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Global Climate Change Mitigation: Strategic Interaction or Unilateral Gains?

by

Sigit PERDANA
Business School,
University of Western Australia

and

Rod TYERS
Business School
University of Western Australia,
Research School of Economics,
Centre for Applied Macroeconomic Analysis (CAMA)
Australian National University

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Sigit PERDANA
Business School,
University of Western Australia

Rod TYERS
Business School
University of Western Australia,
Research School of Economics,
Centre for Applied Macroeconomic Analysis (CAMA)
Australian National University

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Author contact details:

Sigit Perdana
UWA Business School,
Crawley, WA 6009
Australia
sigit.perdana@research.uwa.edu.au

Rod Tyers
Winthrop Professor of Economics
UWA Business School
rod.tyers@uwa.edu.au

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Global Climate Change Mitigation: Strategic Interaction or Unilateral Gain?

Abstract

Global agreement to reduce carbon emissions has been weakened by slowing growth and burden-sharing conflicts. This paper examines strategic interaction amongst regions by simplifying the policy choice to that between carbon taxation and free riding. Benefits from climate change mitigation are constructed via a meta-analysis of existing studies that link carbon concentration with average surface temperature and measures of economic welfare. Implementation costs are then derived by modeling national and global economic performance. Multiplayer, normal form games with payoffs derived by netting costs from shared benefits are then constructed, revealing that the US economy is a net gainer in net present value terms from unilateral implementation. The comparative net benefits to Europe and China are negative but small, making their choice sensitive to the discount rate. The dominant strategy for all other countries is to free ride. Taking the three large economies as a group, there are net gains from implementing carbon taxes, which would be bolstered by universal adoption. Yet compensatory side payments that would induce universal adoption are still not affordable. Moreover, the net gains to all regions do not begin to appear for at least two decades, rendering commitment to abatement politically difficult.

1. Background

Preventing global warming has been the focus on international agreement to mitigate the climate change that include the Kyoto Protocol and the more recent the climate convention on COP 21 Paris (Cooper et al. 2016; Dimitrov 2016). Current evident suggests that these have not been effective in mobilizing all countries to reduce emissions.[1] This paper examines at least five substantial factors that contribute to this failure. The first factor is the disagreement over the scale of mitigation cost and who should bear them (Mahapatra & Ratha 2017). There is an inevitable trade-off between effective mitigation and the growth performance, which is arguably difficult in a slowing global economy, especially for the developing countries where growth performance remains the policy priority.

Second, achieving collective agreement on the voluntary mitigation commitment is problematic. The climate experts believe regional voluntarism on Kyoto Protocol action plans created weaknesses (Clarke & Waschik 2012). Attempts to create markets for carbon emission have thus far, fail to internalize the externalities properly and such emission reduction as have occurred, has stemmed largely from exogenous moderation in economic activity. The implementation European Trading Scheme (ETS), in particular, tended to advantage the Kyoto non-binding parties, while its volatile market mechanisms failed to offer sustained incentives for the control carbon emission (Richstein,

[1] Victor (2011) refers to the problems of the ineffective international commitment as "*the global warming gridlock*".

Chappin & de Vries 2015). Even the COP Paris 21 "*pledge and review*" commitment are claimed to be ineffectual, deferring from firm implementation (Falkner, Stephan & Vogler 2010). The reluctance of large advanced economies to commit to binding emission control stems understandably from political constraints but it exacerbates the difficulties in achieving reciprocity with the emerging and poorer economies, whose future growth will contribute most substantially to the incremental burden of mitigation.

Beyond this, the common property characteristic of global warming leaves voluntary mitigation policies depending on altruism at the national level, which is insufficient for success at the scale required (Fehr & Gächter 2000). The political preference to freeride is strong, amongst other things underlying the failure of the US Congress to ratify the Kyoto Protocol (Hovi, Sprinz & Bang 2010). The final factor weighing on effective international commitment is the issue of the carbon leakage. Poorly implemented and heterogeneous incentives have already triggered the reallocation of dirty industries to comparatively poor countries lacking of domestic environmental policies. Reviews of Burniaux and Martins (2012) and Aldy and Stavins (2012) emphasize this shortcoming, which acts via the trade and investment channel.

Yet, there are numerous alternative approaches of which 13 are surveyed by Aldy, Barrett and Stavins (2003). Some force participation via "fair treatment among regions", by imposing penalty distortions against trade and investment flows. These provide the means to implement the uniform carbon taxation regime of Cooper (1998; 2001;2007) and Nordhaus (2007; 2013). Despite numerous studies, the macroeconomic implications of carbon taxation by participating subgroup of countries, and the global benefits of associated impacts on climate, have not thus far been comprehensively studied.

This paper offers evaluations of both the climate benefits and macro effects of carbon taxation, emphasizing the strategic interactions between countries and regions of different size. The analysis is conducted over the period 2004-2050 with benefits and costs measured annually and strategic decisions based on present values. The benefits of climate change mitigation are derived from a meta-analysis of prior studies linking carbon emissions to average surface temperature and economic welfare. These are then compared with the costs of mitigation via carbon tax in each participating region, measured using a dynamic model of the global economy. The climate gains and mitigation costs then populate the payoff matrices in multi-region normal form game the solutions. Critical mass turns out to be smaller than the individual contribution of the US so that no coordination game appears. It contributes enough carbon emissions to the climate gains from US abatement alone exceed US individual mitigation costs. Side payments are then examined and it is noted that payments sufficient to induce universal adoption are not quite affordable in present value terms and net gains do not turn positive for two decades.

Section 2 briefly reviews the literature on carbon taxation to date. Section 3 applies global economic modeling to the calculation of mitigation costs and their distribution and section 4 reviews studies that quantify the climate impacts of different levels of mitigation and their consequences for global economic welfare, combining these in a meta-analysis. Section 5 uses the results from previous two sections to construct multiplayer normal form games and to derive policy relevant equilibria. The section 6 then concludes and summarizes the research findings.

2. The Debate over Carbon Taxation

Carbon taxation is central to a number of approaches in climate change problem. A key focus in the literature has been on the implementation of a constant carbon tax rate at the global level. Barrett (2002) and Cramton, Ockenfels and Stoft (2015) see uniform carbon taxation as the most "*dynamically efficient*" by virtue of its embodiment of collective reciprocity, the tendency for broad participation to minimize the necessary rate of taxation and the minimisation of carbon leakage.[2] Such a uniform tax rate is seen as easier to regulate and to coordinate than permit trading system (Avi-Yonah & Uhlmann 2009) since the global agreement is unidimensional, centring on tax rate instead of country specific quantities and prices.[3]

The uniform carbon tax has numerous detractors, however. First, it is criticised as shallow (Schmalensee 1998), since such a global agreement will create different effects to different countries. If it is applied at the point of fuel production, the cost would fall on comparatively small countries while the eventual benefits from mitigation accrue mostly to the larger ones. Second, free riding incentives present considerable difficulties. Carbon mitigation is often seen as taking the form of a coordination game (Bolton & Ockenfels 2000, Kraft-Todd et al. 2015) under which first movers lose and agreement is required across a substantial critical mass of participants before collective gains are possible. And third, there is uncertainty regarding both the benefits and the costs of mitigation given the emerging science and extended time spans involved. Numerous studies on benefits of mitigation, in which could be summarized, give a wide variance of welfare effect (Tol 2009).

Perhaps because of these difficulties, the impacts of uniform carbon taxation have not been widely analysed. Amongst few studies are those by Weitzman (2013) Rezai and van der Ploeg (2014) who address the effectiveness of uniform tax in two different perspectives. Weitzman establishes that the extra cost to agents from a rising carbon price would be counter-balanced by an additional benefit for all parties' in the form of emission reductions, thus ensuring an efficient and equally shared median

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[2] Dynamic efficiency addressed by Aldy et al. (2003) as a criterion to evaluate global climate policy regimes. An efficient policy will achieve maximum aggregate net benefit where the whole society is better off in the long run. The dynamic efficiency concept relaxes the Pareto Efficiency criterion to the level of Kaldor-Hicks which emphasises the potential of Pareto efficiency with appropriate transfer.

[3] A further concern about trading system alternatives is that it creates financial instruments, the quality of which opaque and heterogeneous. This inevitable leads to excess volatility in markets and potential market failure (Shiller1981; LeRoy 2005).

marginal benefit per capita. On the other hand, Rezai and Van der Ploeg note that the mitigation gains are larger than the costs at the optimal tax rate and that the impacts are heterogeneous across countries. They suggest that the effects of global carbon tax will fall through time as intergenerational inequality arises. These studies fall short, however, of complete analyses of the strategic benefits and costs associated with participation in carbon taxation regimes by countries small and large.

3. Estimating the Future Economic Cost of Mitigation

This work proceeds in two phases. First, a dynamic model of global economy is adapted to the assessment of carbon taxation at the regional level, the structure chosen is described and the database used is detailed. The model is then applied to the construction of baseline projection of global, economic performance through 2050, beyond which a range of mitigation scenario is considered. We begin with the model.

3.1 Modelling Global Economic Performance with Carbon Taxation

A dynamic, global general equilibrium model is used that is based primarily on global dataset of Global Trade Analysis Project (GTAP-7), as described in Narayanan and Walmsley (2008). The dataset consists of 113 countries and 57 commodities that were produced using the factor endowment in 2004 as the base year. It includes five type endowments of land, natural resource, skilled and unskilled labor and capital. The 57 commodities are further condensed into 12, where the energy sector consists of coal, crude oil, gas and petroleum products. For our purpose, the data are aggregated, then mapped into eight regions: Indonesia, Australia, China, Japan, and the USA, the European Union (EU), ASEAN and rest of the world (ROW). [4]

The Model

The model applied to this data is an adaptation of Gdyn-E Model of Golub, Hertel and Kemal (2013).[5] It merges *Dynamic GTAP* with the energy model of Burniaux and Truong (2002). The resulting dynamics offer better treatment of long-run projections by accommodating current account imbalances, codified international capital mobility, capital accumulation and an adaptive adjustment theory of investment at the country or regional level. Populations and labor supplies are projected exogenously to 2050, consistent with Fouré, Bénassy-Quéré and Fontagné (2010). Changes in factor and input productivity by industry broadly follow Golub, Hertel and Kemal (2013). Critical to the scenarios constructed is the productivity performance in China, which is the single largest carbon emitter, and in the base period at least, the most rapidly expanding economy. The baseline, about

[4] Regional Aggregation and Mapping Commodity/ sectoral aggregation are listed in the Appendix Table A1, A2, A3 respectively

[5] This model merges GTAP Dynamic (Ianchovina & Walmsley 2012) with GTAP-E, a static model that expands on the energy industries and fuels, and is equipped with complete emission coefficients for each industry. GTAP-E in based in turn on the original GTAP comparative static model (Hertel 1998) and the energy model of Buniaux and Truong (2002).

which more is said in the next subsection, assumes initial Chinese productivity growth of around six per cent, consistent with Golub et al., but this is assumed to slow considerably after 2010.

