WINPEC Working Paper Series No.E1422
March 2015

Labor Market Distortions and Welfare-Decreasing International Emissions Trading

Shiro Takeda, Toshi H. Arimura, Makoto Sugino

Waseda INstitute of Political EConomy
Waseda University
Tokyo,Japan

Labor Market Distortions and Welfare-Decreasing International Emissions Trading

Shiro Takeda*
Toshi H. Arimura†
Makoto Sugino‡

March, 2015

Abstract
International emissions trading (IET) has been widely recognized as a preferred approach for tackling the climate change because it would equalize total abatement costs and generates gains for all participants. However, this argument is heavily premised on the notion of partial equilibrium and ignores general equilibrium effects of IET.

Using a multi-region, multi-sector CGE model, this paper analyzes effects of IET with focus on labor market distortions. We construct four separate models with several different labor market specifications: i) a model without labor market distortions (i.e. where the labor supply is determined exogenously and wages are flexible); ii) a model with tax-interaction effects in the labor market (i.e. where the labor supply is endogenously determined and a labor tax exists); iii) a model with a minimum wage; and iv) the final model is one in which a wage curve determines wages. We use these models to analyze how the effects of IET change according to model specification.

The main results from the analysis are as follows. First, we found that IET generates gains for all participants in the model without labor market distortions. Second, even in the models with labor market distortions, importers of emissions permits are highly likely to benefit. Conversely, we show that the possibility of a welfare loss from IET is not as small for exporters of permits. In particular, in the minimum wage and wage curve models, we found that the exporters of emissions permits are likely to be disadvantaged. However, this also depends on the region in question. For example, China is likely to suffer under IET, whereas Russia, also an exporter, is likely to benefit. We also make clear that if policies are employed to correct (i.e. reduce) labor market distortions when emissions regulation is introduced, all participants will benefit from IET in almost all cases.

It is generally recognized that IET is a desirable policy that benefits all participating regions. However, we show that an analysis that does not take account of such labor market distortions will likely overestimate the benefits of IET for permit exporters.

JEL classification:
Keywords: international emissions trading, labor market, computable general equilibrium analysis, tax-interaction effect, minimum wage, wage curve.

* Kyoto Sangyo University. Email: <shiro.takeda@gmail.com>
† Waseda University. Email:<toshi.arimura@gmail.com>
‡ Yamagata University. Email:<makoto.sug@gmail.com >

1. Introduction

Emissions trading has been widely recognized as a preferred approach for tackling the climate change. While many countries are moving forward independently with its own emissions trading system, there are ongoing discussions about how these different schemes could link together, with one proposal being the establishment of international emissions trading (IET). IET is desirable for two main reasons (Jaffe and Stavins 2009, IPCC 2001). First, IET would equalize the marginal abatement cost (MAC) internationally, and thereby minimize the total abatement cost worldwide. Second, all regions would be able to reduce emissions with a lower burden because regions with a high MAC would import emissions permits while those with a low MAC would export them.

However, this view is heavily premised on the notion of partial equilibrium. In other words, it only takes into account the emissions permit market. In reality, IET would extend beyond the emissions permit market to affect other markets indirectly. If this indirect impact works negatively by affecting the various distortions in the economy, IET would no longer necessarily benefit all of the regions participating in the scheme. In fact, research employing general equilibrium models has already shown that IET would not necessarily benefit all participants. Examples of such analysis include Ishikawa et al. (2010), Babiker et al. (2004), and Webster et al. (2006). For example, Ishikawa et al. (2010) conducted a theoretical analysis to demonstrate that if the introduction of IET causes the terms of trade to deteriorate significantly, participation in IET would be actually harmful.

Alternatively, Babiker et al. (2004) and Webster et al. (2006) focused on two types of effect: a “terms-of-trade effect” and a “tax-interaction effect in energy markets”. Using a computable general equilibrium (CGE) model, these studies found that IET would not necessarily be beneficial for all regions. Together, these findings suggest that when the analysis of IET draws upon a general equilibrium model, it is not necessarily beneficial to all participants. The purpose of this paper is to focus on labor market distortions, which have not been addressed until now, and analyze the effects of IET using a CGE model. More specifically, we clarify whether IET benefits all regions when labor market distortions are taken into account.

Many studies on climate policy have already focused on labor market distortions. In the double-dividend analysis, in particular, labor market distortions resulting from the existence of a labor tax are a key factor and a large number of studies have already been conducted (e.g.

Goulder 1995, Parry 1995, and Bovenberg and Goulder 2002). However, because many of the CGE models used to analyze IET assume that the labor supply is exogenously fixed, the relationship between IET and the labor market distortions caused by a labor tax have not been analyzed.

