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Output-Based Allocation of Emissions Permits for Mitigating the Leakage and Competitiveness Issues for the Japanese Economy

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Abstract

The adoption of domestic emissions trading schemes (ETS) can impose a heavy burden on energy-intensive industries. In particular, energy-intensive industries competing with foreign competitors could lose their international edge. Although the abatement of carbon dioxide (CO_2) emissions in industrialized countries entails the reduction of their energy-intensive production, a corresponding increase in the production of energy-intensive goods in countries without CO_2 regulations may lead to carbon "leakage." This paper examines the effects of various allocation methods for granting emissions permits in the Japanese ETS on the economy and CO_2 emissions using a multiregional and multisector computable general equilibrium model. Specifically, we apply the Fischer and Fox (2007) model to the Japanese economy to address carbon leakage and competitiveness issues. We compare auction schemes, grandfathering schemes, and output-based allocation (OBA) schemes. We further extend the model by examining a combination of auctions and OBA. Though the auction scheme is found to be the best in terms of macroeconomic impacts (welfare and GDP effects), the leakage rate is high and the harm to energy-intensive sectors can be significant. OBA causes less leakage and damage to energy-intensive sectors, but the macroeconomic impact is undesirable. Considering all three effects—leakage, competitiveness, and macroeconomics—we find that combinations of auctions and OBA (with gratis allocations solely to energy-intensive, trade-exposed sectors) are desirable.

Key Words: climate change, emissions trading, emissions permit allocations, output-based allocation, auction, grandfathering, international competitiveness, carbon leakage, CGE analysis

JEL Classification Numbers: C68, D42

Contents

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1. Introduction

To address climate change issues, the European Union has adopted a domestic system, the European Union Emission Trading Scheme (EU ETS). Other developed economies are now considering the adoption of domestic emissions trading schemes, and permit allocation methods have become an important issue. Many studies find that auctioning of permits is desirable in terms of both macroeconomic impact (effects on welfare and gross domestic product, GDP) and equity. However, auctioning permits would impose a heavy burden on energy-intensive industries. In particular, energy-intensive industries competing with foreign competitors could lose their edge and end up severely reducing production. In fact, because of the competitiveness issue, such industries have demonstrated strong opposition to the emissions trading schemes. Naturally, political support from industry, including energy-intensive industries, is essential to the adoption of an ETS. For this reason, to ensure smooth adoption of emissions controls, regulators must pay attention to the burden on energy-intensive industries and macroeconomic effects.

Reasons for lessening the burden on energy-intensive industries go beyond politics. Although emissions regulations can cause such industries in developed nations to reduce production, they also could cause carbon leakage by shifting production to countries where energy efficiency is lower and regulations are looser, such as China and India. This shift weakens the benefits of carbon regulations in developed countries by increasing emissions in developing countries. Major contractions in energy-intensive industries in regulated countries could simply result in large-scale leakage to countries without tight regulations. In light of the

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potential for such leakage, policymakers need to be cautious when placing a heavy burden on energy-intensive industries.

The gratis allocation of emissions permits, as opposed to auctioning, has been proposed to ease burden on energy-intensive industries. In fact, EU ETS employs a grandfathering method in Phase II (2008–2012).[1] Recently, another type of free allocation method, output-based allocation (OBA), has attracted attention. Under OBA, emissions permits are distributed gratis to firms involved in international competition, based on their output. In the United States, the Lieberman-Warner and Waxman-Markey bills have proposed OBA to protect domestic industries that compete in international markets while preventing leakage.

In response to the growing interest in OBA, Fischer and Fox (2007) employ a computable general equilibrium (CGE) model for a quantitative analysis of three methods: auctioning, grandfathering, and OBA in the United States. Their analysis suggests that OBA is somewhat effective in both helping energy-intensive industries and reducing leakage. Fischer and Fox (2010) extend this work by looking at specific combinations of OBA with either auctioning or grandfathering, to further explore the role of tax interactions as well as leakage. They find that, from a U.S. perspective, combining auctioning with OBA for energy intensive sectors—particularly the trade-exposed ones—is more cost effective policy than auctioning alone. The rationale involves a combination of tradeoffs in tax interaction effects, carbon leakage, and terms-of-trade effects. However, it is not clear if this result would extend to any country undertaking a unilateral policy. Because full-fledged emissions trading may be adopted in Japan, a quantitative economic analysis of the different permit allocation methods is needed to provide information for policy decisionmaking. In this study, we apply the Fischer and Fox model to Japan to compare the various permit allocation methods.

We construct a multiregional and multisector static CGE model with 14 regions and 26 sectors. We assume that each country and region consists of three economic agents—households, firms, and governments—and that households and firms behave optimally. To analyze energy production activities in detail, we have designated two types of production functions compliant with the GTAP-EG model: a fossil fuel production function and a non–fossil fuel production function. We also assume that household utility depends on consumption and leisure—that is, households choose the supply of labor endogenously.

[1] However, it must be noted that the targets of reductions in the first (2005–2007) and second (2008–2012) phases of the EU ETS are limited to sectors such as manufacturing and the energy conversion sector.

As emissions regulations, our analysis assumes a cap-and-trade scheme restricting total emissions. In addition, we assume that emissions controls are adopted by Japan, the United States, and the 27 EU member states, reducing emissions in these entities by 30 percent, 20 percent, and 16 percent, respectively, from 2004 levels. We also assume that no scheme for international emissions trading is adopted; emissions permits are traded only internally, within each country or region. In addition, because the primary aim of this study is to analyze emissions trading in Japan, we assume that the United States and the EU-27 countries always allocate quotas using an auctioning method, with only Japan changing allocation methods.

Following Fischer and Fox, we compare three allocation methods: auctioning (AUC), grandfathering (GF), and output-based allocation (OBA). GF and OBA allocate permits gratis. As opposed to GF, in which permits are allocated independently of firm behavior, permits are to firms' outputs under OBA. Because this allocation method has the effect of subsidizing production, prices of outputs do not rise when emissions controls are imposed. This reduces negative effects caused by the tax-interaction effects[2] and mitigates the leakage and competitiveness issues.

In theory, auction and gratis allocation (GF and OBA) are handled separately. In discussions of emissions controls, however, a combination of auction and gratis allocation methods has been proposed: some industries would receive permits gratis and others obtain permits through auctioning. For example, although plans call for the EU ETS to shift to an auctioning method in the future, gratis allocation would continue for industries exposed to "significant risk of carbon leakage," such as the steel industry.[3] Such a hybrid allocation method is under consideration in Japan as well. Therefore, we also analyze gratis allocation to only certain industries. Specifically, we analyze two scenarios with auctioning for most industries but gratis OBA for (1) eight energy-intensive trade-exposed (EITE) sectors, electricity, and refined petroleum and coal products (Scenario AO-E), and (2) only EITE sectors (Scenario AO-ET). The sectors receiving gratis allocation have been selected according to criteria used in the U.S. Clean Energy and Security Act of 2009 (see Sugino et al. 2010). We also assume that the government would adjust labor taxes to keep real government expenditures at a fixed level. This revenue-recycling effect reduces the distortion in labor markets.

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[2] See Bovenberg and Goulder (2002) for a detailed discussion of the tax interaction effect (and the revenue-recycling effect).

[3] Planned to begin with the third phase, starting in 2013.

Our model has many resemblances to but some important differences from Fischer and Fox (2007, 2010). First, whereas they use U.S. data for endogenizing labor supply in all regions, this study employs Japanese data for specifying the labor supply in Japan; furthermore, of importance for tax interaction effects, we note that labor tax rates are higher in Japan than in the U.S. Second, whereas Fischer and Fox (2007) use GTAP6 data with 2001 as the base year, like Fischer and Fox (2010) we use GTAP7 data with 2004 as the base year. Third, this study analyzes different hybrid allocation methods combining the auction and OBA methods likeFischer and Fox (2010). Fourth, unlike the Fischer and Fox studies, we assume that some major trading partners—notably the U.S. and the EU—already have emissions regulation in place, so the policy is not simply a unilateral one. But the main difference is our focus on the *Japanese* perspective, and how these climate policy options affect welfare, GDP, permit price, leakage, and production in each sector.

In addition to Fischer and Fox, other researchers have analyzed emissions trading from the perspective of initial permit allocation methods. Parry et al. (1999) employ a static CGE model to compare emissions trading using auctioning and free allocation under conditions of taxation leading to distortions in the United States.[4] In another study focusing on the United States, Goulder et al. (1999) compare various controls on carbon dioxide emissions, including emissions trading. Employing a forward-looking dynamic CGE model, Jensen and Rasmussen (2000) compare the three allocation methods of auctioning, grandfathering, and an OBA system based on market share in emissions trading in Denmark. Böhringer and Lange (2005) analyze the effects of emissions trading in the EU (primarily Germany), under auctioning, OBA, and free allocation based on emissions volume (i.e., share of emissions). Finally, Dissou (2006) employs a forward-looking dynamic CGE model to analyze emissions trading in Canada under auctioning, grandfathering, and OBA.

Those studies focused on ETS in Europe or North America. The competitiveness and leakage issues, however, may be more relevant for Japan because its industrial rivals, such as China and Korea, face no carbon caps and are geographically nearby. Thus, it is important to analyze the leakage and competitiveness issues under an ETS for the Japanese economy specifically. Analyzing an ETS for Japan is important from a European perspective as well. The EU is promoting an ETS for all countries of the Organisation for Economic Co-operation and Development by 2020. For that purpose, it is essential that Japan have a domestic ETS as early

[4] In fact, they compared a revenue-neutral carbon tax (reducing taxes on labor) with emissions trading through gratis allocation. However, the former policy was equivalent to the revenue-neutral auction-based emissions trading (reducing taxes on labor).

as possible. Unless the regulatory agencies can deal with the competitiveness and leakage issues to some degree, it will be extremely difficult for the Japanese government to adopt an ETS. This paper focuses on emissions trading in Japan by establishing parameters, data, and scenarios that provide useful information to assist Japanese policymakers in addressing the leakage and competitiveness issues.

Taking the Japanese perspective, we find some subtle and some significant differences compared to earlier studies. The most important results of our analysis can be summarized as follows. First, our analysis shows that when allocation methods are compared for macroeconomic effects (i.e., welfare and GDP), the least disruptive method is AUC, followed by AO-ET, AO-E, OBA, and finally, GF. Conversely, the results show that OBA and AO-E are superior for controlling carbon leakages and minimizing the burden on domestic energy-intensive industries. Still, in sensitivity analysis holding global emissions constant, the welfare ranking remains robust, indicating that the value of the leakage reductions does not offset the policy costs, which differs from previous studies for other regions. For example, Fisher and Fox (2010) showed that combining auctioning with OBA for energy intensive sectors is more cost effective policy than auctioning alone. The reason why we obtain different results for Japan may be attributed in part to the fact that the labor tax rates in Japan are higher than those in the U.S. Taking all results into consideration, AUC is the best allocation method if top priority is given to macroeconomic effects, but it causes overseas leakage and harms domestic energy-intensive industries. OBA causes the least leakage and the least harm to energy-intensive sectors, but its macroeconomic effects are undesirable. AO-ET provides balance: its macroeconomic effects are close to AUC and it simultaneously alleviates leakage effects and the burden on EITE sectors.

2. Model and Data

2.1 Model

We construct a static CGE model with 14 regions and 26 sectors (Table1). The structure of the model is similar to that of Fischer and Fox (2007) and GTAP-EG (Rutherford and Paltsev 2000).[5] In each region, there are three types of agents: representative households, government, and firms. A household supplies capital, labor, land, and natural resources and then allocates its factor income to the purchase of goods and investment (savings). The utility of the household

[5] The supplementary document describing the model structure in detail is available from the authors.

depends on consumption and leisure, and it determines consumption and leisure so as to maximize utility, subject to a budget constraint. We assume that capital and labor are mobile within a region and that land and natural resources are sluggish factors.

In the model, the tax rate on labor income is assumed to be determined endogenously so that real government expenditures are held constant. In addition to tax revenue, the government collects permit revenue, which is assumed to finance a reduction in the tax on labor income. Finally, firms produce goods with constant returns to scale technology and maximize profits using primary factors and intermediate inputs. To explain bilateral cross-hauling in the goods trade, we use the so-called Armington assumption: goods produced in different regions are qualitatively distinct (Armington 1969).

We assume two types of production functions: the fossil fuel production function and the non–fossil fuel production function. Fossil fuel production activities include the extraction of coal (COA), crude oil (OIL), and natural gas (GAS). Production has the structure shown in Figure 1. Fossil fuel output is produced as a constant elasticity of substitution (CES) aggregate of natural resources and non–natural resources input composite. The non–natural resources input is a Leontief composite of capital, labor, and intermediate inputs.

Non–fossil fuel production, including electricity (ELY) has the structure shown in Figure 2. Output is produced with Leontief aggregation of nonenergy goods and an energy–primary factor composite. The energy–primary factor composite is a nested CES function of the energy composite and the primary factor composite. In addition, with respect to refined petroleum and coal products (P_C sector), we assume that OIL enters into the production function at the top-level Leontief nest because most OIL is used as feedstock. Similarly, for the chemical products sector (CHM), we divide its energy use into feedstock requirements, which are treated as nonenergy intermediate inputs, and the remainder. For this, we use the feedstock ratio data of Lee (2008).

The utility function for the representative household is a nested CES function shown in Figure 3. We assume that the representative household derives utility from leisure and aggregate consumption. Aggregate consumption is a CES aggregation of a nonenergy composite and an energy composite. The nonenergy composite is a Cobb-Douglas aggregate of nonenergy goods, and the energy composite is a Cobb-Douglas aggregate of energy goods. Finally, investment is fixed at the benchmark level.