Our adaptation of these models retains their neoclassical perfect competition, Armington product differentiation, and their non-homothetic consumer demand. It also retains the nested Constant Elasticity of Substitution (CES) production structure, illustrated in Figure 1, with its unique energy sector substructure. The uppermost level production of good i can be presented as:

$$y_i = \left[\sum_j \alpha_{ij} v_{ij}^{\frac{\sigma-1}{\sigma}} + \alpha_{VAE} vae_i^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \quad \text{(i)}$$

Final output depends on net substitution between an energy values added sub-nests, vae, and sub nest of intermediate input v and σ depicts the elasticity of substitution. Energy, as feedstock, enters as intermediate input, while the value added in energy sub nest embodies complementarity between capital and energy nest. The adapted model uses five types of energy input: coal, crude oil, petroleum products, gas and electricity.

Inter-fuel and fuel to factor substitution are embodied in all nests in the production structure. As a part of composite factor of production, energy is divided between electricity and non-electricity groups, in which the later comprises coal and non-coal input groups. Aggregated energy complemented with capital, then produces a CES energy capital composite, which in turns contributes to value-added productions, along with the factor of endowments commodities. Final production level combines the value added and the intermediate products.

Private household consumption applies the constant difference of elasticities of substitution (CDE) demand system. The function follows the approach of Hanoch (1975), representing non-homothetic preferences realistically and ensuring that the pattern of consumption changes as the income grows. The consumption nest is illustrated in Figure 2. Government consumption separates energy and non-energy commodity groups using CES nest. The government demand structure is then illustrated in Figure 3.

In capturing international capital mobility the model tracks investment flows and international factor income payments, indirectly simulating portfolio management in each region. Each region's portfolio comprises home and foreign financial assets, representing indirect claims on firm physical capital, which are added to from home saving each year.[6] Physical capital is differentiated across regions so yields on assets differ. Risk is presented by exogenous premia that are calibrated from investment data.

[6] To minimize portfolio complexity, the model has all foreign assets held via a global trust. This way each portfolio has only two elements, home capital and foreign capital in the form of units in the global trust.

Emission coefficients are calculated based on energy *consumed* by firms, households and government. In this application only carbon dioxide (CO_2) emissions from energy consumption are accounted for, representing carbon released from the burning of coal, gas, oil and their derivative products. Regional emissions are then proportional to the sum of all energy used, as embodied in both locally consumed domestic and imported goods, in each case adjusted via process-specific emissions data. This procedure follows the study by Lee (2008) and the values emerging are consistent with GTAP-7 emission database and with the 1996 IPCC Guidelines. The CO_2 emissions are calculated as:

$$CO2_{ijr} = \frac{\left(FC_{ijr}\ CC_{ijr}\left(1 - CST_{ijr}\right)\ EF_i\ FOC_i\ \left(\frac{44}{12}\right)\right)}{1000}$$

$$i \in EGY_{COMM}, \qquad j \in ALLSEC, \qquad r \in REG \qquad \text{(ii)}$$

CO_2 emissions (in gigagrams, or Gg) are the products of fuel consumption (FC measured in 1000 tonnes of oil equivalent, or 1000 toe) of six energy commodities (coal, crude oil, gas and gas products, petroleum products and electricity) and the respective emission conversion factors. First, the variable CC is the conversion coefficient (in terajoules per 1000 toe) to convert energy measurement from toe to terra joules. CST represents ratio of carbon storage, so that (1-CST) is the ratio of carbon released. The variable EF is the emission factor (tonnes of carbon per tera joule) and FOC symbolizes the fraction of carbon oxidized from each energy commodity. [7] The calculation is based on the IPCC (1996) guidelines, and all subsequent factors follow this standard. The estimated total emissions from fossil fuel combustion amount to 25,996 million metric ton of petroleum equivalent in the base year of our study, 2004.

Emissions in the Database

Among the 21 aggregated regions, the USA emitted the most CO_2 in 2004, followed by China and the European Union. The USA emitted around 6,000 million tonnes of carbon or 23 per cent of global emissions. China emitted 4,500 million tonnes or 17 per cent of the global total. These large shares ensure that the USA and China are the most significant regions in affecting carbon emission control. Emissions released by such countries as Japan, India, Australia and Indonesia all contribute less than five per cent. The electricity sector is the largest single user of raw energy commodities and so it is also the largest emitter. Around 50 per cent of global emissions are from this source, of which more than 70 per cent is due to the burning of coal. The emissions from burning gas contribute about a fifth, while smaller contributions are from petroleum used in energy intensive industries and transport.

[7] See Lee (2008) for commodity specific value of CC, EF and FOC. The value of CST derived from IEA/OECD Energy Balance Report 2006.

Emissions from manufacturing industries are not significant at the global level, contributing only three per cent of the total.[8]

Emissions from private consumption stem mostly from the burning of petroleum products that, for many regions, come from imports. Petroleum usage contributes about 90 per cent of the total private emission in each region, except China. There, at least in 2004, coal consumption by private households contributed half the emissions from private consumption. Indeed, China was the world's largest consumer and importer of coal, making China's mitigation strongly dependent on fuel substitution.

3.2 Baseline Mitigation Costs and Carbon Taxation Scenarios

The model is solved over the period 2004-2050 with a focus on the effects of carbon taxation on measures of economic welfare and the associated interactions between economies through trade and investment flows. A baseline projection is first constructed. It is designed to represent the path of global economy with no additional carbon taxation, nor any other changes to government intervention. Current emission mitigation action has taken the form of technological improvement in fossil fuel energy usage in the production process for several countries.[9] Its construction is a non-trivial task. We discuss it briefly here, before summarising the results from shocks to carbon tax rates.

The Baseline

The drivers of continued global growth, for each region, are changes to its population and to the total factor productivity of each of its industries. The global population is set to grow at a positive yet declining rate, following the study of Fouré, Bénassy-Quéré and Fontagné (2013). Productivity changes are then derived by constructing a "pre-base" simulation to 2050 in which the path of real GDP and real investment in each region are specified exogenously so as to yield smooth performance paths consistent with projections by the IMF (2016).

When population, productivity and the region-specific risk premia are set as exogenous, GDP and investment are endogenously determined. The productivity changes have two components: a national productivity shifter that supplements the implied level of technical change in each region and an underlying set of pre-determined industry-specific productivity growth paths that, in combination with the non-homotheticity of demand, drive changes in economic structure through time. The risk premia apply to yields on capital that drive the allocation of investment between countries. They capture the extent to which non-modelled factors limit investment in some regions even where such things as low wage growth might otherwise make these attractive destinations. To ensure that the baseline

[8] Appendix Table A4 summarises Sectoral Contribution of emission globally.

[9] Technical improvement rate is represented in the improvement on energy intensity in Japan, USA and EU, as well as China and India. This energy intensity rate is based IEA ETP 2010 Report on each Region energy intensity improvement from 1990-2007. The rate listed on the table A5 in the appendix.

projection is internally consistent while offering sufficient neutrality to focus the analysis on changes in economic policy, in this case carbon taxation, a pre-base simulation is first constructed with exogenous paths for regional investment and GDP levels, rendering the national productivity shocks and risk premia endogenous. The values for these are then held constant in further analysis, so that all the policy simulations have endogenous investment and GDP levels.

The resulting baseline projection yields the paths of real regional GDP growth rates illustrated in Figure 4. The overall Asian economy grows at around four to five per cent per year while advanced economies retain lower yet stable growth. China's growth rate declines from 10 per cent per year in the early years (after 2004) to less than five per cent per year by 2050. Since this growth rate remains comparatively high, China's prominence as a carbon emitter remains high throughout. Indeed, the projection has China the largest emitter by 2050, with 16.7 per cent of global emissions, followed by emerging India with 12.1 per cent.

Because the projection holds policy variables constant in ad-valorem terms it is not consistent with proposed carbon reduction targets at the regional level. As of 2004, the biggest emitter was the USA. The Obama government chose to target a reduction of 25-28 per cent relative to 2005. [10] Yet the USA mitigation target is less aggressive than other regions. China's target is a reduction by 40-45 per cent, per unit GDP, by the year 2020 and 60-65 per cent by the year 2030. Japan uses 1990 as the baseline year with 25 per cent reduction target; while the EU has a reduction target of 40 per cent by 2030. Even Indonesia, which is a substantial emitter amongst developing countries, is planning a reduction of 26 -41 per cent. Our simulations with carbon taxes therefore embody variants on these commitments but are compared against a baseline in which they do not occur.

Scenarios

Several scenarios are constructed to examine the global and regional effects of carbon taxation. Since GDP is a measure of the total income generated within an economy, the immediate cost of mitigation is calculated based on the deviation of regional real GDP from baseline levels. To make the task manageable, the carbon tax rate considered in all regions is restricted to 20 USD per tonne. This rate is central among those discussed and it has been proven to be sufficient to achieve static targets in numerous countries, including China's 65 per cent declared reduction by 2030.[11]

Importantly, the simulations apply the tax to the point of emission, so it is borne predominantly by fuel users downstream rather than by upstream fuel producers. The tax applies to the amount of fuel consumed, which makes it most significant for electricity generators, though it is also important for energy intensive activities in other sectors, such as refineries, chemical manufacturing and

[10] https://www.whitehouse.gov/the-press-office/2015/03/31/fact-sheet-us-reports-its-2025-emissions-target-unfccc.
[11] USD 20 per tonne CO_2 tax rate could fulfil Indonesian's ambitious target of 26-41 per cent, based on preceding study: Unilateral Carbon Taxation in Indonesia: Economic Implications (2016).

transportation. The fuel prices facing each industry two components, the pre-existing *ad volarem* company or production tax (τ) and the new carbon tax (φ), where the latter is a specific tax based on each industry's carbon emissions per unit of output. The overall price decomposition from consumption of type *i* of fuels (coal, crude oil, gas and petroleum) in sector *j* and region *r*, is described below:

$$Pc_{i,j,r} = (1-\tau)PM_{i,j,r} + \varphi_{i,j,r} \quad \text{(iii)}$$

Clearly, there are as many unilateral carbon tax implementation scenarios as there are regions defined in the model. Although all of these have been implemented, it is not possible to represent all of the emerging results. We return to a number of the unilateral implementation scenarios when strategic behaviour is considered below. For now, we turn to the case of global, or universal, implementation.

Carbon Taxation Globally

When all regions in the world commit to the USD 20 carbon tax, the effects are generally but slightly contractionary. Figure 5 exhibits these negative effects on real GDP levels. The imposition of tax and mitigation responses causes economic restructuring both regionally and globally (Ekins & Speck 1999). This alters the terms of trade between regions with the effect that some regions enjoy gains that more than offset the cost of implementing the tax. Japan and the European Union, in particular, enjoy expansions in their GDP levels, relative to the baseline. This departs from what would be observed had either region implemented the tax unilaterally, in which case real GDP growth would be curtailed. The difference is due in part to their comparatively strong baseline emission controls, which reduce the burden of the eventual tax and to their assumed relative energy-intensive productivity performance paths. These cause the rate of return on future investment in these regions to grow relative to other regions subject to the tax and so they enjoy faster capital growth.