Moreover, because almost all CGE models of climate policy analysis assume that wages flexibly adjust and the labor market always clears, barely any studies have analyzed distortions in the form of wage rigidity[1]. The exceptions include Bohringer et al. (2003), Babiker and Eckaus (2007), Kuster et al. (2007), and Guivarch et al. (2010). These studies reveal that the cost of climate change policy can depend strongly on labor market distortions. In fact, real-world labor markets feature many elements that bring about downward rigidity in wages, including minimum wage regulations, wage bargaining by labor unions, and efficiency wages[2], and these factors are argued to make wages inflexible, especially over the short term. In the field of macroeconomics, where unemployment is a key analytical theme, the rigidity of wages is one of the most important factors, and so the aim of this study is to analyze the impact of IET while taking into account some of the labor market distortions described.

We use multi-region, multi-sector static CGE models based on the GTAP data. To shed light on the impact of labor market distortions on IET, we construct four separate models with different labor market specifications: i) a model without labor market distortions (i.e. where the labor supply is determined exogenously and wages are flexible); ii) a model with tax-interaction effects in the labor market (i.e. where the labor supply is endogenously determined and a labor tax exists); iii) a model with a minimum wage; and iv) the final model is one in which a wage curve determines wages. We use these models to analyze how the effects of IET change according to model specification.

The main results from the analysis are as follows. First, we found that IET generates gains for all participants in the model without labor market distortions. This result is consistent with the results of many previous CGE studies. Second, even in the context of models with labor market distortions, importers of emissions permits are highly likely to benefit. Conversely, we show that the possibility of a welfare loss from IET is not as small for exporters of permits. In the case of the minimum wage and wage curve models (under which unemployment arises

[1] The rigidity of wages (and unemployment) is often referred to as an “imperfection” rather than a “distortion” (for example, Babiker and Eckaus 2007). However, we use the term distortion to represent not only the insufficient labor supply resulting from a labor tax, but also the rigidity of wages.
[2] See, for example, Layard et al. (2005).

because of the downward rigidity in wages), we find in particular that the exporters of emissions permits are likely to be disadvantaged. However, this also depends on the region in question. For example, China is likely to suffer under IET, whereas Russia, also an exporter, is likely to benefit.

The results also make clear that if policies are employed to correct (i.e. reduce) labor market distortions when emissions regulation is introduced, exporters of emissions permits will benefit from IET in almost all cases. For this reason, it is generally recognized that IET is a desirable policy that benefits all participating regions, and so interested persons in various circles are calling for its introduction. However, these calls ignore the indirect impact of IET on labor market distortions. We show that an analysis that does not take account of such labor market distortions will likely overestimate the benefits of IET for permit exporters.

The remainder of the paper is organized as follows. Section 2 explains the model and data. Section 3 discusses the basic idea of IET, while Section 4 explains the labor market specification employed. Finally, Section 5 provides the results of the simulation and Section 6 reports the results of a sensitivity analysis.

2. Model and data

We construct a static CGE model with eight regions and 16 sectors as detailed in Table 1. The structure of our model is similar to the models used in Rutherford and Paltsev (2000), Paltsev (2001), Fischer and Fox (2007) and Takeda et al. (2010). The details of the model are in the appendix. We assume perfect competition in all markets and production is subject to constant returns-to-scale technology (CES production functions). We divide the production sector into two, fossil fuel and non-fossil fuel sectors, and assume that these have different production structures.

Fossil fuel production activities include the extraction of coal, crude oil, and gas. Figure 1 depicts the structure of the nested CES production function. Fossil fuel output is produced as a CES composite of natural resources and non-natural resource inputs. In turn, the non-natural resource input is a Leontief composite of capital, labor and other intermediate inputs.

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

A representative household represents the demand side of each region. The representative household's utility has the structure depicted in Figure 3 although in some cases we modify this specification[3]. The representative agent makes decisions to maximize utility subject to the budget constraint. The household's income consists of factor income minus a tax payment. We assume that the endowments of primary factors are exogenously constant. We treat the international trade in goods in the same way as the GTAP model (Hertel 1997) and there is no international movement of primary factors. In addition, we assume that government expenditure and investment are constant at the benchmark values.

For the benchmark data including CO_2 emissions data, we employ the GTAP 8.1 database with 2007 as the base year. For elasticity parameters in production functions, we use the values in Fischer and Fox (2007) and the GTAP data, and for the Armington elasticity parameters, we use the GTAP values. The elasticity of substitution between resource and non-resource inputs in fossil fuel sectors (e_es(j) in Figure 1) is calibrated from the benchmark supply elasticity of fossil fuels, which is assumed to have a value of 2 for all fossil fuels.