2.2 Benchmark Data and Parameter

For the benchmark data, we employ the GTAP 7 database with 2004 as the base year. For CO_2 emissions data, we generally follow the data provided by Lee (2008), except for the case of the CO_2 emissions of the Japanese iron and steel sector (I_S), since her data are far below than the actual values. Because I_S is of great importance in the analysis of emissions regulation, we correct the data according to the data provided by 3EID (Nansai and Moriguchi 2009). For elasticity of substitution parameters in production functions, we generally use the values from Fischer and Fox (2007) and GTAP data; for Armington elasticity parameters, we use GTAP values. The elasticity of substitution between resource and nonresource inputs in fossil fuel sectors (e_es(j) in Figure 1) is calibrated from the benchmark elasticity of supply for fossil fuels, which is assumed to be two for all fossil fuels.[6]

One of the major parameters in our model is the elasticity of substitution between leisure and consumption in the utility function. For the Japan parameter, we use a value of 0.73, which is estimated by Hatano and Yamada (2007) from leisure and labor data in Japan. In addition, we derive the benchmark labor tax rate and leisure time for Japan from labor and tax data for Japan (ESRI 2007; MFPRI 2008; MHLW 2008).[7] To derive the leisure-consumption elasticity and the leisure time for other regions, we use the same approach as Fischer and Fox (2007).

Data on the Japanese economy are also important for the modeling. Figure 4 depicts carbon intensity (tons of CO_2 per $1,000 of output) for each sector in Japan. As expected, the iron and steel (I_S), nonmetallic minerals (NMM), nonferrous metal (NFM), chemical products (CRP), paper and pulp products (PPP), and transport sectors (OTP, ATP, WTP) have high carbon intensities. In addition, Japan's fishery (FSH) sector is also carbon intensive. These sectors are likely to be significantly affected by carbon regulations. According to carbon intensity, we categorize I_S, FSH, NMM, OMN, CRP, NFM, and PPP as energy-intensive, trade-exposed (EITE) sectors. Table 2 shows the share of benchmark CO_2 emissions in Japan, the United States and EU-27 (EUR). Figure 5 and Figure 6 illustrate Table 2. Figure 5 exhibits the sum of direct and indirect emissions; Figure 6 shows direct CO_2 emissions only. Compared with the United States or EU-27, the share of emissions from Japan's iron and steel sector (I_S) is much greater,

[6] Note that overall leakage estimates can be sensitive to fuel supply elasticities (Burniaux and Martins 2000). In the appendix, we will conduct a sensitivity analysis on these elasticities.

[7] The estimated share of leisure time in total available time is 58.5 percent, and the estimated labor tax rate is 50 percent in the net term (33 percent in the gross term).

as is the share of Japan's fishery sector (FSH). Figure 7 reports export and import shares for Japan by destination and source. It shows that China (CHN), Korea (KOR), and other Asian regions (ASI), which are not obliged to reduce CO_2 emissions, are Japan's major trading partners. This suggests that emissions regulation in Japan is likely to damage the competitiveness of Japanese EITE sectors against those in China, Korea, and the rest of Asia.

3. Policy Scenarios

Although our main purpose is to analyze emissions regulations in Japan, it is unlikely that Japan will implement regulations alone. So we assume that the United States and the EU-27 impose emissions regulations in the baseline equilibrium, and then we analyze the incremental effects of regulation in Japan. The reduction rates (from 2004 levels) for Japan, the United States, and the EU-27 are 30 percent, 20 percent, and 16 percent, respectively. All these targets are translated from the Copenhagen pledges. We assume that a cap-and-trade scheme is introduced in the abating regions and that there is no international emissions trading. In addition, since the primary aim of this study is to analyze emissions trading in Japan, we assume that the United States and the EU-27 always allocate permits using auctioning with revenue recycling, while Japan considers alternate allocation methods. Across all policy scenarios, we assume that the representative household always obtains permits through the auction.

To analyze the effects of various allocation methods on the Japanese economy, we set up five scenarios (summarized in Table 3). Scenario AUC is the auction scheme, in which all permits are allocated to industries by auction. GF is the grandfathering allocation, in which permits are allocated free of charge to industries independent of firms' behavior. OBA is the output-based allocation scheme, in which the allocation of permits is determined by two stages: intra-industry allocation and inter-industry allocation. Intra-industry allocation is determined in proportion to firms' output, and inter-industry allocation is determined by the baseline CO_2 emissions share. Moreover, we consider the combinations of auction and OBA schemes, which are divided into two cases. In Scenario AO-E, the energy-intensive sectors as a whole (EITE, electricity, and refining sectors) are given gratis allocation, and all other sectors receive permits by auction. In Scenario AO-ET, only EITE sectors are given gratis allocation. The details of the allocation schemes are presented in the next section.

Under this framework, we analyze how allocation methods for emissions permits change the effects of the emissions controls on permit price, welfare, GDP, carbon leakage, production in each sector and trade, and other conditions.

3.1 Permit Allocation

Previous studies have defined gratis allocation differently. For example, in some studies grandfathering is synonymous with gratis allocation, and others define grandfathering as one method of gratis allocation. To avoid confusion, we explain the details of the allocation methods in the following.

In all cases, we consider a representative firm in sector *i*. Because firms produce goods under constant-returns-to-scale technology, we can define the unit cost function of production—inclusive of emissions permit liabilities—as $wa_i + p^{\mathrm{CO2}}e_i$, where w is the input price, a_i is input coefficient, p^{CO2} is the permit price and e_i is emission coefficient per unit of output. Let y_i be the output of the firm. Then $e_i y_i$ is the demand for permits in sector *i*, which is equal to the permits purchased (E_i).

3.1.1. Auction (AUC)

When permits are auctioned, the firm's profit is given by

$$\pi_i = (p_i - wa_i - p^{\mathrm{CO2}}e_i)y_i.$$

where p_i is the market price for the goods produced. Because the firm does not receive gratis permits, the profit does not include the value of gratis permits. By the profit maximization condition with respect to output, we obtain $p_i = wa_i + p^{\mathrm{CO2}}e_i$, which means that the profit is equal to zero ($\pi_i = 0$). The government collects permit revenue $\mathrm{p}^{\mathrm{CO2}} \sum_{\mathrm{i}} \mathrm{E}_{\mathrm{i}}$, and recycles it to reduce the tax on labor income.

3.1.2. Grandfathering (GF)

Let A_i be the amount of gratis permits allocated to sector *i*. The profit in the grandfathering scheme is given by

$$\pi_i = (p_i - wa_i - p^{\mathrm{CO2}}e_i)y_i + p^{\mathrm{CO2}}A_i \qquad (1)$$

where A_i is a fixed, lump-sum transfer. From this assumption, the first order condition for profit maximization is $p_i = wa_i + p^{\mathrm{CO2}}e_i$, which is the same as that of the auction scheme. As in the auction scheme, the demand for permits is given by $e_i y_i$. However, the amount of permits purchased is $E_i = e_i y_i - A_i$ (the negative value means that the firm sells permits to other firms). The government does not collect permit revenue because it allocates all permits for free. $p_i = wa_i + p^{\mathrm{CO2}}e_i$ implies that the firm obtains the excess profit

$$\pi_i = p^{\mathrm{CO2}}A_i.$$

We assume that this excess profit is transferred to the household in a lump-sum fashion. The same profit maximization condition with the auction scheme means that the condition for determining firms' behavior is the same in AUC and GF.

3.1.3. Output-Based Allocation (OBA)

Output-based allocation (OBA) is also a form of gratis allocation, distinct from GF in that the allocation of permits to a given firm is based on its current level of output, rather than a fixed amount. Let a_i^{OBA} be the amount of free permits per unit of output.[8] Therefore, the firm's profit becomes

$$\pi_i = (p_i - wa_i - p^{\mathrm{CO2}} e_i) y_i + p^{\mathrm{CO2}} a_i^{\mathrm{OBA}} y_i.$$

With output-based allocation, the allocation to individual firms in a sector is updated based on their output shares within the sector. The more the firm produces, the more gratis permits it receives, and more profit. The link between gratis permits and a firm's behavior (output) is the main characteristic of OBA. The profit maximization condition is given by

$$p_i = wa_i + p^{\mathrm{CO2}} \left(e_i - a_i^{\mathrm{OBA}}\right).$$

Although firm's cost increases as a result of CO_2 emissions controls, both because of a change in input costs as well as permit liabilities, the increase in the price of the good is constrained by the existence of $p^{\mathrm{CO2}} a_i^{\mathrm{OBA}}$. Hence, the increase in a good's price in an OBA scheme is lower than in auctions and grandfathering. This weakens the tax-interaction effect induced by emissions control (Fischer and Fox 2010). The number of permits that the firm needs to purchase is $E_i = \left(e_i - a_i^{\mathrm{OBA}}\right) y_i$ Although the allocation of permits within a sector is determined by output shares, the allocation of permits among sectors is set in proportion to the baseline emissions share.[9]

In the OBA scenario, we assume this method of allocation is used economywide, except for final demand.

3.1.4. Auctions with Output-Based Allocation (AO-E and AO-ET)

In Scenarios AO-E and AO-ET, OBA applies to some industries and auctioning (AUC) with revenue recycling applies to the remaining industries. We consider two cases, because there

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[8] a_i^{OBA} is regarded as constant by individual firms, but it is adjusted so that $A_i = a_i^{\mathrm{OBA}} y_i$ holds for exogenous A_i.

[9] Some studies assume that permit allocations among sectors are based on OBA (their output shares) as well. See Böhringer and Lange (2005).

is not yet a consensus on which sectors will be assigned gratis allocations. In AO-E, 9 energy-intensive sectors (electricity, EITE, and t refining sectors) are given OBA. In AO-ET, only EITE sectors receive OBA. The number of permits allocated free of charge decreases from AO-E to AO-ET. In the remainder of the paper, Scenario AO refers to both AO-E and AO-ET.

3.2 Volume of Gratis Permits

Table 4 reports the initial allocations of gratis permits for the scenarios with full or partial OBA. In OBA, allocations *within* sectors are determined according to output level, but allocations at the sector level are set in proportion to each sector's baseline direct emissions (i.e., indirect emissions from electricity are excluded). The same rule applies to AO, but the number of sectors with gratis allocation is limited. The total number of gratis permits is 725.7 MtCO_2 (87 percent of total emissions quotas) in OBA, and it falls to 193.7 MtCO_2 (23 percent) in AO-ET. Table 4 does not report allocations in GF because sector allocation has no effect on the results; the rents are passed through to the representative consumer/shareholder.

4. Simulation results

4.1 Macroeconomic Effects

We now explore the simulation results for the five allocation methods. We begin with the macroeconomic effects on Japan. In the following, the baseline equilibrium with abatement action only in USA and EUR is called business-as-usual (BaU). Table 5 summarizes the results across all scenarios. A permit price (U.S. dollars per metric ton of CO_2) is the highest in OBA, followed by AO-E, AO-ET, AUC, and GF, in descending order. Permit prices range from a high of $132.6 in the OBA scenario to a low of $93.9 in the GF scenario; thus, permit prices differ across allocation methods by around $40. The highest permit price occurs under OBA because carbon-intensive sectors get relatively higher subsidies, and the lack of incentives to conserve or find alternatives means that the other sectors or households must reduce their emissions more, and this requires a higher permit price. The permit price under AO comes closer to that under AUC (OBA) when the share of auctioned permits increases (decreases). Although the permit price in AO-E is the almost the same as in economywide OBA, the permit prices in AO-ET are very close to AUC. This suggests that permit price depends on whether the high-emitting energy sectors—electricity (ELY) and refined petroleum and coal products (P_C)—receive output-based allocation.

We report the impacts on Japanese welfare (in percent equivalent variation) for reaching the domestic target, excluding any valuation of differences in global emissions. These impacts are negative for all allocation methods. The negative welfare effects are the smallest in AUC, followed by AO-ET, AO-E, OBA, and GF. Although welfare loss in OBA is very close to that in GF, welfare loss in AO-ET is close to that in AUC. This also indicates that the gratis allocation to the electricity and petroleum and coal product sectors makes a large difference in the results. GDP loss is the smallest in AUC, followed by AO-ET, AO-E, OBA, and GF in ascending order. The ordering of allocation methods by GDP loss is the same as by welfare loss, but the dispersion of GDP losses is larger (as the value of changes in leisure are not included). Taking the above results together, we can conclude that in terms of macroeconomic effect *for a given domestic target*, AUC is the most desirable allocation method. This result contrasts to that in Fischer and Fox (2010), who found a preference for AO-ET. The difference may be attributed in part to the higher labor tax rates in Japan, which strengthen the tax interaction effect, and also to different terms of trade effects. In sensitivity analysis, we will compare the welfare costs of policies meeting a common *global* target, which holds the environmental benefits consistent across scenarios.

Because welfare and GDP depend on consumption, let us examine the change in consumption. The dampening effect on consumption is the smallest in AUC, followed by AO-ET, AO-E, OBA, and GF. This ordering is the same as that for welfare and GDP effects, which are closely linked to the effects on consumption. The AUC scenario yields an increase in consumption. In the AO-ET scenario, the decrease in consumption is small. The reason for the positive or small negative changes in consumption is the revenue-recycling effect. Because permit revenue is used to lower the labor tax, an AUC that generates a large amount of permit revenue increases the real wage for the representative household. As a result, labor supply, which is at an insufficient level in BaU, increases. This increase in labor supply raises labor income, and consumption increases as a result. In the AUC scenario, the government collects a permit revenue of roughly US$82 billion, and the revenue-recycling effect lowers the labor tax rate by six percentage points (from 50 percent in BaU to 44 percent). This leads to increases in the real wage and employment by 0.92 percent and 0.89 percent, respectively, which raises labor income and total income by 1.82 percent and 0.04 percent, respectively. As a consequence, consumption increases by 0.04 percent. Permit revenue for AO-ET is smaller than that for AUC because fewer permits are auctioned (permit revenue is roughly US$67 billion for AO-ET). Nevertheless, the revenue-recycling effect reduces the decrease in consumption under Scenario AO-ET (–0.25 percent for AO-ET).