The Chinese economy suffers a comparatively large loss of output relative to the baseline, which grows rapidly in the early years, peaks at more than two per cent in the late 2020s and recedes thereafter. Clearly, some of the costs to the Chinese economy are eventually offset by terms of trade gains associated with changes in energy-intensive activities in other regions and China's continuing comparatively strong overall productivity growth. Other regions also experience negative GDP deviations. Unlike Japan and the European Union, these regions bear significant losses due to the tax, which are compounded by negative shifts in their terms of trade and industrial output that, subsequently, attract declining shares of new global investment.

Central to these changes are rises in electricity production costs. As shown in Figure 6, this rise is highest for China and at least for Japan and the EU. Low energy price inflation in Japan and the EU is consistent with both regions comparatively low dependency on conventional fossil fuels. Both use nuclear power extensively, along with renewable, and the EU's carbon trading scheme has played some role in shifting energy use away fuels (Sovacool 2008), all of which cause their fossil fuel use to be comparatively small. [12] Cost rise in energy intensive industries on the imposition of the tax are therefore comparatively small, so that investment is attracted from high-cost regions and industrial structural changes, yielding net gains in aggregate output.

As the second largest emerging economies represented, Indonesia has the same adverse effects as China from the implementation of carbon tax. From Figure 5, it can be seen that Indonesia suffers a decline in output that is almost as large as China, but which is more sustained.[13] Its dependence on exports of coal and other commodities, combined with the substantial rises in electricity cost indicated in Figure 6, causes contraction in its share of global investment that reduces it current account deficit and its trade surplus. Its manufacturing and energy-intensive industries expand nonetheless, suggesting a domestic efficiency gain from the carbon tax.

In the short run, the allocation of global saving to investment shifts from newly high-cost regions like China toward lower-cost regions like Japan and the EU. The realized rate of return on physical capital declines in all regions, yet by least in Japan and the EU. As illustrated in Figure 7 and 8, relative to baseline there is stronger growth in both domestic and foreign investment in Japan and the EU. By contrast, Chinese investment moderates, rising again subsequently with positive net effect 2040, in response to comparative growth in Chinese productivity and energy efficiency. This resurgence is not in evidence for Indonesia, and for other comparatively high-cost countries.

The income earned from the ownership of foreign assets is important in determining regional per capita incomes. As shown in Figure 9, for the EU, the gains in GDP relative to the baseline are associated with gains in real per capita income. For Japan, dependence on income generated in foreign regions that have slower growth causes real per capita income growth to be slower than output growth. For other regions, real per capita income levels fall short of the baseline. In China's case, the shortfall is greatest in the medium term by 2.5 per cent, and unlike its real output, there is no later resurgence. This is due, in part, to the resurgence in foreign investment in China so the income from the new capital is repatriated out of China. Indonesia's real income per capita also falls short of the baseline levels, but by just a per cent, about the same rate as for other ASEAN Countries.

4. Estimating Mitigation Benefit

It is impossible to evaluate the strategic interaction between regions over mitigation policies without consideration of the benefits that might be expected from the associated levels of climate stabilization. Notwithstanding a large literature devoted to such benefits, the results have considerably greater variance than the more readily modeled economic costs of mitigation. One of the reasons for this is

[12] Electricity sector spending is based on input-output database. See Appendix for detail.
[13] Deviation in Output and Export Growth are summarised in the Figure 10 for all regions represented in the model.

that the benefits are public – non-rival and non-excludable. Another is that they rely on at least three research links, each of which carries uncertainty, namely the link between fossil fuel burning and atmospheric carbon, that between atmospheric carbon and temperature change and that between temperatures change and economic welfare. Here we rely on a survey of the literature that covers these links and a meta-analysis to quantify them.

We first link projected total carbon emissions (in Gigatonnes, or GT) and to average global temperature (^{o} Celsius) via the atmospheric concentration of greenhouse gas (Parts per Million/ ppm). In particular, we link the projected level of total carbon emission in year 2050 to average surface temperature using the 2000-2100 global temperature scenarios of the Intergovernmental Panel on Climate Change (IPCC). First, each carbon taxation scenario yields a separate simulated trajectory for carbon emissions. The IPCC temperature estimates based on GHG Emission (CO_2 combined with other greenhouse gases, including Methane, CFC and Nitrous Oxide). Since the relative contribution of CO_2 is estimated at substantial level of 80.3 per cent from total greenhouse (Nordhaus 1991), we neglects the contributions of other greenhouse gases. Second, the associated rise in surface temperature is taken from IPCC scenario range, which is projected through 2090 from year 2000 with a very wide error band.[14] For this reason, we adopt IPCC terminology and construct three different temperature scenarios: “low”, “best” and “high”. Figure 11 illustrates total emission and temperature estimates under these three IPCC scenarios.

Next, we investigate the global welfare impacts of changes in average surface temperature. Based on the survey by Tol (2009), 15 studies are included in our meta-analysis of the economic welfare impacts of warmer temperatures.[15] These include enumerative studies which are based natural experiments, and statistical studies. In enumerative approach, the welfare estimates are extrapolated from individual location to the global scale and from the immediate past to distant future. The statistical studies rely on uncontrolled experiment and measured differences across regions in climate and income. Despite the difference in analytical approach, these studies tend to agree that a rise in the average surface temperature by a single degree Celsius would actually benefit the economy on average. Rises above two are injurious, however. Figure 12 illustrates the fitted relationship between welfare impact (global GDP loss) and the corresponding global average surface temperature rise, based on these studies.

The final step in estimating the mitigation benefit involves calculating the welfare impacts of changes in global emissions, for each of the three IPCC scenarios. This is done by combining the fitted polynomial functions illustrated in Figure 11 and 12. The global welfare reduction per gigatonne of emissions is derived as shown in Figure 13. The high variance of IPCC temperature scenarios results

[14] IPCC temperature scenarios are detailed in the Table 2.
[15] Refer to Table 3 for Studies on Temperature and Welfare Impacts.

in considerable divergence in welfare reduction estimates. The low-temperature scenario indicates the lowest risk. For 2050 global emission of 90 GT, there would be no economic loss under this scenario, whereas the best scenario would yield a decline of 10 per cent and the high more than 30 per cent. In comparison, current global emission is around 37.2 GT, so projected best scenario will be more likely to achieve. In global uniform carbon taxation projection discussed in previous sub-section, it is shown that carbon emission would be reduced by 36 GT. From figure 13 this would confer a gain in 2050 a global GDP between eight and 45 per cent.

5. Strategic Interaction Analysis: Static Games

To determine the payoffs for each region it is assumed that all share the gains due to averted warming.[16] The scale of these gains depends, however, on the mix of regions participating. Moreover, it arises in triplicate given the three IPCC temperature scenarios discussed previously. Regions that participate have the cost of implementing the tax deducted (or benefits from its implementation by others added, if terms of trade effects suggest net gains), where this cost is specific to the region concerned and, like the benefits; it depends on the particular mix of other regions participating.

Our starting hypothesis is that these payoffs are structured to resemble a coordination game, where there are multiple Nash equilibria but no country or region can gain by moving unilaterally. All, or at least a "critical mass", of countries and regions must act together. A classic example of a coordination game is the "*stag-hunt*" game, illustrated in Table 4. Schelling (1980) identified "focal points" as means to help resolve the coordination problem, favoring the constant-rate carbon tax as a device for simplifying the interaction choice (Avi-Yonah & Uhlman 2012).

Here the payoffs are constructed from results the cumulative present value of net welfare effect of year 2016 to 2050, with total global emissions and the relationships in Figure 12 indicating the gains from abatement and simulated GDP shortfalls associated with carbon taxation indicating regional costs. The net welfare effect in dollar value is gained by multiplying the net percentage change with the projected GDP value for each region, before being discounted to year 2004 using the current ten years Treasury bond yields of 2.35 per cent.

Significant emission contributions from China, the US and the EU distinguish these large, regions from others. For this reason, the first scenario considered focusses on these three regions, other regions are assumed to defect (not to participate in carbon taxation and hence abatement). Since there are more than two players, the normal form game requires more than four combinations. The

[16] We realize that there is considerable evidence that warming will not affect all regions equally. Indeed, the Russian administration appears to look forward to it, as a means of securing navigation on its Northern coastline. This diversity of effects can be incorporated into the analysis conducted here but is not included in this paper for reasons of parsimony.

combination of decision options follows Pascal's triangle, where the number of *k* combination of *n* elements is the sum of the *n-th* row of the binomial coefficients.

$$\sum_{0\le k\le n} C_k^n = \sum_{0\le k\le n} \binom{n}{k} = 2^n \qquad \text{(iii)}^{17}$$

And the number of subsets on each combination is obtained by calculating the whole number between 1 and n, where $n, k \in Real$, or:

$$\sum_{0\le k\le n} \binom{n}{k} = \frac{n!}{(n-k)!\,k!} \qquad \text{(iv)}$$

It follows that the game between the three largest players (the US, China and Europe), each facing just the two options (participate in the carbon tax program or defect), has eight strategic combinations, which comprise one zero-participation subset, three subsets where one country participates, three subsets where two countries participate and one subset in which three countries participate. The static, normal form game analysis for this case is illustrated in Figure 14.

5.1 Strategic Game Analysis: Three Countries (China, USA, EU)

Consider first the IPCC "low temperature" case. The payoffs in this case prove inconsistent with the hypothesized coordination game. A single Nash Equilibrium appears and it combines defection by all three regions. In this case, the global welfare loss due to average surface temperature changes very modest and so there is a disincentive to participate for all regions. Further investigation on Table 5 reveal, even if all three regions were to participate, estimated global emissions would be reduced to 87.35 GT in year 2050, suggesting a global welfare gain of only 0.12 per cent. By comparison, China's participation cost would be 1.18 per cent of its projected GDP. The calculus is similar for the US and EU.

The equilibrium of the dominant strategy to defect has resulted in the best economic outcome for at least, China and the US. The option of all participation doesn't give any superior combination, hence fail to prove any prisoners dilemma in this scenario. Defecting makes China avoiding the loss of two trillion USD, while the US enjoying higher benefit instead of participating. In contrast, despite EU's best strategy is to defect, it would be better off in case all three choose to do mitigation action.

For the best temperature IPCC cases, even though equally fail to yield the coordination game, the game theory analysis found new finding, in which only the US economy now has unilaterally incentives to do the tax. The Nash equilibrium lies on the options where the US doing the mitigation while China and Europe will be better off by free riding. The US welfare impact would have been improved slightly, around 0.20 trillion USD, by reversing its strategy to participate if China and EU

[17] The number of *k* combination from given set S of *n* element is denoted as C_k^n. It comes with various combinations in many literatures. It occurs in many mathematical context, where it denotes as $\binom{n}{k}$, read as *n* choose *k*.

defect. However, doing mitigation seems not to be the dominant strategy the US would choose. If either China or Europe would have decided to do the tax, the US best strategy is still not taking part of the agreement.

Gains from mitigation are more likely to be the determining factors behind defection by China and Europe and participation by the US. In the low and best temperature IPCC cases, the benefits to China and Europe from reduced warming is still insufficient to compensate for the high mitigation cost. The mitigation gains start to be significant in the high-temperature case, where all three regions choose to participate. In this most serious case the benefit far exceeds the US mitigation cost and so it faces a strong incentive to participate and hence to impose the carbon tax. The China and EU contributions are equally substantial and so they face similar incentives.

