most in the trade-exposed sectors. Because durable goods are a large part of the investment goods purchased for investment, the global reduction in investment directly impacts this sector in all countries.

Figure 28: U.S. Imports and Exports of Durables and Nondurables in 2035 By Country of Origin and Destination

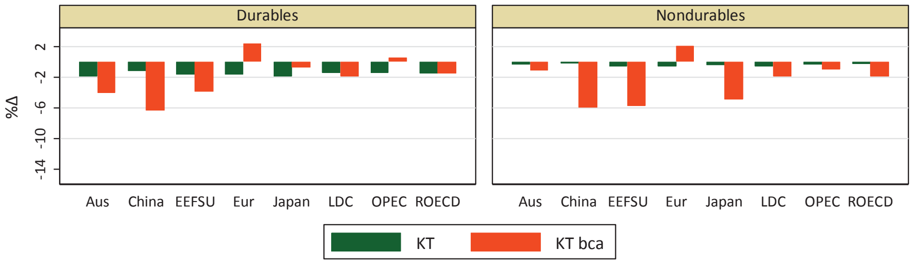
Imports



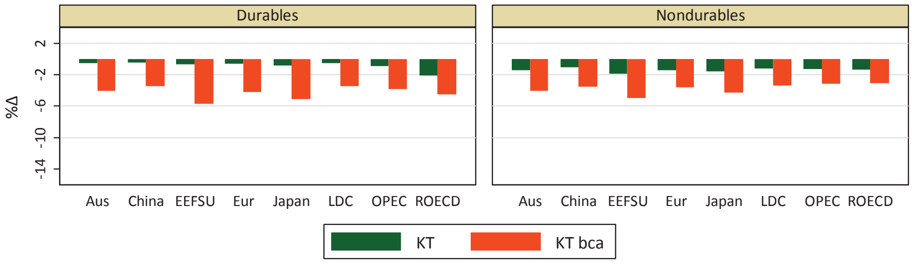
Exports



Imports

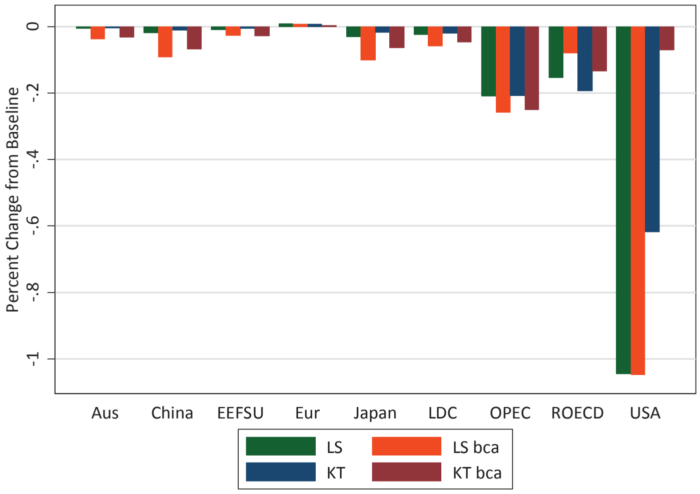


Exports



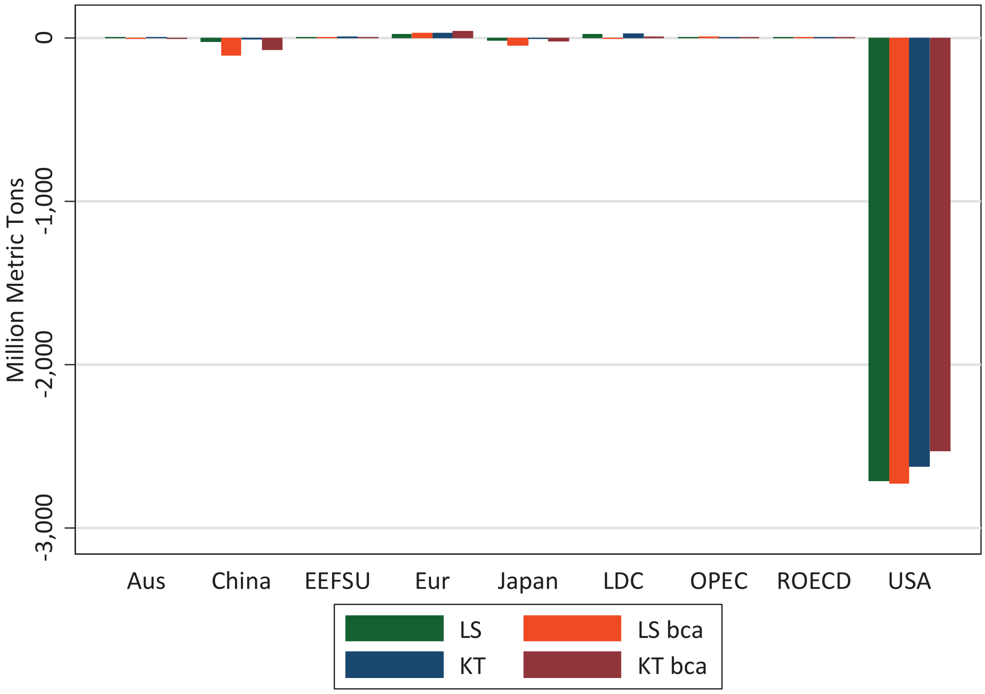
As shown in Figure 29, U.S. policies cause changes in the real GDP of other regions. By 2035 real GDP falls slightly for most regions. Because there are no BCAs on imports from the E.U., GDP in the E.U. is very slightly higher reflecting a switch in world demand towards Europe as a result of the U.S. border carbon policy. The negative spillovers of the carbon policies are largest for OPEC and ROECD (which in G-Cubed is mostly Canada). The BCAs accentuate the spillovers for all regions except for ROECD.