Conversely, we observe a large decrease in consumption under grandfathering. This is attributed to the following two reasons. First, because permits are allocated to sectors for free, there is no revenue-recycling effect under GF.[10] Second, the negative tax-interaction effects become more apparent in GF than in other scenarios. Compared with OBA, which has an effect similar to a production subsidy, the output price increases more under GF. This increase in output price lowers real wages and thereby decreases the labor supply (which is already insufficient). The reason for the large decrease in consumption under GF is the small revenue-recycling effect and the large tax-interaction effect.

Under OBA, the revenue-recycling effect is as small as in GF. However, the increase in output price under OBA is smaller than under GF because OBA allocates gratis permits to firms in proportion to their output and is thus equivalent to a production subsidy. As a result, the tax-interaction effect is smaller in OBA than in GF, and therefore the decrease in consumption is smaller in OBA.

4.2 Carbon Leakage

The carbon leakage rate differs among our five allocation methods.[11] Table 5 shows that the leakage rate is the smallest with OBA, followed by AO-E, AO-ET, GF, and AUC. Except for GF, the leakage rate decreases with the number of sectors given gratis permits. OBA and AO-E have a smaller leakage effect; AUC and GF have more leakage. The leakage in AO-ET is between that of AUC and AO-E. We can conclude that in terms of leakage, OBA and AO-E are the most effective and AO-ET is the second best.

Table 6 reports the leakage rates to nonabating regions, by sector. It shows the contribution of each sector to the overall leakage rate in each allocation scenario. For example, the iron and steel sector (I_S) accounts for 4.14 percentage points of the total leakage rate of 20.58 percent under the AUC scenario. The leakage in the ELY and EITE sectors is large with all allocation methods. Although Japan does not trade electricity, the leakage in electricity is large because carbon regulation in Japan lowers international fossil fuel prices, which induces other regions to generate more electricity. Table 7 summarizes the leakage rates for EITE sectors

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[10] Strictly speaking, there is a small revenue-recycling effect because permits are always allocated by auction to households.

[11] The carbon leakage rate is defined as the ratio of total additional CO_2 emissions in regiongs other than Japan to total CO_2 emissions abated by Japan. For example, when the decrease in CO_2 emissions by Japan of 1 $MtCO_2$ leads to the increase in CO_2 emissions by the nonabating countries of 0.3 $MtCO_2$, the leakage rate is 30 percent.

using another calculation of leakage—the ratio of the increase in emissions from each sector in foreign countries to the decrease of CO_2 in the same sector of the Japanese economy. With this notion of leakage, nonferrous metal (NFM) and other mining (OMN) have very high leakage rates. One should note, however, that the volume of emissions from OMN is relatively small in Japan (Table 2). These two leakage tables show that all three OBA scenarios are highly effective at reducing leakage in the EITE sectors, particularly iron and steel, but other sectors are less responsive. Carbon leakage among non-energy-intensive and transportation sectors increases in the AO scenarios (Table 6).

Table 8 breaks out the contribution of each nonabating region to the overall leakage rate in each allocation scenario. For instance, China accounts for 6.43 percent of the total leakage rate of 20.58 percent under the AUC scenario. In all scenarios, the leakage rates to CHN, ASI, and FSU are high. In addition, the change in allocation schemes has the largest effect on the leakage to CHN. This indicates that China is the most important region when we analyze the leakage from Japan.

4.3 Effects of CO_2 Emissions Abatement on Each Sector

The main reason for adopting gratis allocation methods is to lessen the burden on energy-intensive industries. We now turn to the effects of allocation methods on the sectors. Although many possible indicators could represent differences in sectoral burdens, we analyze effects on output, exports, and imports.

Table 9 summarizes percentage changes in output from BaU. It shows that output in many sectors tends to decrease. The rate of the output decrease, however, differs by allocation method. With GF and AUC, the rates of decrease in output for energy-intensive sectors—in particular, ELY and I_S—are very steep. With OBA and AO, however, the decline in output for energy-intensive sectors is significantly mitigated. With OBA and AO-E, the rates of decrease in output of energy-intensive sectors as a whole become smaller. With AO-ET, which gives no gratis permits to the electricity sector, the reductions in output are mitigated only in EITE sectors, and to a lesser extent than the other OBA scenarios, since upstream electicity production is receives no offsetting subsidies.

Table 10 presents the percentage change in exports and imports. Because Japan does not trade ELY, its value is zero. Table 10 shows that the effects on the exports of individual sectors differ across allocation schemes. With AUC and GF, exports of energy-intensive sectors—in particular, I_S, FSH, NMM, OTP, and ATP—decrease significantly. However, this effect is mitigated with OBA and AO-E, particularly in I_S and NMM and somewhat in FSH. Similarly, AO-ET can mitigate the decline in exports of EITE to a large extent. Harmful effects on imports are generally smaller than those on exports except for fossil fuels, but imports for EITE sectors—in particular, I_S, FSH, and NMM—significantly increase with AUC and GF. The effects on imports are also mitigated with OBA and AO.

We analyzed how the effects of CO_2 emissions abatement differ by the allocation methods in terms of sectoral output, exports, and imports. Overall, our numerical results suggest that AUC and GF cause significant harm to energy-intensive sectors and that OBA and AO can mitigate the effect to a large extent.

4.4 Effects on Other Regions

This subsection examines the effects of emissions abatement on China, Korea, and other Asian countries, all of which have strong trade relationships with Japan. To do so, we examine changes in these countries' output and CO_2 emissions by sector. In the following, we look only at AUC, OBA, and AO-ET because GF is inferior to other allocation methods in all aspects and because the effects of AO-E and OBA are similar.

Table 11 represents the changes in output in Asian countries, as a percentage of their BaU production. It shows that emissions regulations in Japan generally have small effects except on EITE sectors—in particular, I_S. The increase in the output of EITE sectors is less under OBA and AO-ET because OBA and AO restrain the relocation of energy-intensive production to Asia. Non-energy-intensive sectors face smaller but opposite effects: their output is larger under OBA and AO than under AUC, which generally causes decreases in production in China and Korea.

Table 12 reports changes in CO_2 emissions in Asian countries. With the exception of extractive resources, emissions increase nearly across the board. With AUC, CO_2 emissions from the ELY and EITE sectors increase to a large extent, especially in China; the change in electricity emissions is in part due to increased demand from EITE sectors, and in part due to fuel price changes that leave carbon intensive energy cheaper in nonabating countries. Roughly half of the increase in CO_2 emissions from EITE sectors is counteracted under OBA and AO-ET (somewhat less for ASI), indicating that OBA and AO-ET are effective in preventing carbon leakage to these regions.

4.5 Sensitivity Analysis

In implementing the simulation, we made various assumptions, some of which may be less sound than others. We therefore conducted a sensitivity analysis to examine how the results change when the assumptions are modified. The assumptions we consider here are (1) the elasticity of substitution between consumption and leisure in utility; (2) Armington elasticity; (3) the benchmark value of fossil fuel supply; and (4) the case of fixed global emissions, in which the Japanese emissions target is endogenously set depending on the leakage to other regions.[12] The sensitivity analysis shows that although the quantitative results are significantly different in some cases, the qualitative results are not greatly affected in most cases. In particular, we find that the allocation policy rankings do not change when global emissions are held constant. (To save space, we do not present the numerical results here. The complete results of the sensitivity analysis are available from the authors upon request.)

5. Conclusions

Using a static CGE model with 14 regions and 26 sectors, this paper examines the effects of various permit allocation methods for a Japanese domestic ETS. Our analysis assumes that Japan, the United States, and the EU-27 countries implement a cap-and-trade scheme to reduce CO_2 emissions by 30 percent, 20 percent, and 16 percent, respectively, from 2004 levels. With these models and assumptions, we have explored how allocation methods affect Japan. We compare five allocation methods: auctioning (AUC), grandfathering (GF), output-based allocation (OBA) and the two combined schemes of output-based allocation and auction (AO-E and AO-ET).

The most important results of our analysis are summarized as follows, from the perspective of the Japanese economy. First, GF is inferior to all other allocation methods from all three perspectives: macroeconomic effect, leakage, and burden on domestic energy-intensive sectors. There are two reasons for GF's poor performance: it has a small positive revenue-recycling effect, and it has a strong negative tax interaction effect.

AUC is the most desirable allocation method in terms of macroeconomic effects. AUC, however, not only leads to large leakage rates but also has considerable negative effects on domestic energy-intensive sectors. The result that AUC is the best in terms of welfare is contrast to Fisher and Fox (2010), which showed that combining auctioning with OBA for energy intensive sectors is more cost effective policy than auctioning alone. Although there are many possible reasons for the different result, it may be attributed in part to the fact that the labor tax

[12] See Table A-1 in the Appendix for the case of a constant global emission scenario. In this scenario, the emission reduction target of the Japanese economy is reduced in OBA because of the smaller leakage rate. Overall, the effect is reduced. The ranking of the allocation methods, however, does not change. The difference across various allocation methods becomes smaller. One can also point out that the burden on EITE is reduced as expected.

rates in Japan are higher than those in the U.S. OBA and AO-E generally have similar effects, which is interesting to note since implementing OBA among all the non-energy-intensive and transportation sectors would be practically challenging. These two scenarios perform best in terms of leakage and effects on energy-intensive sectors. However, they are inferior in terms of macroeconomic effects. AO-ET is relatively desirable in terms of macroeconomic effects because its welfare effects are similar to those under AUC and because the GDP effect is far superior to that under GF, OBA, and AO-E. In addition, leakage under AO-ET is only slightly inferior to that under OBA and AO-E. With respect to sectoral effects, the damage to EITE sectors is relatively small in AO-ET, though the effects on the electricity sector are large, as they are with AUC.

To summarize, if macroeconomic effects are the top priority, AUC is the most desirable allocation method. If leakage and competitiveness issues are most important, OBA and AO-E are desirable. However, for all three issues, AO-ET is most preferable: its macroeconomic effect is close to that under AUC, and at the same time it has low leakage and a low burden on EITE sectors. Economists often evaluate policy solely on the basis of macroeconomic consequences and therefore tend to support auctioning of permits. Taking the other issues in account as well, however, other allocation methods may be more desirable. Indeed, our quantitative analysis supports the conclusion that combining the auction and OBA schemes can be a well-balanced allocation method.

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Tables and Figures

Table1. Regions and sectors

Symbol	Regions
USA	United States
CAN	Canada
JPN	Japan
OOE	Other OECD
EUR	EU27
FSU	Former Soviet Union
OEU	Other Europian regions
CHN	China (+ Taiwan)
KOR	Korea
IND	India
BRA	Brazil
ASI	Other Asia
MPC	Mexico + OPEC
ROW	Rest of world

Symbol	Sectors	
FSH	Fishery	Energy-intensive Trade Exposed Sectors (EITE)
OMN	Other mining	
PPP	Paper-pulp-print	
CRP	Chemical industry	
NMM	Non-metallic minerals	
NFM	Non-ferrous metals	
I_S	Iron and steel industry	
ELY	Electricity	
P_C	Petroleum and coal products	
COA	Coal	Fossil Fuel Sectors (FENE)
OIL	Crude oil	
GAS	Gas	
OTP	Transport nec	Transport Sectors (TRANS)
WTP	Water transport	
ATP	Air transport	
AGR	Agriculture	Non-energy Intensive Sectors (NEIT)
FPR	Food products	
TWL	Textiles-wearing apparel-leather	
LUM	Wood and wood-products	
TRN	Transport equipment	
OME	Other machinery	
OMF	Other manufacturing	
CNS	Construction	Services Sectors (SVCES)
TRD	Trade	
CMN	Communication	
SER	Commercial and public services	

Table 2. Share of benchmark CO2 emissions in Japan, United States, and European Union, by sector (percentage direct + indirect emissions)

	JPN		USA		EUR	
FSH	1.6	(1.6)	0.1	(0.1)	0.4	(0.3)
OMN	0.4	(0.3)	0.5	(0.0)	0.6	(0.3)
PPP	3.2	(1.5)	3.7	(1.8)	3.6	(1.5)
CRP	10.4	(7.2)	8.4	(4.3)	8.5	(4.4)
NMM	3.6	(2.4)	2.6	(1.9)	5.7	(4.3)
NFM	1.3	(0.3)	1.7	(0.5)	1.9	(0.6)
I_S	20.0	(16.6)	2.7	(1.4)	5.3	(3.2)
ELY	1.7	(0.0)	3.1	(0.0)	2.4	(0.0)
P_C	1.8	(1.3)	5.3	(4.6)	2.6	(1.9)
COA	0.0	(0.0)	0.2	(0.0)	0.3	(0.1)
OIL	0.0	(0.0)	0.7	(0.6)	0.4	(0.4)
GAS	0.0	(0.0)	1.2	(1.0)	0.5	(0.4)
OTP	19.8	(18.5)	20.0	(19.3)	23.9	(22.5)
WTP	2.1	(2.0)	1.0	(0.9)	4.1	(4.0)
ATP	1.4	(1.3)	11.1	(11.0)	5.7	(5.7)
AGR	1.7	(1.6)	1.2	(1.2)	3.3	(2.6)
FPR	2.0	(1.2)	3.0	(1.7)	4.4	(2.6)
TWL	0.2	(0.1)	0.8	(0.3)	1.3	(0.6)
LUM	0.1	(0.0)	0.7	(0.3)	0.6	(0.2)
TRN	0.1	(0.0)	1.1	(0.4)	1.3	(0.5)
OME	1.5	(0.2)	1.3	(0.4)	1.7	(0.7)
OMF	3.7	(0.9)	1.7	(0.5)	2.0	(0.8)
CNS	1.4	(1.3)	0.4	(0.4)	1.0	(0.8)
TRD	4.7	(1.6)	9.1	(1.7)	5.5	(2.2)
CMN	0.6	(0.2)	0.4	(0.0)	0.5	(0.1)
SER	16.8	(8.5)	18.1	(4.8)	12.6	(4.6)
SUM	100.0	(68.7)	100.0	(59.1)	100.0	(65.4)

Notes: Values in parenthesis are share of direct emissions.
Direct emissions from ELY are allocated to other sectors as indirect emissions.