5.2 Strategic Game Analysis: Five Countries

In the three region analysis and the "best" and "high" temperature cases, we have seen that each region's contribution to global emission abatement plays a critical role in determining its incentive to participate. It is therefore likely that strategic incentives differ for regions with smaller emissions. Here we add to the analysis two smaller regions that, nonetheless, generate high emissions per capita, namely Indonesia and Australia. With five regions the game has 32 combinations (2^5), including the subsets in which either no regions or all regions participate in implementing the tax. There are also five subsets pairing one region with four and ten pairing two and three. The payoff matrices for this multi-player game are summarized and illustrated in Figure 15.

In the IPCC "low temperature" case the unsurprising result is that all regions defect. There is no coordination game between regions, all facing dominant non-participation strategies. For the two smaller regions the cost of mitigation is high compared with the benefits that would accrue from it. Implementing unilaterally would, for Australia and Indonesia, cause accumulated GDP losses of 0.05 T USD and 0.19 T USD respectively, yielding no abatement action. This dominant strategy, for all to defect, is also not consistent with a prisoner's dilemma, in that participation by all does confer net benefits for almost all regions, except Europe.

The corresponding analysis for the "best" temperature scenario shows no coordination game, as before, but all economies, except the US would choose to free ride. The costs they face in implementing the tax would yield comparatively small increments to shared global welfare from the resulting mitigation. By contrast with the "low" scenario, and consistent with the earlier unilateral analysis, the US enjoys unilateral gains from abatement while all other countries defect. This finding gives emphasis to the central role of the US in global climate change abatement. When the temperature scenario is "high", however, there is a more striking result. While the structure is still not a coordination game, the smaller economies, here Australia and Indonesia, still choose to free ride.

Even with larger benefits from abatement, the implementation cost is too high to justify it in these small emitters. The accumulated present value of their net impact is negative if both commit to the tax. Yet universal participation does yield net benefits at the global level.

Although this strategic analysis exhibits no coordination game, the free riding that emerges proves, indirectly, that there is indeed a coordination problem. The approach of "all or nothing at all" has been central to the global negotiations. At least in our "high" IPCC scenario, global participation is shown to yield net gains at the global level.

Thus, even in the "high" scenario, where global net gains arise, free riding incentives are shown here to prevent participation by all regions. If the free rider losses are smaller than the collective welfare or revenue gains by the larger regions that would participate, then this excess gain could feasibly finance side payments to induce universal participation. The following subsection will assess the potential affordability of side payments to overcome this free rider problem.

5.3 Free Riding and the Potential Affordability of Side Payments

We have seen that the US economy consistently derives net gains in both the "best" and the "high" IPCC temperature scenarios, while the EU and China, are net gainers from unilateral implementation only in the "high" scenario. In both these scenarios the three largest economies (the "big three") would implement the tax irrespective of the behavior of other regions. Yet this raises difficult politics. It is easier to advocate the implementation of a tax that is costly in the short term if other regions are committed to it. Free riding therefore remains a stumbling block. Moreover, if the rest of the world were also to implement the tax the global gains from mitigation would be substantially increased.

It is therefore important to consider whether side payments to smaller economies, like Indonesia and Australia, are feasible. If the total addition to the benefit from mitigation by the large emitters, from participation by these smaller economies, exceeds the total additional cost to participate for Indonesia and Australia, the transfer payment is feasible and improving of collective welfare.

The most practical way to explore the feasibility of side payments is to ask whether the receipts from carbon taxation in China, the US and the EU are sufficient to compensate the smaller regions for their net costs from implementation. This approach has a drawback in our analysis, however, since it is assumed in our modelling that the revenue from the carbon tax is recycled to domestic households and its diversion abroad would create unaccounted-for, indirect national losses in implementing regions. We therefore consider affordability from the accumulated present value of net benefits. If net benefits from abatement are sufficient to compensate for the losses in other regions then side payments are affordable.

In determining the net economic impact of carbon mitigation, our analysis has proceeded in phases. The first measures the present value of the stream of global welfare improvements, relative to a no-abatement case, in each carbon tax implementation scenario (only the year 2050 is quantified in Table 6). In the second, this number is adjusted by each country mitigation cost and the corresponding present value of their projected GDP to get the net welfare effect of carbon mitigation, both in regions that implement the tax and those that do not. Where side payments are possible we adjust this procedure by changing the second phase.

We calculate the present value of the stream of extra benefits gained by the top three carbon taxing emitters (China, the US and the EU) when all the otherwise free-riding regions also implement the tax. This extra benefit arises both from reduced global surface temperature and from terms of trade changes due to taxation in the other regions. We then estimate the present value of actual net losses that would be incurred by the previously free-riding regions, due to their switch to the implementation of the abatement strategy. Should the present value of the extra gains by the top three exceed the present value of aggregate incremental losses by these regions, there is room for side payments. For parsimony, we limit the side payment analysis to only the "best" temperature scenario, where in that case, and the "high" temperature scenario, the free riding and the prisoner's dilemma structure are clearest. Table 7 summarizes the total extra benefit of the big three emitters from the global implementation and the aggregated loss of other regions due to their switching from free riding to implementation. The present value of the additional net welfare benefits to China, the US, and the EU, which arises from the implementation of the tax by all other regions is estimated roughly 10.06 T USD. Unfortunately, this would still not be enough to compensate for a present-value incremental net loss of 12.20 T USD in the other regions.

If this analysis is implemented on an annual basis, rather than in present value terms, there are years in which the capacity for compensation is sufficient and years in which it is too small. Sadly it is during the early years that the compensation would be inadequate. Indeed, the extra benefit gained by the big three would not be sufficient to compensate the total loss carried by other regions, at least until year 2040. As illustrated in Figure 16, the total loss due to switching from free riding to the implementation of the tax in the smaller regions is stable througout the simulation period at something under 0.5 trillion USD per year. For the big three, however, the net gains are negative throughout the first two decades. Indeed, as Figure 17 shows, within the first two decades the big three would experience net negative benefits from carbon abatement by implementation of the tax. The turning point would be the year 2040 for China and Europe slightly earlier for the US. While this is consistent with our finding that only the US as the net gainer from the unilateral tax implementation, the task is made politically difficult due to the need to wait almost an entire generation for the net gains to begin to flow.

6. Conclusion/ Further Consideration

The ineffectiveness of the Kyoto Protocol and the constraints facing the success of the Paris Accord arise from hesitation among nations in the face of costly mitigation actions, combined with incentives for smaller regions to free ride on the commitments of larger ones. Because the uniform carbon taxation scheme offers a simple and internationally transparent negotiation target on the one hand and a comparatively efficient economic policy measure on the other, we adopt it as a policy model to explore and quantify these strategic issues.

The effects of varying numbers and sizes of regions that might commit to such a tax are considered by conducting simulations of the global economy and combining these with the results from a meta-study of the temperature and economic welfare impacts of alternative levels of global carbon emission. Three IPCC temperature rise cases are considered: "low", "best" and "high". These yield quite different economic gains from controlling the global temperature rise. In the "best" case, the absence of further carbon mitigation will see the average surface temperature rise by 4 degrees Celsius, bringing with it a loss to the global economy of 15 per cent of its GDP. In the IPCC "high" temperature case this impact is almost doubled. More modest results emerge in the "low" temperature case. When mitigation is added via carbon taxation at 20 USD/tonne, five key conclusions emerge.

First, the more widespread is the implementation of the tax the more the global terms of trade is shifted in favour of just a few comparatively energy-efficient regions, including the EU and Japan. Gains to these regions stem both from the abatement, and hence lower temperatures, and from these terms of trade improvements. Second, in the "best" and "high" IPCC temperature scenarios, in present value terms the US would derive positive net economic gains from its unilateral implementation of the tax, irrespective of the behaviour of other regions. Third, in the "best" scenario, the large carbon-emitting regions, namely the US, the EU and China, have sufficient individual effects on the global climate that the gains each would derive from their joint implementation of the tax, and hence their unilateral effects on the global surface temperature, exceed their collective economic costs of implementing it. Together, they face a purely economic incentive to implement the carbon tax that does not depend on whether other regions choose to do so.

Fourth, in the "best" IPCC temperature scenario, were they able to coordinate, the collective of China, the US and the EU would choose to implement the tax collectively. The question then arises as to whether the additional gains they would derive were the remaining regions also to implement the tax (via lower temperatures and terms of trade changes) would be sufficient for them to afford side payments large enough to induce the other regions to do so. Sadly, their additional gains are not quite sufficient to finance such side payments. Fifth, and finally, it is shown that carbon abatement policies will be politically difficult to implement by all countries, even the US, which is the only unilateral gainer under the “best” temperature scenario. This is because the annual net gains do not turn positive for at least two decades.