Figure 29: Impacts on Real GDP by Region in 2035



Finally, as seen in Figure 30, positive and negative leakages arise in different regions from the carbon tax and BCAs, but in all cases they are very small relative to the emissions decline in the United States. Emissions in China fall on net as a result of the U.S. carbon tax policy because lower U.S. economic growth slows GDP there and reduces the demand for energy more than emissions rise from a competitiveness advantage from the U.S. carbon price. BCAs induce a larger negative impact on Chinese emissions but also very slightly greater leakage to Europe because Europe is not subject to the BCA.

Figure 30: Carbon Dioxide Emissions by Region in 2035



4. CONCLUSION

In this study, we examine an illustrative carbon tax imposed only in the United States. The tax applies economy-wide to all sources of CO_2 emissions from fossil energy use. We impose the tax beginning in 2020, starting at $27 per ton of CO_2, and we increase the tax rate annually by 5 percent over inflation until 2050. In years after 2050, we hold the carbon tax rate constant at its 2050 level.

We model two different assumptions about how the carbon tax revenue is used. One assumes the revenue is returned to households each year as a lump sum rebate, and the other assumes the revenue is used to reduce the marginal tax rate on capital income.

We also run a variation on each policy in which import BCAs are imposed to account for the total embodied carbon in each non-fuel import from each country of origin other than Europe. The revenue from the BCAs is returned to households or firms according to the same assumptions as the core policies. We treat European goods as exempt from border adjustments on the grounds Europe has adopted policies that are very roughly comparable to the tax being imposed in the United States.

Consistent with earlier studies, we find that the carbon tax raises considerable revenue and reduces CO_2 emissions significantly relative to baseline, no matter how the revenue is used. Gross annual revenue from the carbon tax with lump sum rebating and no BCA begins at $110 billion in 2020 and rises gradually to $170 billion in 2040. By 2040, annual CO_2 emissions fall from 5.5 billion metric tons (BMT) under the baseline to 2.4 BMT, a decline of 3.1 BMT, or 57 percent. Cumulative emissions over 2020 to 2040 fall by 48 BMT.

Also consistent with earlier studies, we find that the carbon tax has very small overall impacts on GDP, wages, employment, and consumption. Different uses of the revenue from the carbon tax result in slightly different levels and compositions of GDP across consumption, investment and net exports. Overall, using carbon tax revenue to reduce the capital income tax rate results in better macroeconomic outcomes than using the revenue for lump sum transfers. Indeed, even while achieving remarkable emissions reductions, the policy results in the U.S. economy reaching the output projections in 2040 only about three months later than it would without the carbon tax.

The G-Cubed model is uniquely suited to investigating the effects of these policy scenarios on emissions leakage, trade, and investment flows. We find no evidence of significant leakage. If anything, the slight slowing of the U.S. economy and demand for imports result in lower emissions abroad. We find that the carbon tax increases the input price of energy, which lowers U.S. exports and slows the U.S. economy, which in turn reduces demand for imports. When an import BCA is imposed, imports become more expensive, and the demand for imports falls further. The BCA also leads to a conventional result from the international trade literature for an increase in tariffs: the U.S. dollar strengthens. A tariff generally causes an appreciation of a country's currency: as the demand for imports falls, the demand for foreign currency falls, which strengthens the home currency relative to the foreign currency. The appreciation of the U.S. dollar also makes U.S. goods more expensive in world market so the demand for U.S. exports falls. Thus although a BCA doesn't affect the U.S. net trade position much, it reduces both imports and exports of U.S. goods.