Table 3. Scenarios

Symbol	Scenario
AUC	All permits are allocated by auction.
GF	Gratis allocation by grandfathering.
OBA	Intra-industry allocation is based on OBA and inter-industry allocation is based on baseline emissions share.
AO-E	OBA for EITE, electricity, and petroleum and coal products sectors and auction for other sectors.
AO-ET	OBA for EITE sectors and auction for other sectors.

Table 4. Initial allocation of permits in Japan ($MtCO_2$)

	OBA	AO-E	AO-ET
FSH	10.2	10.2	10.2
OMN	1.7	1.7	1.7
PPP	9.5	9.5	9.5
CRP	46.8	46.8	46.8
NMM	15.9	15.9	15.9
NFM	1.8	1.8	1.8
I_S	107.8	107.8	107.8
ELY	280.2	280.2	0.0
P_C	8.2	8.2	0.0
OTP	120.0	0.0	0.0
WTP	13.2	0.0	0.0
ATP	9.0	0.0	0.0
AGR	10.6	0.0	0.0
FPR	7.5	0.0	0.0
TWL	0.4	0.0	0.0
LUM	0.0	0.0	0.0
TRN	0.1	0.0	0.0
OME	1.4	0.0	0.0
OMF	6.1	0.0	0.0
CNS	8.2	0.0	0.0
TRD	10.5	0.0	0.0
CMN	1.1	0.0	0.0
SER	55.3	0.0	0.0
Gratis	725.7	482.2	193.7
Auction	107.5	351.0	639.5
Total	833.2	833.2	833.2

Notes: Gratis is total amount of gratis permits. Auction is total amount of permits by auction. Total is total emissions cap.

Table 5. Macroeconomic indicators in Japan

	AUC	GF	OBA	AO-E	AO-ET
CO2 emissions	-30.48	-30.48	-30.48	-30.48	-30.48
Permit price ($/tCO2)	97.91	93.85	132.58	129.70	104.47
Welfare	-0.28	-0.54	-0.52	-0.44	-0.34
Real GDP	-0.07	-0.86	-0.66	-0.48	-0.24
Consumption	0.04	-1.34	-1.01	-0.65	-0.25
Export	-3.10	-3.64	-2.96	-2.89	-2.86
Import	-2.87	-3.43	-2.75	-2.46	-2.52
Terms of trade	0.79	0.90	0.73	0.89	0.80
VNPR (bil.$)	81.58	78.20	14.26	45.52	66.81
Labor tax rate (%)	44.35	50.00	50.57	48.02	45.75
Wage rate	0.92	-2.29	-1.38	-0.59	0.27
Labor supply	0.89	-0.48	-0.01	0.31	0.63
Labor income	1.82	-2.77	-1.39	-0.29	0.89
Total income	0.04	-1.34	-1.01	-0.65	-0.25
Leakage rate (%)	20.58	20.36	15.27	15.31	16.92

Notes: Percentage change from BaU unless otherwise indicated.
VNPR is value of net permit revenue (US$ billion).

Table 6. Leakage to nonabating regions, by sector (percentage)

	AUC	GF	OBA	AO-E	AO-ET
FSH	0.07	0.05	0.07	0.07	0.06
OMN	0.12	0.12	0.08	0.08	0.10
PPP	0.09	0.09	0.12	0.11	0.12
CRP	1.79	1.78	1.46	1.33	1.51
NMM	1.36	1.36	0.93	0.90	1.08
NFM	0.28	0.28	0.26	0.24	0.34
I_S	4.14	4.10	1.16	1.07	1.63
EITE	7.85	7.79	4.07	3.80	4.84
ELY	10.09	10.08	8.23	7.53	8.52
P_C	0.24	0.21	0.06	0.12	0.25
COA	-0.46	-0.46	-0.53	-0.53	-0.51
OIL	-0.50	-0.52	-0.57	-0.55	-0.53
GAS	-0.86	-0.85	-0.95	-0.94	-0.92
FENE	-1.82	-1.83	-2.04	-2.02	-1.97
OTP	1.17	1.16	1.17	1.45	1.33
WTP	0.10	0.07	0.05	0.33	0.22
ATP	0.74	0.68	0.49	1.19	0.97
TRANS	2.01	1.91	1.71	2.97	2.51
AGR	0.10	0.07	0.16	0.17	0.15
FPR	0.08	0.07	0.13	0.13	0.12
TWL	0.02	0.01	0.08	0.07	0.06
LUM	0.00	0.00	0.02	0.02	0.01
TRN	0.01	0.02	0.05	0.04	0.02
OME	0.06	0.08	0.15	0.12	0.10
OMF	0.20	0.22	0.29	0.28	0.27
NEINT	2.49	2.38	2.59	3.80	3.26
CNS	0.04	0.04	0.06	0.05	0.05
TRD	0.11	0.11	0.15	0.14	0.14
CMN	0.01	0.01	0.01	0.01	0.01
SER	0.13	0.12	0.21	0.19	0.18
SVCES	0.29	0.28	0.43	0.40	0.37
HH	1.45	1.45	1.94	1.68	1.66
SUM	20.58	20.36	15.27	15.31	16.92

Note: HH is representative household.

Table 7. Alternative expression of leakage to nonabating regions, by sector (percentage)

	AUC	GF	OBA	AO-E	AO-ET
FSH	9.63	7.21	9.01	8.89	9.40
OMN	103.11	100.68	70.74	68.42	83.61
PPP	8.29	8.38	11.51	10.53	10.40
CRP	33.38	33.28	27.76	25.78	28.57
NMM	66.52	67.17	45.69	44.55	52.37
NFM	220.74	228.45	264.00	248.93	258.37
I_S	25.44	25.44	7.98	7.46	11.29
EITE	30.51	30.47	17.09	16.11	20.33

Notes: HH is representative household.
The leakage rate for sector i here is defined as the ratio of the increase in CO2 emissions from sector i in nonabating regions to the decrease in CO2 emissions from sector i in Japan.

Table 8. Leakage to nonabating regions (percentage)

	AUC	GF	OBA	AO-E	AO-ET
CHN	6.43	6.37	3.86	3.70	4.46
KOR	1.09	1.07	0.81	0.81	0.86
ASI	3.33	3.28	2.83	2.89	3.04
USA	0.00	0.00	0.00	0.00	0.00
CAN	0.29	0.28	0.22	0.26	0.28
OOE	1.52	1.51	1.35	1.38	1.49
EUR	0.00	0.00	0.00	0.00	0.00
FSU	2.59	2.57	1.78	1.76	1.95
OEU	0.09	0.09	0.07	0.08	0.09
IND	1.25	1.26	1.12	1.05	1.13
BRA	0.25	0.25	0.14	0.14	0.16
MPC	2.21	2.18	1.94	2.02	2.17
ROW	1.52	1.51	1.15	1.21	1.29
SUM	20.58	20.36	15.27	15.31	16.92

Table 9. Change in output (percentage)

	AUC	GF	OBA	AO-E	AO-ET
FSH	-3.7	-4.3	-3.6	-3.4	-2.7
OMN	-2.1	-2.3	-1.1	-1.2	-1.6
PPP	-0.4	-1.3	-1.0	-0.7	-0.6
CRP	-3.4	-4.0	-2.0	-1.5	-2.1
NMM	-2.3	-2.6	-1.1	-1.0	-1.4
NFM	-3.2	-3.6	-2.2	-1.7	-4.2
I_S	-11.2	-11.4	-2.7	-2.3	-4.0
EITE	-4.2	-4.7	-1.9	-1.5	-2.2
ELY	-12.7	-13.1	-4.7	-4.5	-12.8
P_C	-15.2	-15.5	-15.1	-15.3	-15.4
COA	0.0	0.0	0.0	0.0	0.0
OIL	0.0	0.0	0.0	0.0	0.0
GAS	0.0	0.0	0.0	0.0	0.0
FENE	0.0	0.0	0.0	0.0	0.0
OTP	-1.9	-2.8	-1.4	-2.9	-2.3
WTP	-2.9	-3.2	-1.8	-4.4	-3.6
ATP	-6.4	-7.1	-3.0	-10.5	-8.2
TRANS	-2.3	-3.1	-1.5	-3.6	-2.9
AGR	-0.6	-1.4	-1.4	-1.9	-1.2
FPR	-0.3	-1.4	-1.2	-1.2	-0.6
TWL	1.7	0.3	-1.3	-0.8	0.1
LUM	0.5	0.1	-1.1	-1.1	-0.6
TRN	-0.1	-0.8	-1.6	-0.9	-0.1
OME	-0.3	-0.9	-1.8	-1.1	-0.9
OMF	-0.7	-1.4	-1.6	-1.3	-1.4
NEINT	-0.7	-1.5	-1.5	-1.6	-1.2
CNS	-0.2	-0.3	-0.2	-0.2	-0.2
TRD	0.5	-0.6	-0.7	-0.3	0.1
CMN	0.5	-0.5	-0.7	-0.3	0.1
SER	0.2	-0.6	-0.6	-0.4	-0.1
SVCES	0.2	-0.6	-0.6	-0.3	-0.1

Table 10. Change in exports and import (percentage)

	Export					Import				
	AUC	GF	OBA	AO-E	AO-ET	AUC	GF	OBA	AO-E	AO-ET
FSH	-17.7	-15.5	-13.8	-13.9	-12.4	7.5	5.3	5.0	5.2	4.9
OMN	-3.7	-3.5	-2.3	-3.6	-3.9	-5.9	-6.3	-2.0	-1.5	-3.1
PPP	-2.1	-2.6	-2.6	-1.8	-3.6	0.7	0.1	0.5	0.2	1.4
CRP	-9.2	-9.1	-3.7	-3.0	-5.1	2.9	2.1	0.5	0.5	1.4
NMM	-13.0	-12.9	-3.8	-4.1	-7.4	7.4	6.8	1.5	1.8	3.8
NFM	-8.6	-8.7	-3.5	-2.8	-11.3	1.3	0.7	-0.4	-0.3	1.9
I_S	-44.1	-43.1	-6.0	-5.9	-13.6	35.0	33.1	2.0	2.1	7.1
EITE	-15.6	-15.4	-4.1	-3.6	-7.3	3.6	2.8	0.3	0.4	1.5
ELY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P_C	-8.4	-8.1	-1.6	-1.7	-9.0	-7.4	-7.8	-8.8	-8.9	-6.7
COA	0.0	0.0	0.0	0.0	0.0	-39.4	-39.3	-39.3	-39.2	-39.9
OIL	0.0	0.0	0.0	0.0	0.0	-15.2	-15.4	-14.8	-15.0	-15.3
GAS	0.0	0.0	0.0	0.0	0.0	-41.9	-41.6	-42.9	-42.5	-42.7
FENE	0.0	0.0	0.0	0.0	0.0	-22.2	-22.3	-22.1	-22.1	-22.4
OTP	-10.9	-11.0	-5.7	-18.8	-15.0	2.2	1.2	1.0	4.6	3.7
WTP	-2.7	-2.8	-1.6	-5.0	-3.7	-2.1	-2.4	-1.4	-2.7	-2.3
ATP	-10.0	-10.1	-4.4	-16.3	-12.9	2.5	1.3	0.9	4.8	3.8
TRANS	-5.1	-5.3	-2.7	-8.9	-6.9	1.2	0.3	0.3	2.8	2.1
AGR	-2.5	-1.0	-3.7	-8.0	-5.6	0.6	-1.1	0.5	2.3	1.7
FPR	-0.9	-0.7	-3.9	-5.8	-4.0	0.2	-1.1	0.9	1.9	1.5
TWL	4.9	3.6	-2.4	-1.9	0.1	-1.1	-2.0	0.1	0.4	0.1
LUM	4.4	3.8	-2.8	-3.4	-0.9	-1.6	-1.8	0.3	0.4	-0.3
TRN	0.0	-0.7	-2.4	-1.4	-0.1	-0.2	-0.5	0.5	0.3	0.0
OME	-0.6	-1.4	-2.9	-1.8	-1.5	0.0	0.0	0.7	0.4	0.4
OMF	-1.3	-2.0	-3.3	-3.2	-3.3	0.1	-0.1	0.7	0.9	0.9
NEINT	-1.0	-1.7	-2.8	-2.9	-2.2	0.0	-0.6	0.6	1.1	0.8
CNS	1.9	1.1	-1.8	-2.0	-0.3	-1.0	-0.6	1.0	1.1	0.1
TRD	5.2	4.2	-1.6	-1.1	0.9	-1.7	-2.5	0.2	0.5	0.0
CMN	5.6	5.2	-1.6	-0.7	1.4	-2.1	-3.0	0.1	0.1	-0.5
SER	5.1	4.7	-1.7	-1.1	1.0	-2.6	-3.2	0.0	0.1	-0.8
SVCES	4.7	4.0	-1.7	-1.3	0.8	-2.3	-2.9	0.1	0.2	-0.6
CGD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 11. Change in output in China, Korea, and other Asia (percentage)