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FIGURES

Figure 1: CES Production Nest

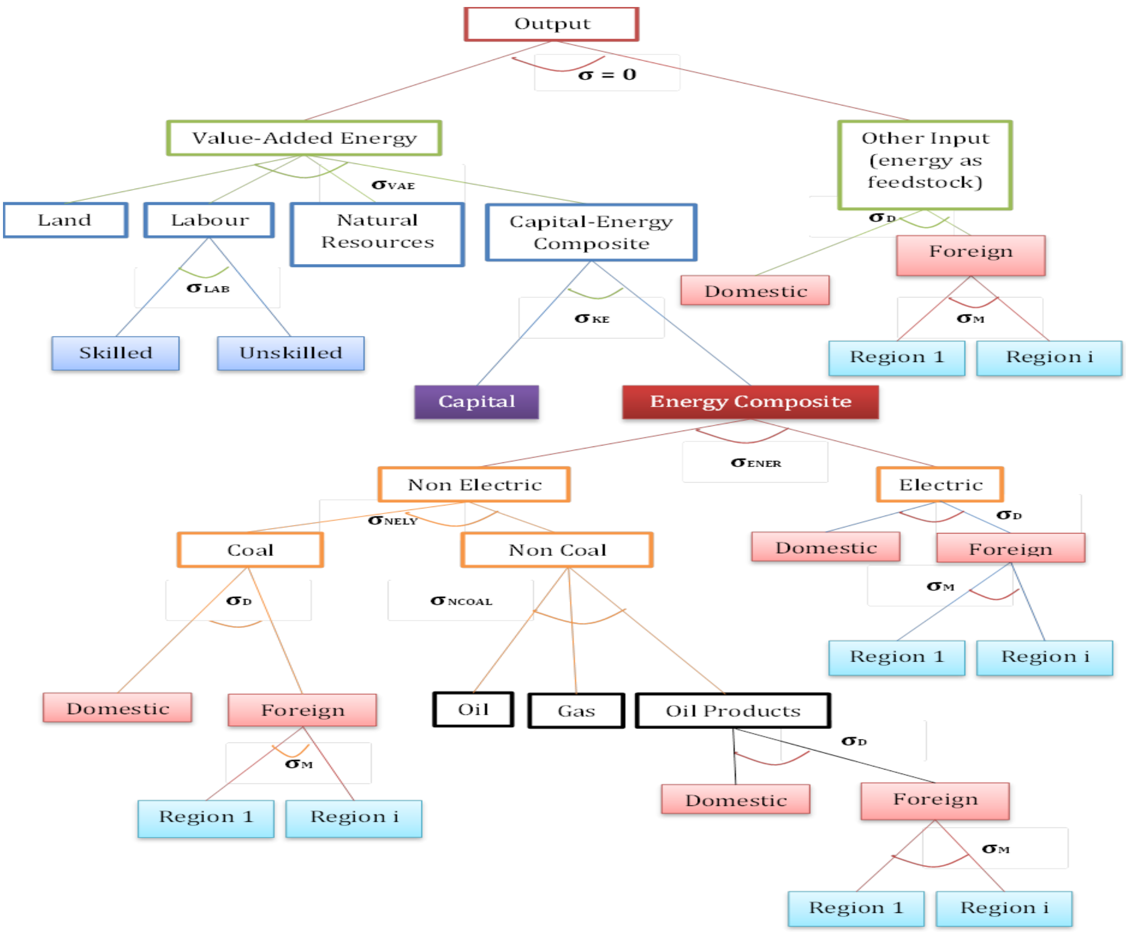


Figure 2: The Household Expenditure Nest

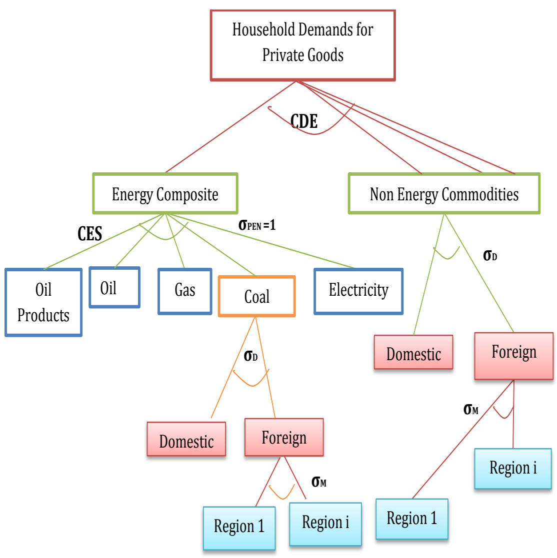


Figure 3: The Government Expenditure Nest

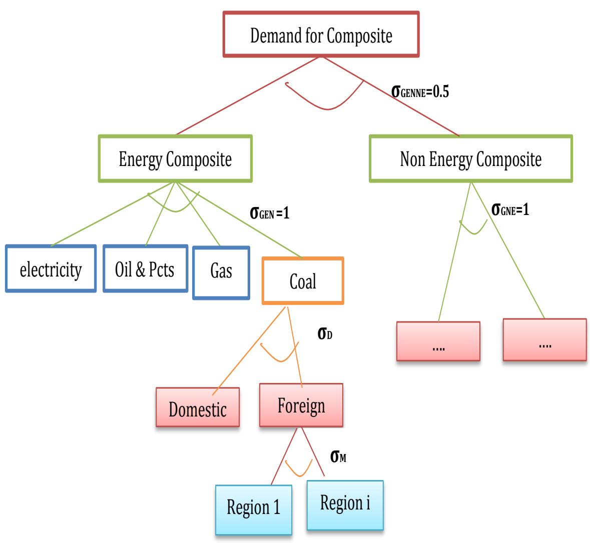
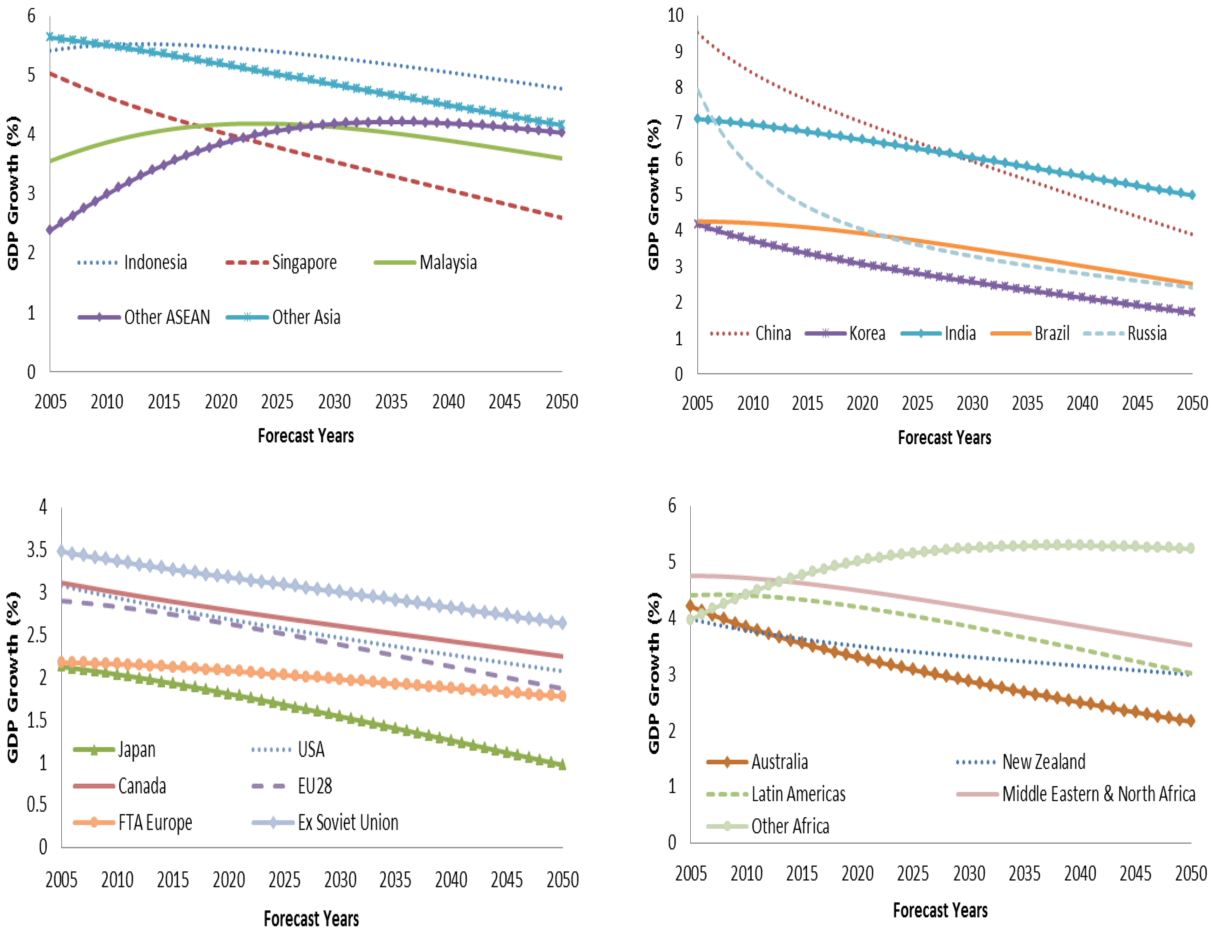
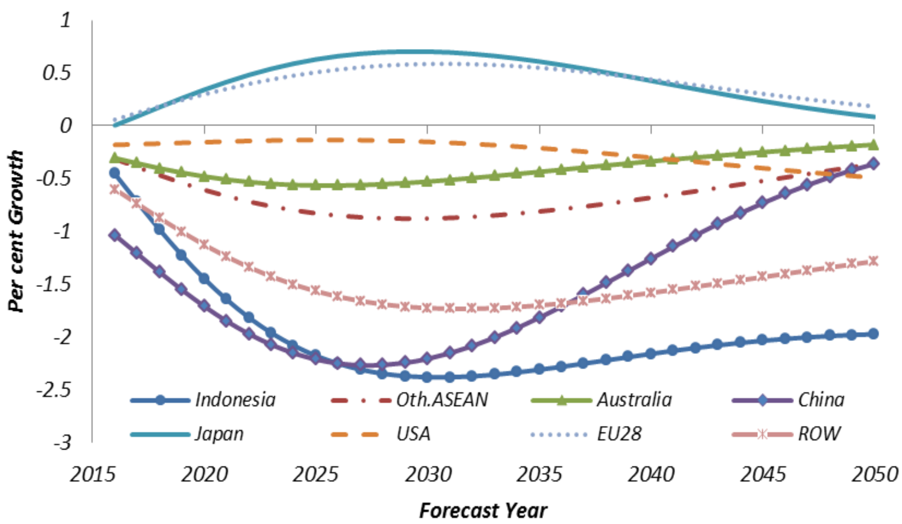


Figure 4: Regional GDP Growth Baseline Projection



Source: Baseline Simulation of the model described in the text.

Figure 5: Real GDP Growth Deviation (Per centage Change from The Baseline), Following the Carbon Tax.



Source: Baseline Simulation of the model described in the text.

Figure 6: Per centage Change of Price Deviation from 1 Unit Baseline Price: Secondary Industries

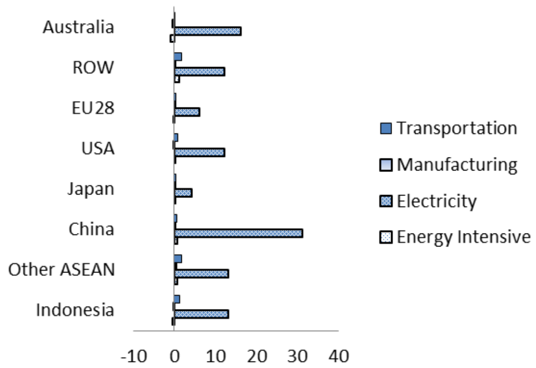


Figure 7: Domestic Purchase of Local Equity following the Carbon Tax: (% Change)

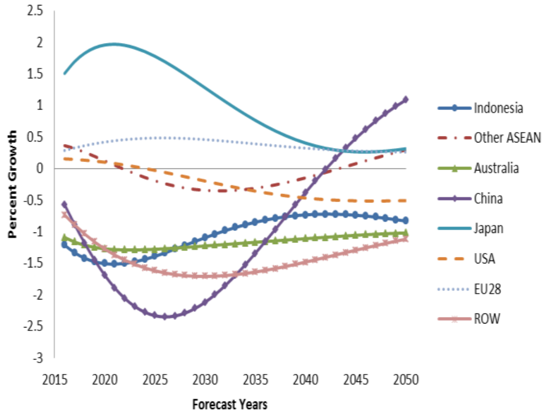


Figure 8 : Foreign Investment Growth (Local Equity Purchase by Foreign Investor) in Region (R)