While the intent of BCAs is to protect U.S. workers from the effects of a carbon tax, we find they can actually have the opposite result, depending on how the revenues are used. To our knowledge, this is the first study to identify the potential linkages between the effect of a BCA and the use of carbon tax revenue. In the lump sum rebate scenarios, the BCAs reduce employment most in the trade-exposed sectors. The largest effect is on durable manufacturing. This is partly a price effect from the stronger U.S. dollar, but it is also because the BCAs reduce global investment through transmission of the macroeconomic impact of the carbon tax to non-U.S. economies. Because durable goods are a large part of the goods purchased for investment, the global reduction in investment directly impacts this sector in all countries. In the capital tax swap scenarios, the BCAs generally improve U.S. employment outcomes, including in trade-exposed sectors.

Future work could extend the analysis to include a border carbon adjustment on exports. Such a policy would provide rebates to U.S. exporters of the carbon taxes paid during production of their goods. The overall impact of an export BCA would depend on the interaction of the similar factors to those discussed above for the import BCA. There would be a price effect as the export BCA lowers the price of energy-intensive exports, which would tend to raise demand, and hence production, of those goods. However, the export BCA would also lower the amount of revenue available for a lump sum rebate or a reduction in the capital tax rate, hence reducing output through macroeconomic reductions in demand. Finally, making U.S. exports more attractive would tend to strengthen the U.S. dollar, partially offsetting the price effect for energy-intensive exports and reducing demand for non-energy-intensive exports.

In sum, a carefully designed carbon tax in the United States can reduce emissions significantly with minimal effect on the economy. We find no evidence of meaningful emissions leakage abroad, even when the U.S. policy is unilateral. Using carbon tax and BCA revenue to reduce distortionary taxes produces better economic outcomes overall and for most individual sectors. To the extent that policymakers wish to protect the interests of energy-intensive trade-exposed industries with BCAs on imports, they should endeavor to tailor the adjustments to narrow, particularly vulnerable, subsectors so as not to inadvertently appreciate the U.S. dollar and do more harm than good overall.

APPENDIX: CALCULATING THE BORDER ADJUSTMENTS

This appendix explains how to calculate and impose a border carbon adjustment (BCA) on imports for a given carbon tax.

Step 1: Construction of carbon intensity coefficients

Let A_R be a matrix of IO coefficients for region R, X_R be a vector of industry outputs, and F_R be a vector of final demands. Total demand for all goods will be the sum of intermediate and final demands: $A_R X_R + F_R$. When demand and supply are equal in every market, the following will hold:

$$A_R X_R + F_R = X_R$$

Solving for the industry output needed to support a given final demand vector F_R, and defining matrix Γ_R to be the Leontief inverse along the way, gives the following:

$$\begin{aligned} F_R &= (I - A_R)X_R \\ \Gamma_R &= (I - A_R)^{-1} \\ X_R &= \Gamma_R F_R \end{aligned}$$

Element Γ_{Rij} will be the total requirement of input i needed in region R to make one final-demand unit of good j.

The carbon intensity of good j can be computed by multiplying good j's total fuel inputs by the carbon coefficient associated with each one. If the carbon coefficient for good i in region R is given by α_{Ri} , the carbon intensity coefficient c_{Ri} of one unit of good j will be:

$$c_{Rj} = \sum_i \alpha_{Ri} \Gamma_{Rij}$$

In many versions of the G-Cubed model, the fossil fuel sectors are 4, 5 and 6. Using a mix of model and algebraic notation, this expression could be written:

$$c_{Ri} = carcoef_{4R}\,\Gamma_{R4j} + carcoef_{5R}\,\Gamma_{R5j} + carcoef_{6R}\,\Gamma_{R6j}$$

The units of c_{Ri} would be the same as *carcoef*: million metric tons of carbon per unit of model output.

As an example, the vector of intensities for China in G-Cubed is shown in Table A1. Note that the coefficients for sectors 2-6 are omitted because they are fossil fuels and imports are taxed directly (no need for border adjustments). Coefficients for sectors 1 and 13-20 are also omitted since they are delivered or generated electricity and are essentially non-traded.

Table A1. Carbon Intensity Coefficients for China in G-Cubed

Sector *j*	c_{Ri} , mmt C per unit of output
7	0.00038
8	0.00010
9	0.00011
10	0.00013
11	0.00042
12	0.00004

Step 2: Construct BCAs

Now suppose that country A imposes carbon tax $TCAR_A$ on domestic production and imports of fossil fuels, and that country B does not have a similar tax. If A wants to impose a border carbon tax on imports from country B it would like to charge the following on good *j* imported to A from B:

$$BCT_{ABj} = c_{Bi} TCAR_A$$

Step 3: Compute revenue from BCAs

The externality revenue in destination country *A* is increased by the following, where *j* ranges over traded goods and *B* ranges over countries of origin:

$$\sum_j \sum_B BCT_{ABj} IMP_{jAB}$$

An equivalent computation that may be more convenient for some purposes would be to compute the total embodied carbon in imports by country *A* (denoted $ECAR_A$) and then multiply by the tax:

$$ECAR_A = \sum_j \sum_B c_{Bj} IMP_{jAB}$$

The revenue is then:

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