CKA outpu	CHN			KOR			ASI		
	AUC	OBA	AO-ET	AUC	OBA	AO-ET	AUC	OBA	AO-ET
FSH	0.10	0.09	0.08	0.58	0.48	0.43	0.09	0.08	0.07
OMN	0.52	0.09	0.23	0.68	0.09	0.27	0.12	0.07	0.21
PPP	-0.01	0.06	0.06	-0.02	0.00	0.03	0.39	0.39	0.40
CRP	0.41	0.19	0.24	0.75	0.41	0.47	1.47	0.89	1.00
NMM	0.46	0.14	0.25	0.70	0.15	0.34	0.95	0.54	0.67
NFM	0.14	0.06	0.37	-0.03	-0.21	0.10	0.90	0.58	1.19
I_S	2.36	0.37	0.69	4.30	0.37	1.06	5.84	1.44	2.20
EITE	0.78	0.19	0.32	1.53	0.29	0.54	1.37	0.70	0.88
ELY	0.38	0.19	0.23	0.67	0.32	0.37	0.76	0.60	0.63
P_C	0.32	0.05	0.15	0.28	-0.03	0.12	0.24	0.08	0.20
COA	-1.13	-1.32	-1.28	0.00	0.00	0.00	-3.74	-3.98	-4.00
OIL	-0.72	-0.90	-0.80	0.00	0.00	0.00	-0.67	-0.93	-0.83
GAS	-1.40	-1.54	-1.52	0.00	0.00	0.00	-3.80	-4.14	-4.05
FENE	-0.98	-1.16	-1.10	0.00	0.00	0.00	-2.27	-2.56	-2.48
OTP	0.09	0.02	0.10	0.28	0.14	0.24	0.22	0.17	0.24
WTP	0.08	-0.04	0.06	-0.37	-0.36	-0.33	0.11	0.03	0.18
ATP	0.34	0.05	0.50	0.38	0.08	0.52	0.65	0.39	0.76
TRANS	0.11	0.01	0.13	0.15	0.02	0.15	0.27	0.18	0.32
AGR	-0.02	0.00	0.01	0.00	0.01	0.02	0.03	0.02	0.03
FPR	-0.05	0.02	0.03	-0.05	0.03	0.02	0.02	0.03	0.04
TWL	-0.31	-0.07	-0.12	-0.26	-0.05	-0.12	0.32	0.31	0.25
LUM	-0.30	-0.08	-0.18	-0.18	-0.08	-0.08	0.02	0.26	0.10
TRN	-0.10	0.14	-0.05	-0.74	-0.05	-0.35	-0.12	0.38	0.07
OME	-0.16	0.28	0.05	-0.52	0.01	-0.17	0.03	0.73	0.39
OMF	-0.15	0.13	0.08	-0.46	-0.16	-0.10	0.14	0.66	0.54
NEINT	-0.11	0.08	0.03	-0.38	-0.05	-0.11	0.12	0.33	0.27
CNS	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00
TRD	-0.04	0.02	0.00	-0.06	0.03	0.00	0.09	0.15	0.12
CMN	-0.04	0.01	-0.01	-0.06	0.01	-0.01	0.09	0.09	0.09
SER	-0.04	0.00	-0.01	-0.03	0.01	0.00	0.03	0.04	0.04
SVCES	-0.03	0.01	-0.01	-0.03	0.01	0.00	0.04	0.07	0.06

Table 12. Change in CO_2 emissions in China, Korea, and other Asia ($MtCO_2$)

CKA CO2_(	CHN			KOR			ASI		
	AUC	OBA	AO-ET	AUC	OBA	AO-ET	AUC	OBA	AO-ET
FSH	0.08	0.09	0.08	0.05	0.04	0.04	0.04	0.05	0.04
OMN	0.17	0.06	0.10	0.00	0.00	0.00	0.04	0.04	0.06
PPP	0.08	0.13	0.12	0.01	0.01	0.01	0.16	0.17	0.17
CRP	1.43	1.03	1.12	0.09	0.07	0.07	1.69	1.29	1.37
NMM	2.55	1.48	1.85	0.24	0.15	0.18	1.52	1.17	1.29
NFM	0.11	0.09	0.20	0.00	0.00	0.00	0.09	0.07	0.10
I_S	5.89	1.33	2.05	0.67	0.12	0.22	1.31	0.44	0.59
EITE	10.32	4.21	5.54	1.05	0.40	0.52	4.85	3.23	3.62
ELY	13.47	9.56	10.43	2.20	1.70	1.74	5.24	4.78	4.90
P_C	0.02	0.00	0.01	0.00	0.00	0.00	0.14	0.05	0.12
COA	-1.32	-1.54	-1.50	0.00	0.00	0.00	-0.06	-0.07	-0.07
OIL	-0.33	-0.41	-0.37	0.00	0.00	0.00	-0.05	-0.07	-0.07
GAS	-0.93	-1.02	-1.01	0.00	0.00	0.00	-0.32	-0.35	-0.34
FENE	-2.58	-2.97	-2.87	0.00	0.00	0.00	-0.44	-0.49	-0.48
OTP	0.38	0.35	0.43	0.26	0.21	0.26	0.49	0.50	0.56
WTP	0.25	0.16	0.25	-0.04	-0.04	-0.04	0.10	0.09	0.15
ATP	0.14	0.07	0.19	0.06	0.03	0.08	0.41	0.29	0.49
TRANS	0.77	0.58	0.87	0.28	0.21	0.31	1.01	0.88	1.21
AGR	0.15	0.25	0.24	0.01	0.01	0.01	0.03	0.04	0.04
FPR	0.09	0.15	0.15	0.01	0.02	0.02	0.14	0.16	0.16
TWL	-0.06	0.09	0.06	0.01	0.02	0.01	0.09	0.09	0.08
LUM	-0.01	0.02	0.01	0.00	0.00	0.00	0.01	0.02	0.01
TRN	0.02	0.08	0.04	0.00	0.02	0.01	0.02	0.03	0.02
OME	0.02	0.20	0.11	0.00	0.00	0.00	0.07	0.13	0.10
OMF	0.01	0.06	0.05	0.00	0.00	0.00	0.22	0.34	0.32
NEINT	0.99	1.42	1.52	0.31	0.29	0.37	1.59	1.69	1.94
CNS	0.06	0.07	0.07	0.00	0.01	0.01	0.02	0.03	0.02
TRD	0.10	0.16	0.14	0.01	0.02	0.02	0.21	0.23	0.23
CMN	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.01
SER	0.13	0.19	0.17	0.11	0.14	0.13	0.33	0.35	0.35
SVCES	0.29	0.42	0.38	0.13	0.17	0.15	0.57	0.63	0.61
HH	1.00	1.44	1.28	0.32	0.41	0.37	0.22	0.45	0.38
SUM	23.50	14.09	16.29	4.00	2.96	3.15	12.17	10.34	11.10

Figure 1. Production function of fossil fuel sectors

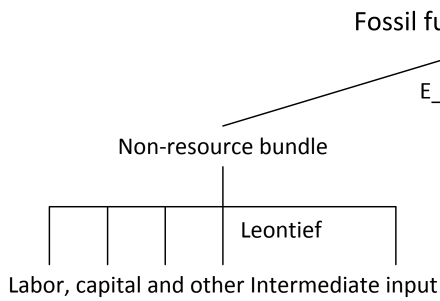


Figure 2. Production function of non–fossil fuel sectors

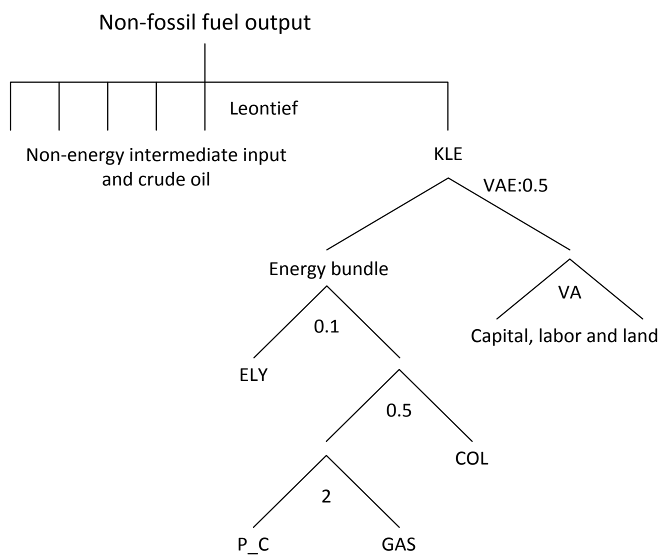


Figure 3. Utility function

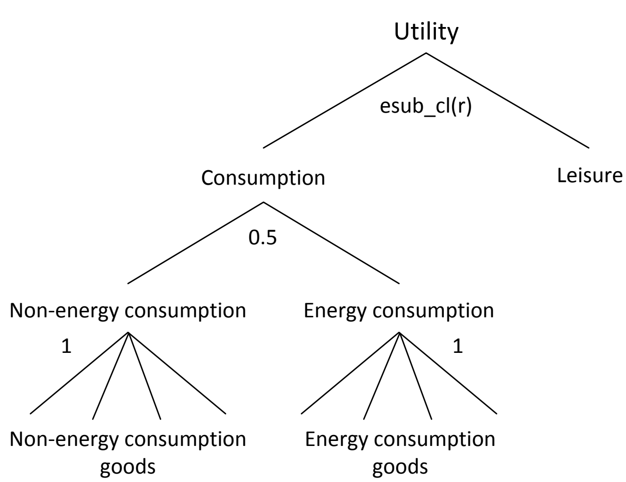
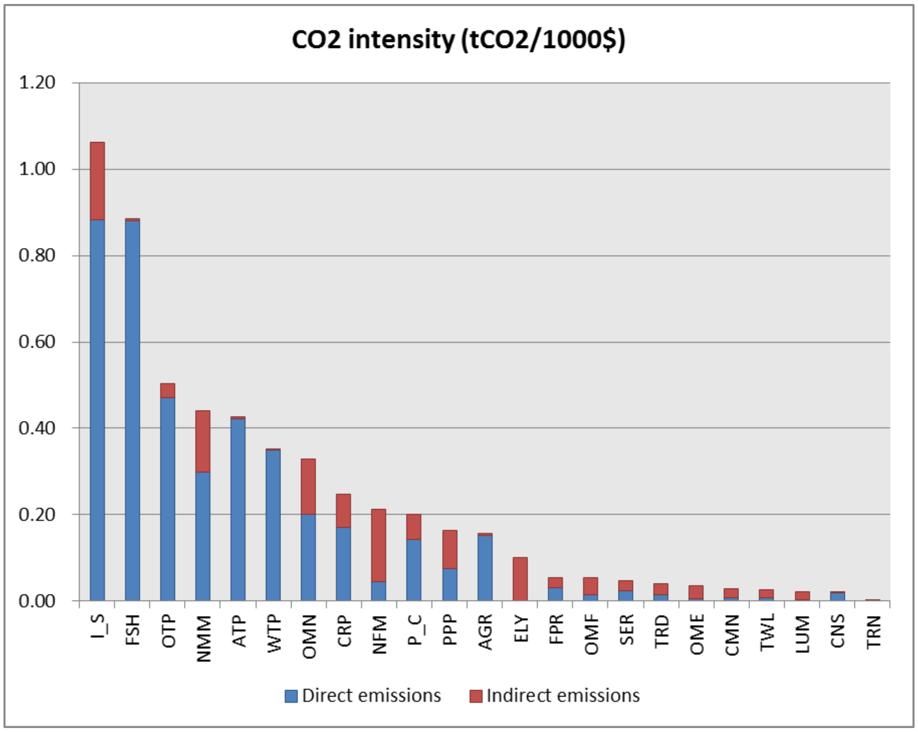


Figure 4. CO_2 intensity in Japan (tCO_2/US$1000)



Source: GTAP7 data.

Figure 5. Share of benchmark CO_2 emissions, by sector (percentage direct emissions + indirect emissions)

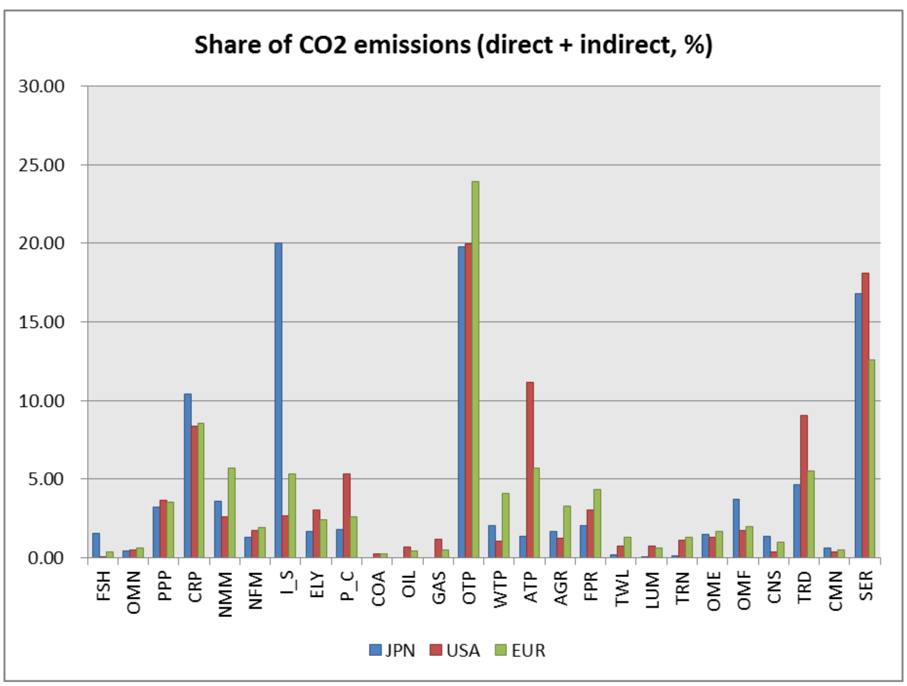


Figure 6. Share of benchmark CO_2 emissions, by sector (percentage direct emissions)