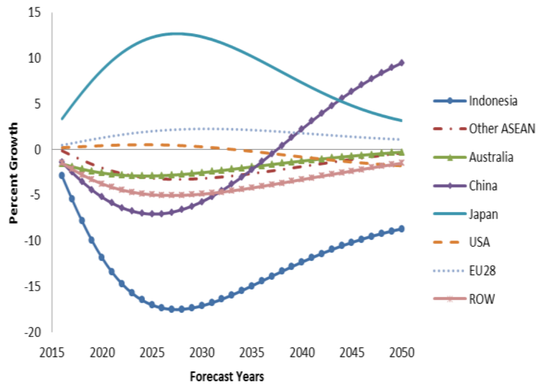
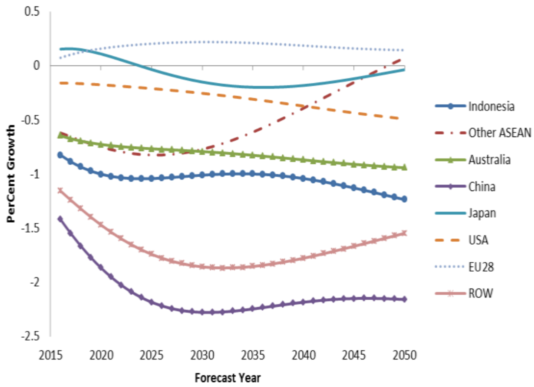
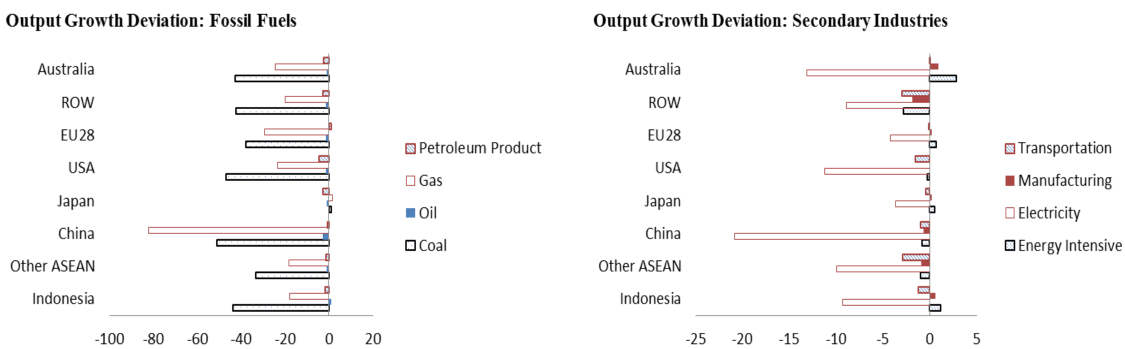


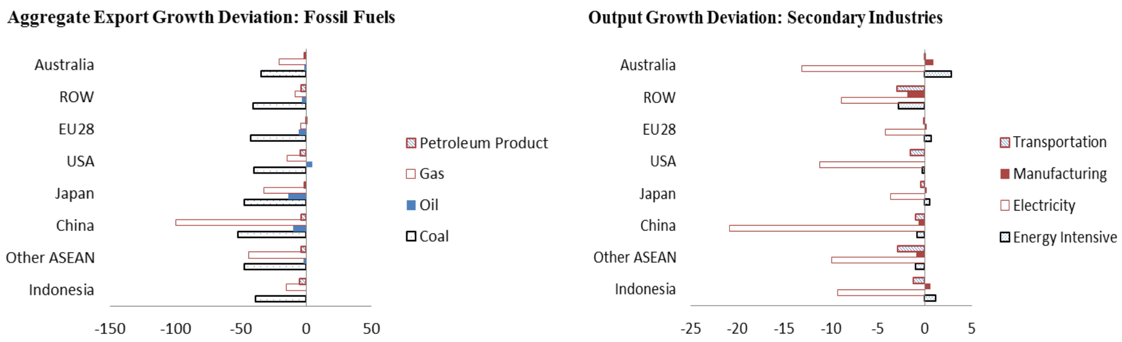
Figure 9: Real per Capita Income Growth Deviation (% Change from Baseline)



Source: Baseline Simulation of the model described in the text.

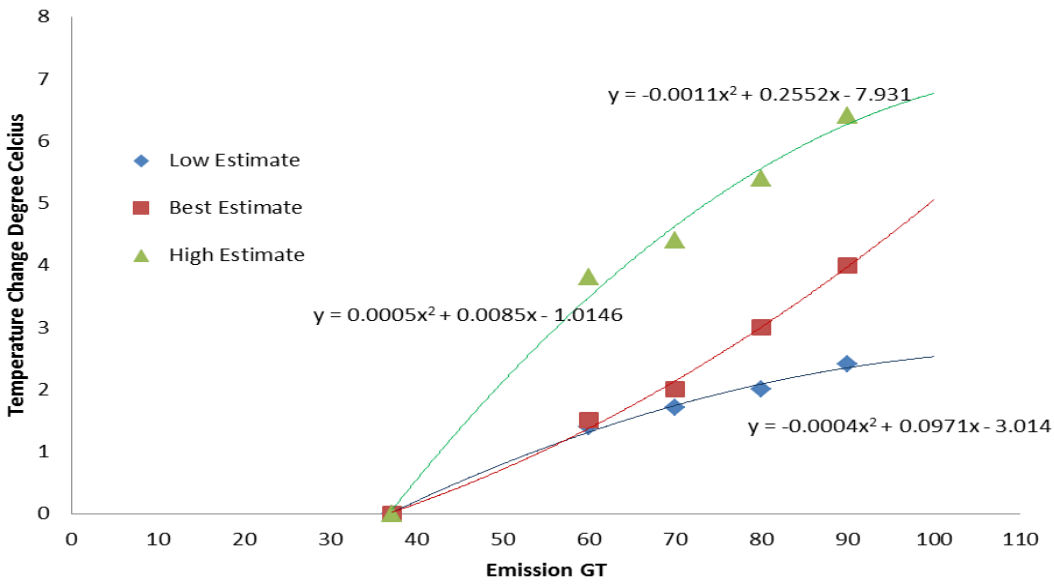
Figure 10: Projected Deviation (% Change from Baseline) Output and Export Growth 2016-2050 due to Carbon Tax





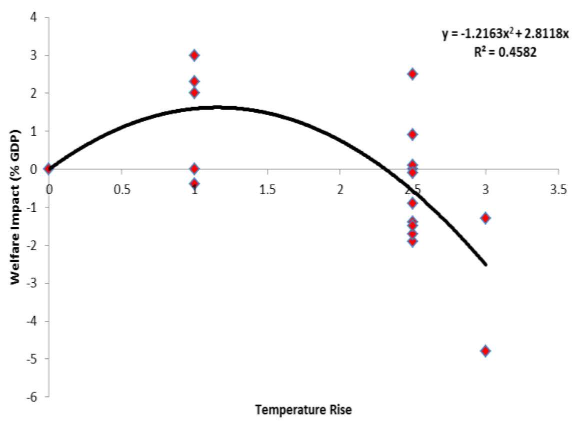
Source: Baseline Simulation of the model described in the text.

Figure 11: Emission and Global Temperature Change from year 2015 (Developed IPCC Scenario)



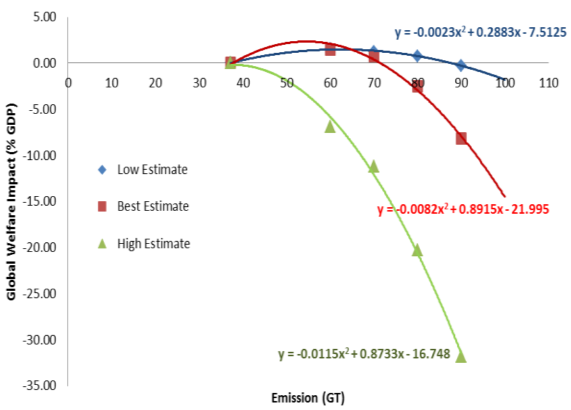
Source: IPCC modified / fitted (IPCC 2007: Synthesis Report)

Figure 12: Estimated Welfare Impacts for Different Temperature Changes



Source: Based on Figures attained by Tol (2009).

Figure 13: Relationship between Global Calculation and Global Economic Welfare (GDP)



Source: Estimation as described in the text.

FIGURE 14: NORMAL FORM: STATIC GAME ANALYSIS 3 Countries (US, China, EU)

LOW Scenario (in Trillion USD)

EU: Participate

USA \ China	Participate			Defect		
	USA	China	EU	USA	China	EU
Participate	2.03	-2.17	4.08	1.45	2.23	2.65
Defect	4.82	-2.59	2.97	3.89	1.66	1.22

EU: Defect

USA \ China	Participate			Defect		
	USA	China	EU	USA	China	EU
Participate	1.79	- 2.45	6.93	1.03	1.86	5.31
Defect	4.48	- 2.91	5.72	3.40	1.26	3.77

BEST Scenario (in Trillion USD)

EU: Participate

USA \ China	Participate			Defect		
	USA	China	EU	USA	China	EU
Participate	-1.99	-4.20	-0.07	-6.54	-1.83	-5.64
Defect	-0.73	-5.43	-2.76	-6.45	-3.56	-9.55

EU: Defect

USA \ China	Participate			Defect		
	USA	China	EU	USA	China	EU
Participate	-2.98	-4.89	2.00	-8.13	-2.79	-4.22
Defect	-2.02	-6.24	-1.01	-8.32	-4.64	-8.44

HIGH Scenario (in Trillion USD)

EU: Participate

USA \ China	Participate			Defect		
	USA	China	EU	USA	China	EU
Participate	-37.43	-20.78	-37.74	-53.40	-23.44	-55.57
Defect	-41.53	-24.35	-46.20	-59.10	-27.70	-65.72

EU: Defect

USA \ China	Participate			Defect		
	USA	China	EU	USA	China	EU
Participate	-41.18	-22.67	-38.63	-57.96	-25.70	-57.36
Defect	-45.67	-26.40	-47.52	-64.03	-30.11	-67.91

FIGURE 15: NORMAL FORM: STATIC GAME ANALYSIS 5 Countries (Summarized)

LOW SCENARIO (TRILLION USD)

NO	COUNTRY	PARTICIPATION	
		PARTICIPATE	DEFECT
1	US	1.03	3.40
2	China	-2.91	1.26
3	EU	1.22	3.77
4	Indonesia	-0.19	0.12
5	Australia	-0.05	0.21

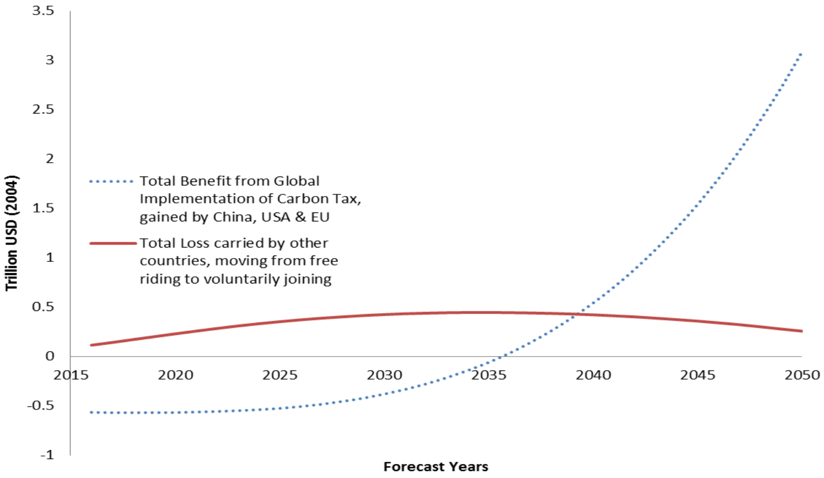
BEST SCENARIO (TRILLION USD)