3. Labor market

Labor market distortion, typically represented by unemployment, is one of the main research themes in the field of macroeconomics and labor economics and various models have been established[4]. The cause and effect of distortion, of course, depend on the model, and the selection of a particular model is an important element for analysis. Although it is ideal to incorporate a variety of models that have been adopted in macroeconomics and labor economics, we base our study on relatively simple models in this paper. This is because it is not easy to

[3] In the model with variable labor supply, we assume that utility depends on not only consumption, but also leisure, as explained in Section 3.2.

[4] For example, see Layard et al. (2005).

introduce a complicated model into a multi-sector and multi-regional CGE model for climate change policy analysis. In addition, with the exception of only some cases, it is uncommon to consider labor market distortions when analyzing climate change policy. Hence, it is sufficiently meaningful to employ a simple model in the first instance. In particular, we analyze the following four models: 1) model without labor market,distortions (FLAB), 2) model with variable labor supply (VLAB), 3) minimum wage model (MWAGE); and 4) wage curve model (WCURVE). We explain these four models in the following subsections.

3.1. Model without labor market distortions (FLAB)

First, as a standard case, we consider a model without labor market distortions. In this model, labor supply is determined exogenously and wage rate changes flexibly. This type of model has frequently been used for climate policy CGE analysis, for example, the MIT EPPA model (Paltsev et al. 2005, Webster et al. 2010) and the OECD ENV-Linkages model (Chateau and Burniaux 2008, OECD 2009). In FLAB, wages always adjust so that the demand and supply of labor are equalized. Therefore, no distortion in the form of unemployment exists. In addition, the labor tax does not generate distortion due to constant employment.

Figure 4 represents a labor market in FLAB. LS is the labor supply curve and LD is a labor demand curve. As labor supply is exogenously determined, it is constructed as vertical at a value of E0. At the initial equilibrium, the wage adjusts to w0 so that the supply and demand of labor become equal. Employment is then equal to the fixed labor supply E0.

Then, suppose that emissions regulation is implemented. The labor demand curve shifts to LDR because production activities are restrained and labor demand decreases. But employment remains at E0 because the wage rate declines to wR. The shift in the labor demand curve leads to a decrease in the labor market surplus of A + B. However, this is a primary effect (burden) of emissions regulation and not attributable to the presence of the labor market distortion itself.

3.2. Model with variable labor supply (VLAB)

In this model, labor supply, which is fixed in FLAB, is assumed variable (hereafter, this model is referred to as VLAB). In particular, labor supply varies endogenously depending on the consumption–leisure choices of the household. Therefore, we modify the utility function in

Figure 3 to:

$$u = \phi\left(\alpha C^{\frac{\sigma_U - 1}{\sigma_U}} + (1-\alpha) LE^{\frac{\sigma_U - 1}{\sigma_U}}\right)^{\frac{\sigma_U}{\sigma_U - 1}} \tag{1}$$

where C is aggregate consumption, LE is leisure, and σ_U is the elasticity of substitution between consumption and leisure. In this model, the labor tax causes distortion in the labor market. For this reason, this model has been widely used for the analysis of the double-dividend hypothesis[5].

It is commonly known that emissions regulation in VLAB exerts an indirect effect, known as the "tax-interaction effect" (TI effect). The TI effect is as follows. Emissions regulation, such as a carbon tax and emissions trading, boosts the price level through the increase in energy prices. The increase in the price level affects the labor supply of the household by causing a decline in the real wage. The household then faces a decline in the real wage and reduces its labor supply because of the substitution effect. This accelerates the decline in the labor supply, which is already at an insufficient level because of the presence of labor taxation, resulting in a worsening of the labor market distortion. In this way, labor market distortions expand through the indirect effect of emissions regulation on labor supply.

3.3. Minimum wage model (MWAGE)

The most important cause of labor market distortion is potentially the downward rigidity of wages and unemployment. In reality, flexible wages are difficult to obtain because of the presence of factors such as wage bargaining by labor unions, long-term wage contracts, and the minimum wage system[6]. Although the causes of downward rigidity in wages and unemployment are diverse, we first consider a simple minimum wage model (hereafter, MWAGE). In this model, the real wage does not drop below a certain level and this causes unemployment[7]. This model has been often used in CGE analysis, for example, Babiker and Eckaus (2007) and Kuster et al. (2007).