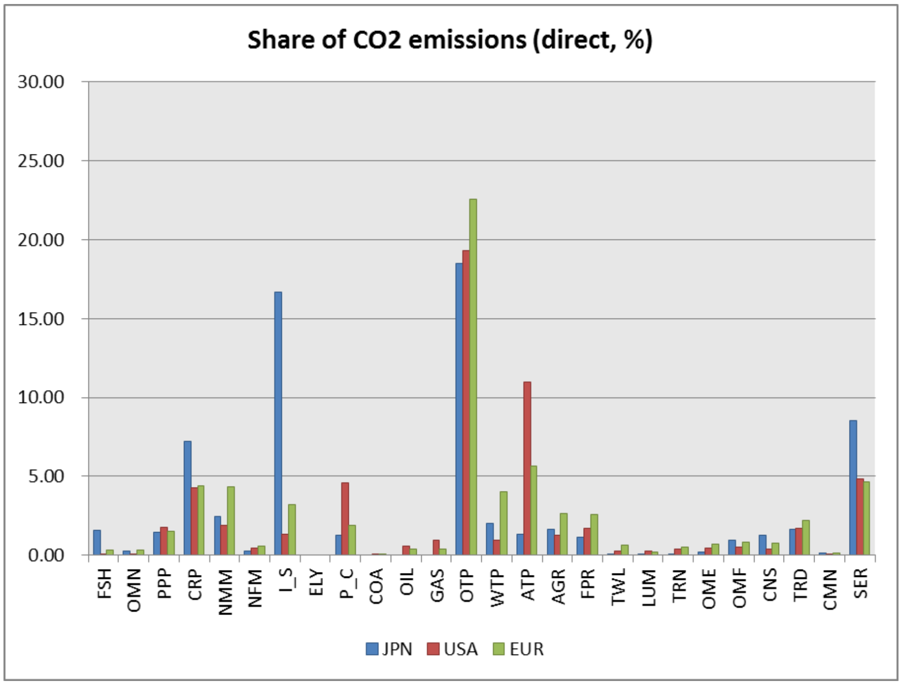
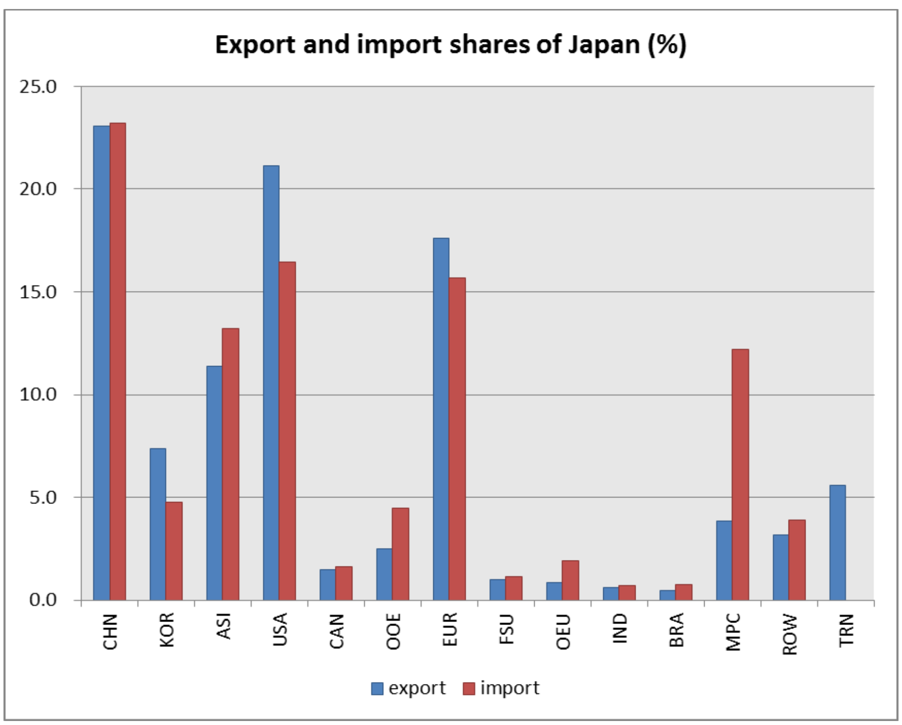


Figure 7. Export and import shares of Japan (percentage)



Note: TRN is global transport sector.
Source: GTAP7 data.

Appendix

See following pages.

1. Model

1.1. Notes

- All taxes except labor and lump-sum taxes are omitted for notational simplicity.
- All functions are written in calibrated share form.
- All reference prices are omitted for notational simplicity.

1.2. Zero profit conditions

Production of goods except fossil fuels ($i \notin FF$):

$$\Pi_{ir}^{Y} = (1 - s_{ir}^{Y})p_{ir}^{Y} - \sum_{j \notin EG} \theta_{jir} p_{jr}^{A} - \theta_{ir}^{VAE} \left[\theta_{ir}^{E} p_{ir}^{E\,1-\sigma_{VAE}} + (1-\theta_{ir}^{E}) p_{ir}^{VA\,1-\sigma_{VAE}}\right]^{\frac{1}{1-\sigma_{VAE}}} = 0 \qquad \{Y_{ir}\}$$

Price index of primary factors ($i \notin FF$)

$$p_{ir}^{VA} = \left[\sum_{f \in MF} \theta_{fir}^{F}\, p_{fr}^{F\;1-\sigma_i^{VA}} + \sum_{f \in SF} \theta_{fir}^{F}\, p_{fir}^{SF\;1-\sigma_i^{VA}}\right]^{\frac{1}{1-\sigma_i^{VA}}} \qquad \{p_{ir}^{VA}\}$$

Production of fossil fuels ($i \in FF$)

$$\Pi_{ir}^{Y} = p_{ir}^{Y} - \left[\theta_{ir}^{R} p_{NRS,ir}^{SF\;1-\sigma_i^{R}} + (1 - \theta_{ir}^{R})\left(\sum_{f \in MF} \theta_{fir}^{FF} p_{fr}^{F} + \sum_{j \notin EN} \theta_{jir}^{NR} p_{jir}^{AF} + \sum_{j \in EN} \theta_{jir}^{NR} p_{jir}^{EF}\right)^{1-\sigma_i^{R}}\right]^{\frac{1}{1-\sigma_i^{R}}} = 0 \qquad \{Y_{ir}\}$$

Sector-specific energy aggregate: ($i \notin FF$)

$$\Pi_{ir}^{E} = p_{ir}^{E} - \left\{ \theta_{ir}^{ELE} (p_{ELY,ir}^{AF})^{1-\sigma_{ELE}} + (1-\theta_{ir}^{ELY}) \left[\theta_{ir}^{COA}\, {p_{COA,ir}^{EF}}^{1-\sigma_{COA}} + \left(1-\theta_{ir}^{COA}\right) \left(\sum_{j \epsilon LQD} \theta_{jir}^{LQD} {p_{jir}^{EF}}^{1-\sigma_{LQD}} \right)^{\frac{1-\sigma_{COA}}{1-\sigma_{LQD}}} \right]^{\frac{1-\sigma_{ELE}}{1-\sigma_{COA}}} \right\}^{\frac{1}{1-\sigma_{ELE}}} = 0 \qquad \{E_{ir}\}$$

Price of energy intermediate goods $(i \in EN)$

$$p_{ijr}^{EF} = p_{ijr}^{AF} + p_{r}^{CO2} a_{ijr}^{CO2F} \qquad \{p_{ijr}^{EF}\}$$

Allocation of sluggish factor $(f \in SF)$

$$\Pi_{fr}^{SF} = \left(\sum_{i} \theta_{fir}^{SF} {p_{fir}^{SF}}^{1+\eta_f} \right)^{\frac{1}{1+\eta_f}} - p_{fr}^{F} = 0 \qquad \{T_{fr}^{SF}\}$$

Armington aggregate for intermediate inputs

$$\Pi_{ijr}^{AF} = p_{ijr}^{AF} - \left(\theta_{ijr}^{AF} {p_{ir}^{Y}}^{1-\sigma_i^A} + \left(1-\theta_{ijr}^{AF}\right) {p_{ir}^{M}}^{1-\sigma_i^A} \right)^{\frac{1}{1-\sigma_i^A}} = 0 \qquad \{A_{ijr}^{F}\}$$

Armington aggregate for private consumption

$$\Pi_{ir}^{AP} = p_{ir}^{AP} - \left(\theta_{ir}^{AP} {p_{ir}^{Y}}^{1-\sigma_i^A} + \left(1-\theta_{ir}^{AP}\right) {p_{ir}^{M}}^{1-\sigma_i^A} \right)^{\frac{1}{1-\sigma_i^A}} = 0 \qquad \{A_{ir}^{P}\}$$

Armington aggregate for government expenditure

$$\Pi_{ir}^{AG} = p_{ir}^{AG} - \left(\theta_{ir}^{AG} {p_{ir}^{Y}}^{1-\sigma_i^A} + \left(1-\theta_{ir}^{AG}\right) {p_{ir}^{M}}^{1-\sigma_i^A} \right)^{\frac{1}{1-\sigma_i^A}} = 0 \qquad \{A_{ir}^{G}\}$$

Aggregate imports across import regions

$$\Pi_{ir}^{M} = p_{ir}^{M} - \left(\sum_{s} \theta_{isr}^{M} {p_{isr}^{MM}}^{1-\sigma_i^M} \right)^{\frac{1}{1-\sigma_i^M}} = 0 \qquad \{M_{ir}\}$$

CIF price of imports

$$p_{isr}^{MM} = p_{is}^{Y} + \sum_j p_j^T \tau_{jisr} \qquad \{P_{isr}^{MM}\}$$

Household utility

$$\Pi_r^U = p_r^U - \left(\theta_r^{LC}\, {p_r^{LE}}^{1-\sigma_r^{LC}} + (1-\theta_r^{LC}){p_r^C}^{1-\sigma_r^{LC}}\right)^{\frac{1}{1-\sigma_r^{LC}}} = 0 \qquad \{U_r\}$$

Price of leisure

$$p_r^{LE} = p_{Lr}^F\,(1 - t_r^L) \qquad \{p_r^{LE}\}$$

Household consumption demand

$$\Pi_r^C = p_r^C - \left(\theta_r^C\, {p_r^{EC}}^{1-\sigma_C} + (1-\theta_r^C){p_r^{CC}}^{1-\sigma_C}\right)^{\frac{1}{1-\sigma_C}} = 0 \qquad \{C_r\}$$

Household nonenergy demand

$$\Pi_r^{CC} = p_r^{CC} - \prod_{i \notin EG} {p_{ir}^{AP}}^{\theta_{ir}^{CC}} = 0 \qquad \{CC_r\}$$

Household energy demand

$$\Pi_r^{EC} = p_r^{EC} - \left(p_{ELY,r}^{AP}\right)^{\theta_{ELY,r}^{EC}} \prod_{i \in EN} (p_{ir}^{EP})^{\theta_{ir}^{EC}} = 0 \qquad \{EC_r\}$$

Price of consumption goods $(i \in EN)$

$$p_{ir}^{EP} = p_{ir}^{AP} + p_r^{CO2} a_{ir}^{CO2P} \qquad \{p_{ir}^{EP}\}$$

Global transport sector

$$\Pi_i^T = p_i^T - \prod_r (p_{ir}^Y)^{\theta_{ir}^T} = 0 \qquad \{Y_i^T\}$$

Government expenditure

$$\Pi_r^G = p_r^G - \sum_i \theta_{ir}^G p_{ir}^{AG} = 0 \qquad \{G_r\}$$

Labor supply

$$L_r^S = \bar{E}_{Lr} + U_r \frac{\partial \Pi_r^U}{\partial p_r^{LE}} \qquad \{L_r^S\}$$

1.3. Market clearance conditions

Mobile factors $(f \in FL \cap MF)$

$$\bar{E}_{fr} = -\sum_i Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{fr}^{F}} \qquad \{p_{fr}^{F}\}$$

Sluggish factors $(f \in FL \cap SF)$

$$\bar{E}_{fr} = T_{fr}^{SF} \qquad \{p_{fr}^{F}\}$$

Sector specific sluggish factors $(f \in FL \cap SF)$

$$T_{fr}^{SF} \frac{\partial \Pi_{fr}^{SF}}{\partial p_{fir}^{SF}} = -Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{fir}^{SF}} \qquad \{p_{fir}^{SF}\}$$

Labor market

$$L_r^S = -\sum_i Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{Lr}^{F}} \qquad \{p_{Lr}^{F}\}$$

Output

$$Y_{ir} = -\sum_j A_{ijr}^{F} \frac{\partial \Pi_{jr}^{AF}}{\partial p_{ir}^{Y}} - A_{ir}^{P} \frac{\partial \Pi_{ir}^{AP}}{\partial p_{ir}^{Y}} - A_{ir}^{G} \frac{\partial \Pi_{ir}^{AG}}{\partial p_{ir}^{Y}} - \sum_s M_{is} \frac{\partial \Pi_{is}^{M}}{\partial p_{ir}^{Y}} - Y_i^{T} \frac{\partial \Pi_{\mathrm{i}}^{T}}{\partial p_{ir}^{Y}} \qquad \{p_{ir}^{Y}\}$$

Sector specific energy aggregate

$$E_{ir} = -Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{ir}^{E}} \qquad \{p_{ir}^{E}\}$$

Import aggregate

$$M_{ir} = -\sum_j A_{ijr}^{F} \frac{\partial \Pi_{ir}^{A}}{\partial p_{ir}^{M}} - A_{ir}^{P} \frac{\partial \Pi_{ir}^{AP}}{\partial p_{ir}^{M}} - A_{ir}^{G} \frac{\partial \Pi_{ir}^{AG}}{\partial p_{ir}^{M}} \qquad \{p_{ir}^{M}\}$$