NO	COUNTRY	PARTICIPATION	
		PARTICIPATE	DEFECT
1	US	-8.13	-8.32
2	China	-6.24	-4.64
3	EU	-9.55	-8.44
4	Indonesia	-0.76	-0.48
5	Australia	-0.80	-0.56

HIGH SCENARIO (TRILLION USD)

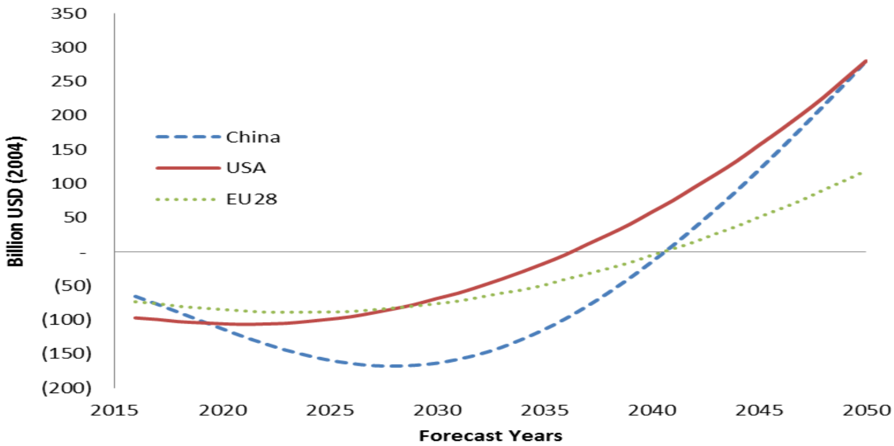
NO	COUNTRY	PARTICIPATION	
		PARTICIPATE	DEFECT
1	US	-57.96	-64.03
2	China	-26.40	-30.11
3	EU	-65.72	-67.91
4	Indonesia	-3.25	-3.02
5	Australia	-4.29	-4.11

Figure 16: Potential Affordability of Side Payment From China, USA and EU to Other Countries



Source: Estimation as described in the text.

Figure 17: Estimated Welfare Benefit of Unilaterally Implemented Carbon Tax for China, USA, and EU



Source: Estimation as described in the text.

TABLE

Table 1: Regional Carbon Emission in 2004 and Projection to 2050

Regions	2004		2050	
	Emission (MT)	% of Global	Emission (MT)	% of Global
Indonesia	357.39	1.37	2673.41	2.7
Singapore	40.84	0.16	175.18	0.2
Malaysia	145.02	0.56	1040.03	1
Other ASEAN Countries	405.40	1.56	1641.94	1.6
Other Asia Countries	513.14	1.97	4058.94	4
Australia	353.68	1.36	1184.46	1.2
New Zealand & Oceania	54.17	0.21	173.89	0.2
China	4471.86	17.20	16704.58	16.7
Japan	1095.64	4.21	2124.24	2.1
Korea	400.51	1.54	1669.29	1.7
India	1061.47	4.08	12126.02	12.1
Brazil	298.05	1.15	910.19	0.9
USA	6069.54	23.35	13415.56	13.4
Canada	566.03	2.18	1643.33	1.6
Latin Americas	1118.76	4.30	4651.82	4.6
EU28	3987.02	15.34	8860.28	8.8
Russia	1552.47	5.97	8925.11	8.9
FTA Europe	109.81	0.42	254.97	0.3
Former Soviet Unions	1031.95	3.97	3545.30	3.5
Middle East & North Africa	1826.78	7.03	10165.43	10.1
Other Africa	536.48	2.06	4342.63	4.3
TOTAL	**25995.99**	**100**	**100286.60**	**100**

Source: GTAP 7 Database and Estimation as described in the text.

Table 2: Temperature Scenarios: IPCC and Developed Estimation

Emission (GT) in 2050/ Lower Border	IPCC (GHG scenario)	IPCC Atmospheric Concentration (PPM)	IPCC Best Temperature Estimate (° C)	IPCC Likely Uncertainty Range (° C)	Developed Temperature Estimate		
					Low Estimate (° C)	Best Estimate (° C)	High Estimate (° C)
90	**A1F1**	660-790	4	2.4-6.4	2.4	4	6.4
80	**A2**	570-660	3	2.0-5.4	2	3	5.4
70	**A1B**	485-570	2.8	1.7-4.4	1.7	2	4.4
60	**A1T**	440-485	2.4	1.4-3.8	1.4	1.5	3.8
37.2	-		-	-	0	0	0

Source: IPCC Synthesis Report (2007).

Table 3: Studies on Temperature Rising & Welfare Impacts

No	Literature	Temperature Rise (° C)	Welfare Effect (% Global GDP)
1	Nordhaus (1994a)	3.0	-4.8
2	Nordhaus (1994b)	3.0	-1.3
3	Fankhauser (2013)	2.5	-1.4
4	Hope (2006)	2.5	0.9
5	Rehdanz & Maddison (2005)	1.0	-0.4
6	Nordhaus & Yang (1996)	2.5	-1.7
7	Plambeck & Hope (1996)	2.5	2.5
8	Nordhaus (2006)	2.5	-0.9
9	Tol (1995)	2.5	1.9
10	Nordhaus & Boyer (2003)	2.5	1.5
11	Mendelsohn et al. (2000a)	2.5	0
12	Mendelsohn et al. (2000b)	2.5	0.1
13	Tol (2002a)	1.0	2.3
14	Tol (2002b)	1.0	3.0
15	Maddison (2003)	2.5	-0.1

Table 4: Stag Hunt/ Coordination Game

		Country II	
		Participate	Defect
Country I	Participate	90,90	82,88
	Defect	88,82	88,88

Table 5: Estimated Welfare Effect from Emission Abatement in Year 2050 (Stemming from Reduction in Global Surface Temperature Change) & Mitigation Cost (% GDP Deviation) USD 20 Uniform Carbon Tax

No	Selected Scenario Carbon Tax Implementation	Global Emission (GT)	Welfare Impact (% GDP)			GDP Deviation on Selected Countries (% GDP)				
			Low	Best	High	China	USA	EU	Indonesia	Australia
1	Global (All Countries)	64.90	1.51	1.32	-8.51	-0.36*	-0.49*	0.18*	-1.98*	-0.18*
2	USA, China, EU, Indonesia, Australia	85.92	0.28	-5.93	-26.61	-1.11*	-0.55*	-0.15*	-1.05	-0.32
3	USA, China, EU	87.35	0.12	-6.69	-28.21	-1.18*	-0.55*	-0.16*	0.52	0.48
4	US China	89.18	-0.09	-7.71	-30.33	-1.30*	-0.60*	0.39	0.61	0.47
5	China EU	90.08	-0.21	-8.23	-31.4	-1.34*	0.03	-0.42*	0.37	0.28
6	US EU	95.01	-0.88	-11.31	-37.59	0.28	-0.53*	-0.29*	0.06	0.22
7	China	92.65	-0.54	-9.79	-34.55	-1.46*	-0.02	0.13	0.45	0.26
8	USA	96.80	-1.16	-12.53	-39.97	0.16	-0.58*	0.26	0.15	0.20
9	EU	98.47	-1.43	-13.72	-42.26	0.12	0.05	-0.55*	-0.09	0.02
10	Indonesia	99.37	-1.58	-14.38	-43.52	0.04	-0.01	0.00	-1.58*	0.01
11	Australia	99.79	-1.65	-14.69	-44.12	0.03	0.00	0.01	0.02	-0.79*
12	NONE	100.28	-1.73	-15.06	-44.82	0.00	0.00	0.00	0.00	0.00

Source: Estimation as described in the text.

Table 6: Improvement Relative to No Abatement Case (Gain in Year 2050) as Percentage of GDP

No	Selected Scenario Carbon Tax Implementation	Global Emission (GT)	Welfare Impact (% GDP)			Benefit From Abatement (Improvement from No Abatement Case)		
			Low	Best	High	Low	Best	High
1	NONE (No Abatement)	100.28	-1.73	-15.06	-44.82	-	-	-
2	Global (All Countries)	64.90	1.51	1.32	-8.51	3.24	16.38	36.31
3	USA, China, EU (TOP 3)	87.35	0.12	-6.69	-28.21	1.85	8.37	16.61
4	TOP 3 + Indonesia	86.42	0.23	-6.19	-27.16	1.96	8.87	17.66
5	TOP 3 + Other ASEAN Countries	86.66	0.20	-6.32	-27.43	1.93	8.74	17.39
6	TOP 3 + Australia	86.84	0.18	-6.41	-27.63	1.91	8.65	17.19
7	TOP 3 + Japan	86.91	0.17	-6.45	-27.71	1.90	8.61	17.11
8	TOP 3 + India	80.42	0.80	-3.33	-20.89	2.53	11.73	23.93
9	Top 3 + Russia	84.32	0.44	-5.12	-24.87	2.17	9.94	19.95
10	TOP 3 + Middle East & North Africas	85.22	0.35	-5.57	-25.84	2.08	9.49	18.98
11	TOP 3 + New Zealand & Oceania	87.31	0.13	-6.67	-28.17	1.86	8.39	16.65
12	Top 3 + Brazil	87.21	0.14	-6.61	-28.05	1.87	8.45	16.77
13	Top 3 + Korea	86.80	0.18	-6.39	-27.59	1.91	8.67	17.23
14	Top 3 + Canada	86.93	0.17	-6.46	-27.74	1.90	8.60	17.08
15	Top 3 + Latin Americas	86.25	0.24	-6.10	-26.98	1.97	8.96	17.84
16	Top 3 + Other Asia	85.90	0.28	-5.92	-26.59	2.01	9.14	18.23
17	Top 3 + FTA Europe	87.32	0.12	-6.67	-28.18	1.85	8.39	16.64
18	Top 3 + Ex Soviet Union	86.14	0.26	-6.05	-26.85	1.99	9.01	17.97
19	Top 3 + Africas	85.04	0.37	-5.48	-25.65	2.10	9.58	19.17

Source: Estimation as described in the text.

Table 7: Cumulative Discounted Dollar Value of Net Welfare Benefit/ Loss of Uniform Tax (US$ Trillions)

Regions (A)	**Unilateral Implementation (B)**	**"BIG Three" Implementation (C)**	**Universal Implementation (D)**	**Extra Benefit By Universal Implementation (D-C)**
China	-1.60	0.44	3.34	2.90
USA	0.18	6.33	9.22	2.89
EU	-1.10	8.38	12.65	4.27
Total "Big Three"	**-2.52**	**15.15**	**25.21**	**10.06**

Regions (A)	**"BIG Three" Implementation/ Benefit As Free Rider (B)**	**Joining "Big Three" (C)**	**Losing Benefit from Altering Mitigation Strategy (C-B)**
Indonesia	0.50	0.20	0.30
Other ASEAN Countries	0.74	0.38	0.36
Australia	0.69	0.43	0.26
Japan	3.50	2.92	0.58
India	1.91	0.47	1.44
Russia	0.70	-1.74	2.44
Middle East & North Africa	1.56	-0.70	2.26
New Zealand & Oceania	0.13	0.09	0.04
Brazil	0.89	0.66	0.23
Korea	0.90	0.48	0.42
Canada	0.92	0.56	0.36
Latin America	2.33	0.71	1.62
Other Asia	1.06	0.63	0.43
FTA Europe	0.53	0.45	0.08
EX Soviet Union	0.53	-0.28	0.81
Africa	1.01	0.45	0.56
Total	**17.91**	**5.71**	**12.20**

Source: Estimation as described in the text.