Figure 4 also depicts a labor market in an MWAGE. Suppose that at the initial equilibrium,

[5] For details of the double dividend, see the survey in Bovenberg and Goulder (2002).
[6] Layard et al. (2005) review the reasons for wage rigidity.
[7] In some cases, emphasis is placed on the downward rigidity of the nominal wage. However, our study utilizes a *real* general equilibrium model in which nominal prices are not meaningful. Therefore, we focus on downward rigidity in the real wage.

the wage is w0, employment is E0, and there is no unemployment. Assuming that the initial real wage w0 is set as the minimum wage rate, we discuss the efficacy of emissions regulation. Emissions regulation will lead to a decrease in labor demand and the labor demand curve shifts toward LDR. In FLAB, the wage adjusts to wR and the labor market clears. However, in MWAGE, the wage cannot fall below w0 and employment instead of wages decreases to ER, causing unemployment of UR. In FLAB, emissions regulation also leads to a decline in surplus. However, in the MWAGE case, this creates unemployment, and hence the decrease in surplus is greater by an amount of C + D. Therefore, the negative effect of emissions regulation becomes more significant in MWAGE. In the simulation to follow, we assume that the initial market-clearing real wage is set to the minimum wage[8].

3.4. Wage curve model (WCURVE)

The minimum wage model is the simplest model that embodies downward rigidity in wages. However, the assumption that there is no wage fall is somewhat extreme. To address this, the wage curve model (WCURVE) takes the downward rigidity of wages more modestly into account. WCURVE assumes that there is a negative correlation between the real wage and unemployment rate (Blanchflower and Oswald 2005). Let the nominal wage be w, the price level p, and unemployment rate γ. Then WCURVE assumes the following correlation between the real wage and unemployment rate:

$$w/p = f(\gamma) \qquad f' < 0 \tag{2}$$

The rationale for WCURVE is based on the labor union and efficiency wage models (Hutton and Ruocco 1999) and this idea has been partly supported by empirical analysis (Blanchflower and Oswald 2005). In addition, the wage curve is frequently used for CGE analysis by studies such as those of Hutton and Ruocco (1999) and Rutherford et al. (2002), who have conducted analyses of tax reform, as well as Kuster et al (2007), Bohringer et al. (2003), and Guivarch et al. (2010), who have conducted analyses of climate policy. In WCURVE, (2) and the following two equations determine the real wage, the unemployment rate, and unemployment (U):

$$\bar{l} - l^D - U = 0 \qquad U = \gamma \bar{l}$$

[8] It follows that there is no unemployment at the initial equilibrium.

where $\bar{l}$ is the total supply labor (including unemployment) and $l^D = \bar{l} - U$ is employment.

Figure 5 depicts the effect of emissions regulation in WCURVE. The labor supply and labor demand curves without emissions regulation are LS and LD. In WCURVE, the wage curve determines the wage and it does not flexibly adjust and therefore, unemployment arises. Assuming that the initial wage rate is w0, employment will be E0 and the unemployment will be U0. If the wage was flexible, it should fall to w1. However, because of the wage curve, the wage remains at a higher level of w0.

Again suppose that emissions regulation is implemented. Because of the regulation, labor demand shifts toward LDR. In accordance with this decline in labor demand, there is pressure on the wage to fall. A fall in the wage on the wage curve indicates an increase in unemployment. Thus, unemployment increases to UR. As a result, the wage and employment become wR and ER, respectively. Consequently, emissions regulation results in a loss of D because of the increase in unemployment as well as a loss of A + B from the shift in the labor demand curve. The wage curve model with limited adjustment of the wage has a mixture of FLAB and MWAGE models.

3.5. Labor market distortions and the effects of IET

We have thus far reviewed three models that include labor market distortions and the effects of emissions regulation. In the models with labor market distortions, emissions regulation increases the distortion and thus the costs associated with emissions regulation are greater than otherwise. There is a question concerning differences in the effect of IET between models with and without labor market distortions. Let us discuss a region that imports emissions permits under IET. With IET, production activities in an importer increase through the purchase of emissions permits. Consequently, its demand for labor also increases. Therefore, the aforementioned negative effect in the labor market is restrained. In other words, in addition to the direct positive effect of IET, an importer benefits from the indirect positive effect resulting from a reduction in labor market distortion.