Armington aggregate for intermediate inputs

$$A_{ijr}^{F} = -Y_{jr} \frac{\partial \Pi_{jr}^{Y}}{\partial p_{ijr}^{AF}} \qquad \{p_{ijr}^{AF}\}$$

Armington aggregate for government expenditure

$$A_{ir}^{G} = -G_{r} \frac{\partial \Pi_{r}^{G}}{\partial p_{ir}^{AG}} \qquad \{p_{ir}^{AG}\}$$

Armington aggregate for private consumption

$$A_{ir}^{P} = -CC_{r} \frac{\partial \Pi_{r}^{CC}}{\partial p_{ir}^{AP}} \qquad \{p_{ir}^{AP}\}, i \notin EG$$

$$A_{ir}^{P} = -EC_{r} \frac{\partial \Pi_{r}^{EC}}{\partial p_{ir}^{AP}} \qquad \{p_{ir}^{AP}\}, i \in EG$$

Household consumption

$$C_{r} = -U_{r} \frac{\partial \Pi_{r}^{U}}{\partial p_{r}^{C}} \qquad \{p_{r}^{C}\}$$

Household utility

$$U_{r} = p_{r}^{U} H_{r} \qquad \{p_{r}^{U}\}$$

Aggregate household energy consumption

$$EC_{r} = -C_{r} \frac{\partial \Pi_{r}^{C}}{\partial p_{r}^{EC}} \qquad \{p_{r}^{EC}\}$$

Aggregate household nonenergy consumption

$$CC_{r} = -C_{r} \frac{\partial \Pi_{r}^{C}}{\partial p_{r}^{CC}} \qquad \{p_{r}^{CC}\}$$

Government expenditure

$$G_{r} = p_{r}^{G} H_{r}^{G} \qquad \{p_{r}^{G}\}$$

Global transport service

$$Y_{i}^{T} = \sum_{j,r,s} \tau_{ijrs} M_{jrs} \qquad \{p_{i}^{T}\}$$

Price of emissions permit with no international permit trade

$$\overline{CO2}_r = -\sum_i E_{ir} \frac{\partial \Pi_{ir}^E}{\partial p_r^{CO2}} - EC_r \frac{\partial \Pi_r^{EC}}{\partial p_r^{CO2}} \qquad \{p_r^{CO2}\}$$

Price of emissions permit with international permit trade

$$\sum_{r \in ET} \overline{CO2}_r = -\sum_{r \in ET} \left[\sum_i E_{ir} \frac{\partial \Pi_{ir}^E}{\partial p_r^{CO2}} + EC_r \frac{\partial \Pi_r^{EC}}{\partial p_r^{CO2}} \right] \qquad \{p^{CO2W}\}$$

Regional permit price with international permit trade

$$p_r^{CO2} = p^{CO2W} \qquad \{p_r^{CO2}\}$$

Output rebate rate in OBA

$$s_{ir}^Y = \frac{p_r^{CO2} a_{ir}^{OBA}}{p_{ir}^Y} \qquad \{s_{ir}^Y\}$$

Unit allocation in OBA

$$a_{ir}^{OBA} = \frac{A_{ir}^{OBA}}{Y_{ir}} \qquad \{a_{ir}^{OBA}\}$$

1.4. Income

Household income

$$H_r = \sum_{f \in FL} p_{fr}^F \, \bar{E}_{fr} + p_r^{LE} \, \bar{E}_{Lr} + p_{CGD,r} \overline{Y}_{CGD,r} + p_{USA}^C \overline{B}_r - p_r^C T_r^L \qquad \{H_r\}$$

Government income

$$H_r^G = t_r^L p_r^F L_r^S + p_r^C T_r^L + V_r^R - s_{ir}^Y p_{ir}^Y Y_{ir} \qquad \{H_r^G\}$$

Lump-sum transfer (tax) to household

$$G_r = \bar{G}_r \qquad \{T_r^L\}$$

Permit revenue

$$V_r^R = p_r^{CO2} \, \overline{CO2}_r \qquad \{V_r^R\}$$

1.5. Notations

Energy goods

Symbol	Description
OIL	Crude oil
GAS	Gas
COA	Coal
P_C	Petroleum and coal products
ELY	Electricity

Sets

Symbol	Description
i, j	Sectors and goods
r, s	Regions
EG	All energy goods: OIL, GAS, COA, P_C, and ELY
FF	Primary fossil fuels: OIL, GAS, COA
EN	Emissions source: OIL, GAS, COA, and P_C
LQ	Liquid fuels: GAS and P_C
MF	Mobile factors: labor and capital
SF	Sluggish factors: land and natural resources
FL	Factors except labor: capital, land and natural resources
ET	Regions participating in international emissions trading
CGD	Index of investment goods
NRS	Index of natural resources

Activity variables

Symbol	Description
Y_{ir}	Production in sector i and region r
E_{ir}	Aggregate energy input in sector i and region r
T_{fr}^{SF}	Allocation of sluggish factors in region r $(f \in SF)$
A_{jir}^{F}	Armington aggregate for good j used for sector i in region r
A_{ir}^{P}	Armington aggregate for good j used for private consumption in region r
A_{ir}^{G}	Armington aggregate for good j used for government expenditure in region r
M_{ir}	Aggregate imports of good i in region r
U_r	Household utility in r
C_r	Aggregate household consumption in region r
CC_r	Aggregate household non-energy consumption in region r
EC_r	Aggregate household energy consumption in region r
Y_i^{T}	Global transport services
G_r	Government expenditure in region r
L_r^S	Labor supply in r

Price variables

Symbol	Description
p_{ir}^{Y}	Output price of goods i produced in region r
p_{ir}^{VA}	Price index of VA for sector i in region $(i \notin FF)$
p_{ir}^{E}	Price of aggregate energy for sector i in region r $(i \notin FF)$
p_{jir}^{EF}	Price of energy intermediate goods j for sector i in region r $(j \in EN, i \notin FF)$
p_{ir}^{M}	Import price aggregate for good i imported to region r
p_{irs}^{MM}	CIF price of goods i imported from r to region s
p_{ijr}^{AF}	Price of Armington good i used for sector j in region r
p_{ir}^{AP}	Price of Armington good i used for private consumption in region r
p_{ir}^{AG}	Price of Armington good i used for government expenditure in region r
p_{r}^{C}	Price of aggregate household consumption in region r
p_{r}^{EC}	Price of aggregate household energy consumption in region r
p_{r}^{CC}	Price of aggregate household non-energy consumption in region r
p_{r}^{U}	Price of household utility in region r
p_{ir}^{EP}	Price of energy consumption goods i in region r
p_{fr}^{F}	Price of primary factor f in region r
p_{fir}^{SF}	Price of sluggish factor f for sector i in region r
p_{r}^{LE}	Price of leisure in region r
p_{r}^{G}	Price index of government expenditure in region r
p_{i}^{T}	Price of global transport service i
p_{r}^{CO2}	Price of emissions permit for region r

Cost shares

Symbol	Description
θ_{jir}	Share of intermediate good j for sector i in region r $(i \notin FF)$
θ_{ir}^{VAE}	Share of VAE aggregate for sector i in region r $(i \notin FF)$
θ_{ir}^{E}	Share of energy in VAE aggregate for sector i in region r $(i \notin FF)$
θ_{fir}^{F}	Share of primary factor f in VA composite for sector i in region r $(i \notin FF)$
θ_{ir}^{R}	Share of natural resources for sector i in region r $(i \in FF)$
θ_{fir}^{FF}	Share of primary factor f for sector i and region r $(i \in FF)$
θ_{jir}^{NR}	Share of non-resource intermediate inputs j for sector i and region r $(i \in FF)$
θ_{ir}^{COA}	Share of coal in fossil fuel demand by sector i in region r $(i \notin FF)$
θ_{ir}^{ELY}	Share of electricity in overall energy demand by sector i in region r
θ_{jir}^{LQD}	Share of liquid fossil fuel j in liquid energy demand by sector i in region r $(i \notin FF), (j \in LQD)$
θ_{fir}^{SF}	Share of sector i in supply of sluggish factor f in region r

θ_{ijr}^{AF}	Share of domestic variety in Armington good i used for sector j of region r
θ_{ir}^{AP}	Share of domestic variety in Armington good i for private consumption in region r
θ_{ir}^{AG}	Share of domestic variety in Armington good i for government expenditure in region r
θ_{isr}^{M}	Share of imports of good i from region s to region r
θ_{r}^{LC}	Share of leisure in utility of region r
θ_{r}^{C}	Share of composite energy input in household consumption in region r
θ_{ir}^{CC}	Share of non-energy good i in non-energy household consumption demand in region r
θ_{ir}^{EC}	Share of energy good i in energy household consumption demand in region r
θ_{ir}^{T}	Share of supply from region r in global transport sector i
θ_{ir}^{G}	Share of Armington good i in government expenditure in region r
θ_{ir}^{EC}	Share of energy good i in energy household consumption demand in region r

Income and policy variables

Symbol	Description
H_r	Household income in region r
H_r^G	Government income in region r
t_r^L	Labor tax rate in region r
T_r^L	Lump-sum tax in region r
V_r^R	Value of permit revenue in region r
T_r^L	Lump-sum tax in region r
$\bar{G}_r$	Exogenous level of government expenditure in region r
$\bar{Y}_{CGD,r}$	Exogenous level of investment in region r
s_{ir}^{Y}	Output rebate rate of sector i in OBA
a_{ir}^{OBA}	Unit allocation for sector i in OBA
A_{ir}^{OBA}	Initial allocation for sector i in OBA

Endowments and emissions coefficients

Symbol	Description
$\overline{E}_r$	Aggregate endowment of primary factor f for region r
$\overline{B}_r$	Balance of payment deficit or surplus in region r $(\sum_r \overline{B}_r = 0)$
$\overline{CO2}_r$	Carbon emission limit for region r
a_{ijr}^{CO2F}	Carbon emissions coefficient for fossil fuel i used for sector j in region r $(i \in FF)$
a_{ir}^{CO2P}	Carbon emissions coefficient for fossil fuel i used for private consumption in region r $(i \in FF)$
τ_{jirs}	Amount of global transport service j required for shipment of goods i from r to s

Elasticities

Symbol	Description	
η_f	Elasticity of transformation for sluggish factor allocation.	$\eta_{NRS} = 0.001$ $\eta_{LND} = 1$
σ_i^{VA}	Substitution between primary factors in VA composite of production in sector i	GTAP values
σ_{VAE}	Substitution between energy and VA in production.	0.5
σ_i^R	Substitution between natural resources and other inputs in fossil fuel production calibrated consistently to exogenous supply elasticities μ_{FF}	$\mu_{COA} = 2$ $\mu_{OIL} = 2$ $\mu_{GAS} = 2$
σ_{ELE}	Substitution between electricity and fossil fuel aggregate in production	0.1
σ_{COA}	Substitution between coal and liquid fossil fuel composite in production	0.5
σ_{LQD}	Substitution between gas and oil in liquid fossil fuel composite in production	2
σ_i^A	Substitution between import aggregate and domestic input	GTAP values
σ_i^M	Substitution between imports from different regions	GTAP values
σ_r^{LC}	Substitution between leisure and consumption in utility	
σ_i^C	Substitution between fossil fuel composite and non–fossil fuel consumption aggregate in household consumption	0.5

2. Sensitivity analysis

Scenario	Description
default	Benchmark case
cgco2	Emissions limit on Japan is endogenously adjusted so that global CO_2 emissions are held constant at level under AUC
eos_a_l	Large values of Armington elasticity (original values × 2)
eos_a_s	Small values of Armington elasticity (original value / 2)
eos_cl_l	Large values of EOS between consumption and leisure (original values × 2)
eos_cl_s	Small values of EOS between consumption and leisure (original value / 2)
eos_ff_l	Large values of fossil fuel supply elasticity (original values × 2)
eos_ff_l	Small values of fossil fuel supply elasticity (original value / 2)

Table A-1. Global emissions constant case: Japan

JPN (cgco2)					
	AUC	GF	OBA	AO-E	AO-ET
CO2 emissions	-30.48	-30.39	-28.61	-28.62	-29.14
Permit price ($/tCO2)	97.91	93.33	114.74	112.57	95.16
Welfare	-0.28	-0.54	-0.44	-0.37	-0.30
Real GDP	-0.07	-0.86	-0.56	-0.40	-0.21
Consumption	0.04	-1.34	-0.84	-0.53	-0.20
Export	-3.10	-3.63	-2.71	-2.65	-2.69
Import	-2.87	-3.42	-2.52	-2.27	-2.38
Terms of trade	0.79	0.90	0.67	0.81	0.76
VNPR (bil.$)	81.58	77.85	14.91	42.01	62.38
Labor tax rate (%)	44.35	50.00	50.31	48.11	46.02
Wage rate	0.92	-2.28	-1.14	-0.45	0.28
Labor supply	0.89	-0.48	0.01	0.28	0.58
Labor income	1.82	-2.75	-1.12	-0.17	0.87
Total income	0.04	-1.34	-0.84	-0.53	-0.20
Leakage rate (%)	20.58	20.35	15.38	15.42	16.92
Output of EITE	-4.16	-4.67	-1.75	-1.41	-2.11
Output of ELY	-12.68	-13.02	-4.55	-4.38	-11.97
Output of P_C	-15.23	-15.41	-13.51	-13.67	-14.27
Output of FENE	0.00	0.00	0.00	0.00	0.00
Output of TRANS	-2.31	-3.09	-1.36	-3.18	-2.62
Output of NEINT	-0.70	-1.46	-1.35	-1.45	-1.08
Output of SVCES	0.21	-0.56	-0.50	-0.26	-0.05
Output of manufacturing	-1.94	-2.61	-1.82	-1.50	-1.54
Export of EITE	-15.55	-15.30	-4.02	-3.55	-6.92
Export of ELY	0.00	0.00	0.00	0.00	0.00
Export of P_C	-8.38	-8.02	-1.51	-1.65	-8.29
Export of FENE	0.00	0.00	0.00	0.00	0.00
Export of TRANS	-5.15	-5.23	-2.43	-7.93	-6.40
Export of NEINT	-0.99	-1.69	-2.54	-2.60	-2.03
Export of SVCES	4.66	4.01	-1.40	-1.05	0.76
Export of manufacturing	-3.48	-4.05	-2.83	-2.27	-2.60
Import of EITE	3.64	2.82	0.36	0.41	1.40
Import of ELY	0.00	0.00	0.00	0.00	0.00
Import of P_C	-7.37	-7.81	-7.76	-7.88	-6.24
Import of FENE	-22.15	-22.20	-20.33	-20.38	-21.18
Import of TRANS	1.17	0.29	0.31	2.42	1.96
Import of NEINT	-0.03	-0.62	0.53	0.96	0.78
Import of SVCES	-2.26	-2.85	0.10	0.19	-0.55
Import of manufacturing	0.54	-0.01	0.19	0.30	0.56

Percentage change form BaU unless otherwise indicated.