Appendix

Table A1: Regional Aggregation, Mapping and Investment Target

GTAP Region	Region Aggregation	Investment Target % (2005-2050)	Aggregated Map
Indonesia	Indonesia	5.5 to 4	Indonesia
Singapore	Singapore	4 to 1	ASEAN
Malaysia	Malaysia	4 to 2	ASEAN
Cambodia, Lao, Myanmar, Philippines, Thailand, Vietnam, Rest of Southeast Asia	Other ASEAN Countries	5 to 3	ASEAN
Taiwan, Rest of East Asia, Bangladesh, Pakistan, Sri Lanka, Rest of South Asia	Other Asia Countries	5 to 4	ROW
Australia	Australia	2.8 to 1.5	Australia
New Zealand and Rest of Oceania	New Zealand	3 to 2.5	ROW
China and Hong Kong China	China	8.5 to 1.5	China
Japan	Japan	2 to 0.2	Japan
South Korea	Korea	3 to 0.5	ROW
India	India	7 to 4	ROW
Brazil	Brazil	3.5 to 1.5	ROW
USA	USA	2.8 to 1.5	USA
Canada	Canada	3 to 1.5	ROW
Mexico, Costa Rica, Guatemala, Nicaragua, Panama, Rest of Central America, Caribbean, Rest of North America, Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America	Latin America Countries	4 to 2	ROW
Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Rep., Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom*	EU28	2.5 to 1	EU28
Russia Federation	Russia	3 to 1	ROW
Switzerland, Norway and Rest of FTA	FTA Europe	2 to 1.5	ROW
Albania, Belarus, Ukraine, Rest of Eastern Europe, Rest of Europe, Kazakhstan, Kyrgyzstan, Rest of Former Soviet Union, Armenia, Azerbaijan, Georgia, Turkey	Ex. Soviet Union and Other Europe	3 to 1.5	ROW
Iran, Rest of Western Asia, Egypt, Morocco, Tunisia, Rest of North Africa	Middle Eastern and North Africa	4 to 2.5	ROW
Nigeria, Senegal, Rest of West Africa, Central Africa, South Central Africa, Ethiopia, Madagascar, Malawi, Mauritius, Mozambique, Tanzania, Uganda, Botswana, South Africa, Rest of South African Custom Unions	Other Africa	5	ROW

Table A2: Sectoral Aggregation

Aggregated Sectors	Explanation	GTAP commodities
Agriculture	Agriculture and Food Processing	pdr, wht, gro, v_f, osd,c_b, pfb, ocr, ctl, oap, rmk, wol, cmt, omt, vol, mil pcr, sgr, ofd, b_t
Other Primary Sectors	Forestry, Fisheries and Mineral Extraction	frs, fsh, omn
Coal	Coal	coa
Crude Oil	Crude Oil	oil
Gas	Gas and Gas Products	gas, gdt
Oil Products	Petroleum and coal Products	p_c
Energy Intensive	Energy Intensive and Non Metallic Mineral Industries	crp, nmm, i_s, nfm
Electricity	Electricity	ely
Manufacturing	Manufacturing Industries	tex, wap, lea, lum, ppp, fmp, mvh, otn, ole, ome, omf
Transportation	Water, Air and Other Transport	otp, wtp, atp
Service	Water, Construction, Trade and Other Services	wtr, cns, trd, cmn, ofi, isr, obs, ros
Non Trading Service	Public administration	osg, dwe

Source: GTAP Database.

Table A3: Sectoral Productivity*[18]

Sectors	Indonesia	China*[18]	Japan	USA	EU28
Agriculture	3.5	6.0 to 3.5	1.5	1.8	1.3
Other Primary	3.5	6.0 to 3.5	1.5	1.8	1.3
Coal	3.5	6.0 to 3.5	0	1.8	0
Oil	0	0	0	1.8	0
Gas	3.5	6.0 to 3.5	0	1.8	0
Oil Products	0	0	0	0	1.3
Energy Intensive	3.5	6.0 to 3.5	1.5	1.8	1.3
Electricity	1.75	3.0 to 1.75	0.75	0.9	0.65
Manufacturing	3.5	6.0 to 3.5	1.5	1.8	1.3
Transportation	3.5	6.0 to 3.5	1.5	1.8	1.3
Service	1.75	3.0 to 1.75	0.75	0.9	0.65
Non Trading Service	1.75	3.0 to 1.75	0.75	0.9	0.65

Sectors	Singapore	Malaysia	Other ASEAN	Other ASIA	Australia	NZ_OC	Korea	India*	Brazil
Agriculture	2.0	3.5	2.7	2.5	1.4	1.4	2.0	5 to 4	2.5
Other Primary	0	3.5	2.7	2.5	1.4	1.4	0	5 to 4	2.5
Coal	0	0	0	0	1.4	0	0	5 to 4	0
Oil	0	0	0	0	0	0	0	0	0
Gas	0	3.5	0	0	1.4	0	0	5 to 4	0
Oil Products	0	0	0	0	0	0	0	0	0
Energy Int.	2.0	3.5	2.7	2.5	1.4	1.4	2.0	5 to 4	2.5
Electricity	1.0	1.75	1.35	1.25	0.7	0.7	1.0	2.5 to 2	1.25
Manufacture	2.0	3.5	2.7	2.5	1.4	1.4	2.0	5 to 4	2.5
Transport	2.0	3.5	2.7	2.5	1.4	1.4	2.0	5 to 4	2.5
Service	1.0	1.75	1.35	1.25	0.7	0.7	1.0	2.5 to 2	1.25
NTR Service	1.0	1.75	1.35	1.25	0.7	0.7	1.0	2.5 to 2	1.25

Sectors	Canada	Latin Americas	Russia	Europe FTA	EX Soviet	Middle Eastern	Africa
Agriculture	1.8	2.0	3.0	1.3	2.0	2.7	2.5
Other Primary	1.8	2.0	3.0	1.3	2.0	2.7	2.5
Coal	0	0	3.0	0	0	0	0
Oil	1.8	2.0	3.0	0	0	2.7	0
Gas	0	2.0	3.0	0	2.0	2.7	0
Oil Products	0	0	0	0	0	2.7	0
Energy Intensive	1.8	2.0	3.0	1.3	2.0	2.7	2.5
Electricity	0.9	1.0	1.5	0.65	1.0	1.35	1.25
Manufacturing	1.8	2.0	3.0	1.3	2.0	2.7	2.5
Transportation	1.8	2.0	3.0	1.3	2.0	2.7	2.5
Service	0.9	1.0	1.5	0.65	1.0	1.35	1.25
NTR Service	0.9	1.0	1.5	0.62	1.0	1.35	1.25

Source: Golub Hertel and Kemal (2013)

[18] China input productivity growth rate is assumed to be positive yet declining throughout forecast period. It growth 6 per cent in 2005, yet declines to only 3.5 per cent in 2050. Same assumptions applied for India (aggregated in ROW) input productivity growth from 5 to 4 per cent in end forecast period.

Table A4: Sectoral Contribution to Global Emission (2004)

Production Sectors	Total Emission (MTOE)	Percentage from Total Emission (%)	Contribution from Fossil Fuel Usage			
			Coal	Crude Oil	Gas	Petroleum Products
Agriculture	654.13	3.01	22.43%	0.02%	16.07%	61.48%
Other Primary	207.20	0.95	14.20%	0.03%	12.22%	73.55%
Coal	102.30	0.47	94.24%	0.00%	0.26%	5.50%
Oil	195.99	0.90	0.01%	8.64%	83.29%	8.05%
Gas	286.62	1.32	20.67%	1.76%	71.58%	5.99%
Oil Products	749.30	3.45	0.00%	0.00%	100.00%	0.00%
Energy Intensive	2764.26	12.72	38.22%	0.73%	30.31%	30.74%
Electricity	10602.61	48.78	70.48%	0.41%	20.16%	8.96%
Manufacturing	723.72	3.33	33.12%	0.18%	32.04%	34.66%
Transportation	4217.26	19.40	0.57%	0.01%	4.61%	94.82%
Service	849.63	3.91	12.12%	0.13%	34.86%	52.88%
Non Trading Service	384.01	1.77	10.62%	0.14%	47.75%	41.49%
TOTAL	21737.04	100.00				

Source: GTAP 7 Database.

Table A5.1: Technological Improvement Rate of Energy Used (Coal) in Production[19]

Sectors	Japan	USA	EU28	China	India
Energy Intensive	0.9	1.5	0.6	5.8	0.75
Electricity	0.9	1.5	0.6	5.8	0.75
Manufacturing	0.9	1.5	0.6	5.8	0.75

Table A5.2: Technological Improvement in Energy Usage (Petroleum Products) in Production

Sectors	Japan	USA	EU28	China	India
Transportation	0.9	1.5	0.6	5.8	0.75

Table A6: Percentage of Electricity Sector Spending 2004 in Selected Regions

Commodity Used in Electricity Sectors	Japan	USA	EU28	China	Indonesia	Australia	R_ASEAN	ROW
Agriculture	0.00	0.00	0.70	0.00	0.00	0.10	0.00	0.17
Other Primary	0.00	0.00	0.70	0.10	6.50	0.10	0.03	0.69
Coal	0.00	21.20	9.40	**44.00**	14.70	**27.60**	2.13	7.21
Oil	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.76
Gas	0.00	20.20	4.80	0.80	10.50	13.10	**39.17**	17.25
Petroleum Products	10.60	8.40	8.40	12.20	**46.40**	5.60	32.47	20.81
Energy Intensive	0.30	0.60	3.50	1.30	0.00	4.00	0.23	1.86
Electricity	10.90	9.90	13.50	15.10	6.60	17.20	8.93	11.69
Manufacturing	6.20	1.40	13.00	9.90	3.30	3.20	4.13	6.43
Transportation	5.60	6.50	3.40	5.20	1.40	6.90	0.97	4.06
Service	**59.60**	**30.90**	**37.40**	11.20	10.40	20.90	11.03	**27.41**
NTR Service	6.60	1.00	5.20	0.10	0.20	1.50	0.97	1.66
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Source: GTAP 7 Database

[19] Technological improvement rate (yoy) applies to coal usage in manufacturing, energy intensive and electricity sectors in selected countries. This energy intensity improvement is also applied for petroleum usage in transportation sector. The rate are based on IEA/ OECD, Energy Technology Perspective Report 2010 and Japan Energy Efficiency Report (Feb 2012). The value are measured based on energy used in 1990-2007 and 1990 to 2010 for Japan.

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