Conversely, because of the export of emissions permits, production activities contract in the exporter of the permits. This accelerates the decline in labor demand that has already decreased through the emissions regulation, expanding the distortion in the labor market. Therefore, exporters suffer from an indirect negative effect. IET has similar effects under VLAB. Here the fall in the price of emissions permits attenuates the effect of the price rise and real wage fall in the emissions permit importer, thereby reducing the negative TI effect. In contrast, the emissions permit exporter experiences an increase in the price of emissions permits. This worsens the price rise and real wage fall, thereby exerting a stronger negative TI effect.[9]

As shown, in a model with labor market distortions, IET exerts an indirect negative effect on the permit exporter. Therefore, not all regions can benefit from IET. Simulation later in the paper will verify how strongly the indirect effect works through the labor market as well as whether IET brings benefits to participants when labor market distortion is considered.

3.6. Labor market specification

VLAB requires us to specify the elasticity of substitution between leisure and consumption (σ_U in Eq. 1) as well as specifying data for leisure. To address this, we use the technique suggested by Fischer and Fox (2007). They exogenously provide the benchmark values of the elasticity of compensation and non-compensation labor supply to calibrate σ_U as well as the amount of leisure. For the elasticities of compensation and non-compensation labor supply, following Fischer and Fox (2007) we specify values of 0.1 and 0.3, respectively. We modify these values in the sensitivity analysis. In addition, we need to identify the labor tax rate. We assume labor taxes of 40% and 20% are imposed on Annex I regions and the remaining regions, respectively. Once again, we vary these values in the sensitivity analysis.

To introduce WCURVE into the simulation, it is necessary to specify a wage curve equation. Following the most existing studies, we adopt the following specification:

$$w/p = \alpha\gamma^{-\phi}$$

where $\alpha > 0$ and $\phi > 0$ are constants[10]. ϕ is referred to as the wage curve elasticity and we assume $\phi = 0.1$ as in the most existing studies[11]. This means that when the unemployment rate rises by 100%, the real wage declines by 10%. For the benchmark unemployment rates, we use the values in column UR of Table 1 which are taken from World Bank's World Development Indicators.

---

9 The possibility of welfare-decreasing IET in VLAB is already pointed out in Babiker et al. (2004).

10 α is calibrated by $\alpha = (w_0/p_0)/(u_0)^{-\phi}$ where variables with subscript 0 are benchmark values.

11 Hutton and Ruocco (1999), Rutherford et al. (2002), Kuster et al. (2007), Bohringer et al. (2003), and Guivarch et al. (2010) all assume a unit-elastic wage curve. In the sensitivity analysis, we consider different values for wage curve elasticity.

4. Simulations

4.1. Scenarios

The simulations in this study analyze the situation after all regions have introduced emissions regulation. The regulation takes a cap-and-trade form and we assume that permit markets are perfectly competitive. In addition, we assume that the government auctions emissions permits and transfers permit revenue to the household in a lump-sum way. To ensure that the results are not excessively dependent on any specific scenario, we consider three abatement scenarios, shown in Table 2. The figures in the table denote the reduction rates in each region[12]. Regions for which no value is given have no obligation to reduce emissions. In S_ANN, only ANNEX I regions (excluding RUS) have an obligation to reduce emissions. In S_RC, we add RUS and CHN to the regions included in S_ANN. Finally, in S_WORLD, all regions reduce emissions.

Under each abatement scenario, we perform calculations when the reducing regions do (TR) and do not (NTR) engage in IET, and compare the difference in the two sets of results. When the regions do not engage in IET, the price of emissions permits (i.e. MAC) varies from region to region. On the other hand, when the regions engage in IET, they establish a common market, and therefore a common price, for emissions permits.

4.2. IET and welfare effects

Here we consider the simulation results[13]. Table 3 shows the volume of permits traded, i.e. net imports of permits in metric tons of carbon dioxide equivalents ($MtCO_2$) and the effect on welfare (percentage change from the benchmark value) for each country under each abatement scenario. We provide the welfare effects with (TR) and without (NTR) IET. We exclude regions without emissions regulation from the table because the focus of our analysis is only on IET participants. Let us examine the results for each scenario.

Under S-ANN, only JPN, USA, EUR, and OOE have emissions regulations, and in all four models, JPN and EUR are importers of permits and USA and OOE are exporters. In other words, the type of model does not affect the pattern of IET. In FLAB, IET reduces the loss of welfare

[12] In the sensitivity analysis, we analyze different reduction rates.
[13] All simulation results are available from the authors upon request.

from emissions regulation for all participating regions. In other words, IET is a policy that benefits all participants in FLAB. This is consistent with the finding from the numerous CGE analyses that fail to account for labor market distortion that IET is desirable. However, the results from the other models are different.