Table A-2. Large values of Armington elasticity (original values × 2)

JPN (eos_a_l)	AUC	GF	OBA	AO-E	AO-ET
CO2 emissions	-30.58	-30.58	-30.58	-30.58	-30.58
Permit price ($/tCO2)	91.93	88.37	131.59	127.90	101.85
Welfare	-0.32	-0.57	-0.56	-0.48	-0.38
Real GDP	-0.06	-0.80	-0.64	-0.47	-0.23
Consumption	-0.04	-1.34	-1.05	-0.70	-0.30
Export	-2.80	-3.32	-2.70	-2.45	-2.54
Import	-2.99	-3.59	-2.80	-2.30	-2.51
Terms of trade	0.34	0.40	0.40	0.55	0.46
VNPR (bil.$)	76.60	73.63	13.96	44.75	65.07
Labor tax rate (%)	44.73	50.00	50.57	48.06	45.87
Wage rate	0.80	-2.21	-1.41	-0.63	0.21
Labor supply	0.88	-0.40	0.03	0.33	0.64
Labor income	1.68	-2.60	-1.39	-0.30	0.86
Total income	-0.04	-1.34	-1.05	-0.70	-0.30
Leakage rate (%)	25.45	25.10	15.97	16.40	19.34
Output of EITE	-6.20	-6.59	-2.06	-1.50	-2.98
Output of ELY	-12.74	-13.10	-4.76	-4.52	-12.78
Output of P_C	-15.91	-16.11	-15.28	-15.48	-16.28
Output of FENE	0.00	0.00	0.00	0.00	0.00
Output of TRANS	-2.86	-3.58	-1.73	-4.64	-3.66
Output of NEINT	-0.01	-0.77	-1.36	-1.45	-0.79
Output of SVCES	0.27	-0.45	-0.58	-0.30	-0.03
Output of manufacturing	-1.94	-2.58	-1.91	-1.33	-1.45
Export of EITE	-24.25	-23.66	-5.24	-4.35	-11.23
Export of ELY	0.00	0.00	0.00	0.00	0.00
Export of P_C	-15.03	-14.43	-2.87	-3.15	-16.68
Export of FENE	0.00	0.00	0.00	0.00	0.00
Export of TRANS	-7.47	-7.51	-3.48	-13.30	-10.36
Export of NEINT	0.89	0.13	-2.28	-2.21	-1.07
Export of SVCES	11.08	10.30	-0.96	-0.18	3.72
Export of manufacturing	-3.38	-3.94	-2.74	-1.56	-2.25
Import of EITE	7.87	6.79	0.78	0.72	2.87
Import of ELY	0.00	0.00	0.00	0.00	0.00
Import of P_C	-5.99	-6.49	-8.53	-8.72	-4.63
Import of FENE	-22.58	-22.67	-22.22	-22.27	-23.11
Import of TRANS	3.68	2.76	1.19	8.13	6.06
Import of NEINT	-0.64	-1.25	0.50	1.46	0.89
Import of SVCES	-5.25	-5.75	-0.24	-0.34	-2.05
Import of manufacturing	0.92	0.32	0.11	0.19	0.73

Percentage change form BaU unless otherwise indicated.

Table A-3. Small values of Armington elasticity (original value / 2)

JPN (eos_a_s)	AUC	GF	OBA	AO-E	AO-ET
CO2 emissions	-30.47	-30.47	-30.47	-30.47	-30.47
Permit price ($/tCO2)	102.72	98.35	134.45	131.93	106.95
Welfare	-0.19	-0.45	-0.44	-0.35	-0.26
Real GDP	-0.10	-0.94	-0.70	-0.51	-0.27
Consumption	0.20	-1.23	-0.88	-0.52	-0.12
Export	-3.66	-4.30	-3.56	-3.57	-3.45
Import	-2.56	-3.08	-2.57	-2.39	-2.36
Terms of trade	1.68	1.92	1.53	1.69	1.58
VNPR (bil.$)	85.59	81.94	14.50	46.36	68.41
Labor tax rate (%)	44.06	50.00	50.60	48.00	45.66
Wage rate	1.11	-2.25	-1.28	-0.48	0.39
Labor supply	0.86	-0.60	-0.08	0.24	0.57
Labor income	1.97	-2.83	-1.36	-0.24	0.97
Total income	0.20	-1.23	-0.88	-0.52	-0.12
Leakage rate (%)	17.37	17.22	14.65	14.53	15.41
Output of EITE	-3.07	-3.72	-1.90	-1.62	-1.95
Output of ELY	-12.73	-13.14	-4.69	-4.52	-12.84
Output of P_C	-14.90	-15.17	-15.06	-15.19	-14.95
Output of FENE	0.00	0.00	0.00	0.00	0.00
Output of TRANS	-2.08	-2.92	-1.47	-3.11	-2.48
Output of NEINT	-1.23	-2.04	-1.73	-1.85	-1.49
Output of SVCES	0.18	-0.63	-0.60	-0.32	-0.07
Output of manufacturing	-2.09	-2.82	-2.23	-1.97	-1.89
Export of EITE	-10.27	-10.44	-3.86	-3.55	-5.44
Export of ELY	0.00	0.00	0.00	0.00	0.00
Export of P_C	-4.67	-4.54	-0.94	-1.03	-4.91
Export of FENE	0.00	0.00	0.00	0.00	0.00
Export of TRANS	-4.31	-4.53	-2.65	-6.94	-5.48
Export of NEINT	-2.60	-3.35	-3.60	-3.70	-3.21
Export of SVCES	0.92	0.32	-2.38	-2.15	-1.04
Export of manufacturing	-3.95	-4.62	-3.73	-3.36	-3.44
Import of EITE	1.79	1.12	0.14	0.27	0.84
Import of ELY	0.00	0.00	0.00	0.00	0.00
Import of P_C	-8.22	-8.70	-8.94	-9.02	-7.86
Import of FENE	-21.98	-22.12	-22.00	-22.04	-22.12
Import of TRANS	0.02	-0.84	0.03	0.28	0.33
Import of NEINT	0.59	0.04	0.86	1.11	1.04
Import of SVCES	-0.40	-1.04	0.51	0.71	0.36
Import of manufacturing	0.66	0.16	0.42	0.57	0.74

Percentage change form BaU unless otherwise indicated.

Table A-4. Large values of EOS between consumption and leisure (original values × 2)

JPN (eos_cl_l)					
	AUC	GF	OBA	AO-E	AO-ET
CO2 emissions	-30.48	-30.48	-30.48	-30.48	-30.48
Permit price ($/tCO2)	99.21	91.77	129.91	128.61	104.90
Welfare	-0.20	-0.68	-0.64	-0.49	-0.32
Real GDP	0.18	-1.28	-1.01	-0.63	-0.17
Consumption	0.47	-2.06	-1.63	-0.91	-0.12
Export	-2.93	-3.92	-3.21	-2.99	-2.80
Import	-2.70	-3.73	-3.01	-2.58	-2.47
Terms of trade	0.75	0.96	0.78	0.91	0.79
VNPR (bil.$)	82.66	76.46	13.97	45.14	67.08
Labor tax rate (%)	44.01	50.00	51.01	48.21	45.65
Wage rate	0.97	-1.98	-1.42	-0.61	0.28
Labor supply	1.32	-1.20	-0.63	0.04	0.75
Labor income	2.30	-3.16	-2.03	-0.57	1.04
Total income	0.47	-2.06	-1.63	-0.91	-0.12
Leakage rate (%)	20.69	20.31	15.37	15.36	17.00
Output of EITE	-3.99	-4.96	-2.15	-1.61	-2.18
Output of ELY	-12.56	-13.28	-5.03	-4.65	-12.73
Output of P_C	-15.15	-15.61	-15.21	-15.31	-15.37
Output of FENE	0.00	0.00	0.00	0.00	0.00
Output of TRANS	-2.07	-3.51	-1.91	-3.74	-2.78
Output of NEINT	-0.45	-1.87	-1.87	-1.77	-1.10
Output of SVCES	0.45	-0.96	-0.93	-0.46	0.01
Output of manufacturing	-1.73	-2.98	-2.33	-1.79	-1.58
Export of EITE	-15.61	-15.25	-4.17	-3.61	-7.27
Export of ELY	0.00	0.00	0.00	0.00	0.00
Export of P_C	-8.48	-7.89	-1.50	-1.69	-9.07
Export of FENE	0.00	0.00	0.00	0.00	0.00
Export of TRANS	-5.11	-5.31	-2.75	-8.91	-6.92
Export of NEINT	-0.77	-2.06	-3.12	-3.00	-2.10
Export of SVCES	4.86	3.70	-1.85	-1.34	0.84
Export of manufacturing	-3.30	-4.37	-3.35	-2.56	-2.69
Import of EITE	3.89	2.42	0.01	0.25	1.54
Import of ELY	0.00	0.00	0.00	0.00	0.00
Import of P_C	-7.22	-8.10	-8.93	-8.94	-6.67
Import of FENE	-22.11	-22.35	-22.11	-22.12	-22.43
Import of TRANS	1.45	-0.18	-0.08	2.56	2.22
Import of NEINT	0.15	-0.94	0.29	0.94	0.89
Import of SVCES	-2.08	-3.17	-0.18	0.10	-0.53
Import of manufacturing	0.71	-0.30	-0.08	0.19	0.64

Percentage change form BaU unless otherwise indicated.

Table A-5. Small values of EOS between consumption and leisure (original value / 2)

JPN (eos_cl_s)					
	AUC	GF	OBA	AO-E	AO-ET
CO2 emissions	-30.48	-30.48	-30.48	-30.48	-30.48
Permit price ($/tCO2)	97.31	95.16	133.87	130.22	104.27
Welfare	-0.32	-0.46	-0.47	-0.42	-0.35
Real GDP	-0.19	-0.60	-0.49	-0.41	-0.28
Consumption	-0.16	-0.89	-0.71	-0.52	-0.31
Export	-3.17	-3.46	-2.84	-2.83	-2.88
Import	-2.95	-3.25	-2.63	-2.41	-2.55
Terms of trade	0.80	0.86	0.71	0.88	0.81
VNPR (bil.$)	81.08	79.29	14.40	45.70	66.68
Labor tax rate (%)	44.51	50.00	50.37	47.93	45.80
Wage rate	0.90	-2.49	-1.37	-0.59	0.26
Labor supply	0.69	-0.04	0.29	0.43	0.57
Labor income	1.59	-2.52	-1.08	-0.15	0.83
Total income	-0.16	-0.89	-0.71	-0.52	-0.31
Leakage rate (%)	20.51	20.40	15.20	15.27	16.88
Output of EITE	-4.23	-4.51	-1.74	-1.43	-2.26
Output of ELY	-12.73	-12.94	-4.56	-4.45	-12.78
Output of P_C	-15.27	-15.40	-15.07	-15.25	-15.40
Output of FENE	0.00	0.00	0.00	0.00	0.00
Output of TRANS	-2.43	-2.84	-1.34	-3.53	-2.88
Output of NEINT	-0.81	-1.22	-1.35	-1.56	-1.20
Output of SVCES	0.10	-0.31	-0.42	-0.24	-0.09
Output of manufacturing	-2.04	-2.40	-1.87	-1.59	-1.68
Export of EITE	-15.52	-15.42	-4.08	-3.57	-7.29
Export of ELY	0.00	0.00	0.00	0.00	0.00
Export of P_C	-8.33	-8.16	-1.58	-1.72	-9.02
Export of FENE	0.00	0.00	0.00	0.00	0.00
Export of TRANS	-5.16	-5.22	-2.62	-8.92	-6.92
Export of NEINT	-1.09	-1.46	-2.68	-2.81	-2.19
Export of SVCES	4.57	4.23	-1.59	-1.23	0.78
Export of manufacturing	-3.57	-3.87	-2.95	-2.38	-2.77
Import of EITE	3.52	3.10	0.46	0.44	1.45
Import of ELY	0.00	0.00	0.00	0.00	0.00
Import of P_C	-7.44	-7.69	-8.66	-8.83	-6.74
Import of FENE	-22.17	-22.24	-22.03	-22.09	-22.45
Import of TRANS	1.05	0.58	0.51	2.85	2.10
Import of NEINT	-0.12	-0.43	0.71	1.13	0.80
Import of SVCES	-2.35	-2.66	0.29	0.30	-0.62
Import of manufacturing	0.46	0.17	0.29	0.35	0.57

Percentage change form BaU unless otherwise indicated.