In VLAB, permit importers also benefit from IET. However, the loss of welfare by the exporting regions (i.e. USA and OOE) is larger with IET. Similarly, with MWAGE and WCURVE, permit exporters are disadvantaged under IET. In Section 3.5, we saw that when labor market distortions are considered, permit exporters suffer indirect negative effects. Our simulation results show that these negative effects are sufficiently large to outweigh the direct positive benefits.

Next, we examine scenario S_RC. Under scenario S_RC, RUS and CHN are included among the regulated regions, and both are exporters of permits. CHN, in particular, is a huge exporter. In FLAB, all participants benefit from IET, as was the case with S_ANN. Moreover, with S_RC, all participants also benefit from IET in VLAB. In MWAGE, however, CHN (an exporting region) is disadvantaged by IET. Similarly, with WCURVE, CHN suffers from IET. Even though the abatement scenario has changed, the result that some exporters suffer from IET remains unchanged. Finally, with S_WORLD, RUS, CHN, IND, and ROW are exporters of permits and it is better for CHN and IND not to engage in IET, which is essentially the similar result to S_RC.

Let us summarize the above findings. First, regardless of the abatement scenarios, all participating regions benefit from IET (i.e. their welfare losses are smaller) in FLAB. Second, even with models that take account of labor market distortions, regions that import emissions permits still benefit from IET. However, we found that IET may not be beneficial for exporting countries, although this depends on the model used. More specifically, in VLAB, the impact of IET on the welfare of exporting regions is ambiguous, whereas in MWAGE and WCURVE there is a greater likelihood of them being disadvantaged. In VLAB, exporters of permits lose from IET in S_ANN but they gain in S_RC and S_WORLD. On the other hand, in MWAGE and WCURVE, all exporters lose in S_ANN and some exporters lose even in S_RC and S_WORLD.

The results also differ from country to country. For instance, CHN, an exporter of emissions permits, is often disadvantaged, while fellow exporter RUS rarely suffers. The above results tell us that when labor market distortion is considered, IET may confer disadvantage.

4.3. Impacts on individual regions

To analyze the effects of IET in details, let us consider the impact on individual regions. Before examining the results, we first confirm the effects of IET. In our model, the effects of IET on welfare are the sum of the following three effects: 1) the direct effect, 2) the effect caused by the labor market distortions and 3) other effects. The direct effect is positive for all participants. The second effect is negative for permit exporters (positive for permit importers). The third effects, which include terms of trade effects and effects caused by other distortions, are positive or negative.

This decomposition partly explains why IET have different effects for different regions. For example, even if the second effect has negative impacts on all permit exporters equally, an exporter with large positive impacts of the first and third effects is likely to gain from IET as a whole.

It is desirable to discuss the outcomes for all of the regions under each of the three abatement scenarios, but it is difficult to do so due to the limit of space. So we will only focus on OOE under S_ANN and CHN and RUS under S_RC. Table 4 details the impacts in three cases. We begin by looking at OOE under scenario S_ANN. For OOE, the price of emissions permits rises significantly following the introduction of IET, resulting in OOE exporting permits. In FLAB, GDP falls to enable the export of permits, and labor income therefore declines. However, because the revenue from selling the permits offsets this reduction, the rate of decline in household income is smaller with IET. It follows that the rate of decline in welfare will also be less with IET.

In VLAB, there is an additional effect: namely, a fall in employment. In fact, the rate of decline in labor income under this model is even larger. With IET, the rate of decline in labor income increases but there is also revenue from the sale of emissions permits, which is the same as under FLAB. The difference with VLAB, however, is that the decline in labor income is larger than the revenue from the sale of emissions permits, so the decrease in household income is larger when there is IET. This is why IET increases the rate of decrease in welfare. Moreover, under MWAGE and WCURVE, unemployment takes place, so the rate of decrease in employment increases further. With these two models, the expansion of labor market distortion by IET is more pronounced, and this causes the welfare loss with IET to increase.

Next, let us consider CHN under scenario S_RC. CHN is an exporter of permits and the qualitative aspects of the impact on CHN are similar to OOE under S_ANN. For CHN, however, IET is preferable under VLAB, just as it is with FLAB. In other words, the welfare effect under VLAB is the reverse of what it is for OOE under S_ANN. Moreover, when compared with OOE, there is a substantial difference in the size of effects on welfare with and without IET under MWAGE. In fact, the welfare loss in the presence of IET for CHN is about 3.5 times higher under MWAGE (for OOE in S_ANN, only 1.1 times).

One of the reasons for the quantitative differences described above may be the difference in the price of emissions permits with and without IET. Because both CHN and OOE are exporters of emissions permits, the price of permits increases with the introduction of IET. However, the nature of the increase is very different for two regions. In OOE, where the price of permits (MAC) is high to begin with, the increase in permit price is small (37.3 to 42.3US$/MtCO2 in FLAB). In CHN, however, where the price of permits is low, IET results in a more than sifxfold increase. Because of this, CHN exports large quantities of emissions permits (and reduces output at the same time). The above findings indicate that the quantitative effects of IET are quite dissimilar across the regions.

Finally, let us consider RUS under scenario S_RC. We have already seen that impacts of IET on CHN and RUS are quite different though they are both exporters of permits. That is, CHN is often disadvantaged from IET, while RUS rarely suffers. The reason why RUS is likely to receive large gains from IET is that the terms of trade (TOT) for RUS improve significantly when he participates in IET. For example, Table 4 shows that TOT for RUS deteriorates by 2.9% in no IET case but it improves by 0.6% in IET. This positive TOT effect generates the large gains from IET for RUS and cancel out the negative impacts caused by the labor market distortions.

5. Sensitivity analysis

In this section, we alter our assumptions concerning the models, parameters, and scenarios, and perform a sensitivity analysis to examine the extent to which this affects the results obtained so far. Scenarios of sensitivity analysis are shown in Table 5. First, we change the reduction rates. Since there is uncertainty about the future reduction rates of many regions, we consider two scenario: in Scenario hrd (the case of the higher reduction rates), the original reduction rates in

Table 2 are multiplied by 1.5 and in Scenario lrd (the case of the lower reduction rates), reductions rates are multiplied by 0. 5.

With VLAB, the elasticity of the labor supply and the benchmark labor tax rate are important. We therefore double and halve their values (Scenario elas_l, elas_h, ltax_l and ltax_h). On the other hand, with WCURVE, the wage curve elasticity and the benchmark unemployment rate are important, so we double and halve the values of each (Scenario phi_l, phi_h, ur_l and ur_h).

From the preceding analysis, we confirmed that labor market distortion makes it possible for IET to confer disadvantage. This means that it should be possible, by simultaneously implementing policies to correct the distortions, to eliminate the indirect negative impact of IET and leave only the positive effects. To confirm whether this is indeed the case, we consider the situation in which policies to curtail the expansion of labor market distortion accompany the introduction of emissions regulation. More specifically, with VLAB we examine a "revenue-recycling" policy under which the revenue from the sale of emissions permits lowers the labor tax, while with MWAGE and WCURVE, we consider a policy of lowering the labor tax to maintain the benchmark level of employment.

5.1. Results of sensitivity analysis

Table 6 to 8 show percentage change in welfare in sensitivity analysis[14]. The benchmark case indicates the case we have seen so far. Let us summarize insights derived from sensitivity analysis. First, under FLAB, welfare improves for all participants as a results of IET in almost all scenarios.[15] Second, under VLAB, high values of labor supply elasticity and labor tax rate tend to make IET disadvantageous for permits exporters. This is because high values of labor supply elasticity and labor tax rate reinforces negative tax-interaction effects. Third, under WCRUVE, low values of wage curve elasticity and high values of the benchmark unemployment rate tend to make IET disadvantageous for permits exporters. This is because low values of wage curve elasticity reinforce the downward rigidity of the wage and high values of the benchmark unemployment rate mean that the existing distortions in the labor market is large. Fourth, change in reduction rates have ambiguous effects. In some models and abatement

[14] Volume of permit trade in sensitivity analysis is reported in the appendix.
[15] One exception is IND in Scenario lrd of S_WORLD.

scenarios, increase in reduction rates makes IET more disadvantageous but in other models and scenarios, not.

Finally, in labor tax cut scenarios, all participants gain from IET. That is, the simultaneous adoption of measures to correct distortion will always ensure that IET improves welfare, even for regions that export emissions permits. This means that by imposing emissions regulation and implementing policies to alleviate labor market distortion at the same time, we can reduce the indirect negative effects of IET and therefore all regions can benefit from its presence.

By changing assumptions and parameter values, the quantitative impacts of IET often change to a large extent, but almost all qualitative insights derived from the benchmark case remain unchanged. It follows that the analysis of the previous sections has a certain level of robustness.

6. Concluding remarks

This paper analyzes IET with a focus on labor market distortion. We develop a static CGE model with eight regions and 16 sectors and use GTAP data for the benchmark data. To analyze the relation between labor market distortion and IET, we develop four models with different labor market specifications: i) a model with no labor market distortion, ii) a model with a labor market tax-interaction effect, iii) a minimum wage model, and iv) a wage curve model. We then compare the effects of IET using these four models.

The main results are as follows. First, we found that IET generates gains for all participants in the model without labor market distortions. This result is consistent with the results of previous studies. Second, even if there is distortion in the labor market, emissions permit-importing regions benefit from IET. On the other hand, we found that the possibility of a welfare loss from IET is not very small for emissions permit exporters. In particular, with the minimum wage model and the wage curve model, IET is likely to generate a loss for emissions permit exporters. However, this result strongly depends on the region in question. For example, both China and Russia are exporters of permits but the effects of IET for both are quite different in that while IET often brings about welfare losses for China, it is likely to benefit Russia. This is because impacts of IET depend on not only the direct effects and the labor market effects but also other effects such as the terms of trade effect. In addition, we show that IET is likely to be beneficial for all participants when policies to remedy labor market distortions take place alongside emissions regulation.

Our analysis is valuable in the sense that there are few researches on the relation between IET and labor market distortions. But at the same time, note that our model only considers limited types of labor market distortions. For example, unemployment is caused by various reasons such as structural unemployment, cyclical unemployment, short-term frictions, hidden unemployment, etc which are not considered in our model. We will address these problems in the future research.

References

Babiker, M. H. and R. S. Eckaus (2007) "Unemployment effects of climate policy," *Environmental Science and Policy*, Vol. 10, pp. 600–609.

Babiker, M. H., J. Reilly, and L. Viguier (2004) "Is International Emissions Trading Always Beneficial?" *The Energy Journal*, Vol. 25, No. 2, pp. 33–56.

Blanchflower, D. G. and A. J. Oswald (2005) "The Wage Curve Reloaded," May. NBER working paper series, 11338.

Bohringer, C., W. Wiegard, C. Starkweather, and A. Ruocco (2003) "Green Tax Reforms and Computational Economics A Do-it-yourself Approach," *Computational Economics*, Vol. 22, pp. 75–109.

Bovenberg, A. L. and L. H. Goulder (2002) "Environmental Taxation," in A. J. Auerbach and M. Feldstein eds. *Handbook of Public Economics*, Vol. 3, Amsterdam: North-Holland, Chap. 21, pp. 1471–1545.

Chateau, J. and J.-M. Burniaux (2008) "An Overview of the OECD ENV-Linkages Model." OECD Economics Department Working Papers, No. 653.

Fischer, C. and A. K. Fox (2007) "Output-Based Allocation of Emissions Permits for Mitigating Tax and Trade Interactions," *Land Economics*, Vol. 83(4), pp. 575–599.

Goulder, L. H. (1995) "Environmental Taxation and the 'Double Dividend': A Reader's Guide," *International Tax and Public Finance*, Vol. 2, pp. 157–183.

Guivarch, C., R. Crassous, O. Sassi, and S. Hallegatte (2010) "The costs of climate policies in a second best world with labour market imperfections." Forthcoming in Climate Policy.

Hertel, T. W. ed. (1997) *Global Trade Analysis: Modeling and Applications*, New York: Cambridge University Press.

Hutton, J. P. and A. Ruocco (1999) "Tax Reform and Employment in Europe," *International Tax and Public Finance*, Vol. 6, pp. 263–287.

IPCC (2001) *Climate Change 2001: Mitigation, Summary for Policy Makers*. IPCC (Intergovernmental Panel on Climate Change) Third Assessment Report.

Ishikawa, J., K. Kiyono, and M. Yomogida (2010) "Is Emission Trading Beneficial?" July 2010.

Jaffe, J., M. Ranson, and R. N. Stavins (2009) "Linking Tradable Permit Systems: A Key Elements of Emerging International Climate Policy Architecture," *Ecology Law Quarterly*, Vol. 36, pp. 789–808.

Kuster, R., I. R. Ellersdorfer, and U. Fahl (2007) "A CGE-Analysis of Energy Policies Considering Labor Market Imperfections and Technology Specifications,"

Layard, R., S. Nickell, and R. Jackman (2005) *Unemployment: Macroeconomic Performance and the Labour Market*, Oxford University Press, 2nd edition.

Lee, H. (2008) “The Combustion-based CO2 Emissions Data for GTAP Version 7 Data Base,” December.

OECD (2009) *The Economics of Climate: Change Mitigation Policies and Options for Global Action beyond 2012*. OECD.

Paltsev, S., J. M. Reilly, H. D. Jacoby, R. S. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian, and M. H. Babiker (2005) “The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4.” MIT Joint Program on the Science and Policy of Global Change, Report No. 125, August 2005.

Paltsev, S. V. (2001) “The Kyoto Agreement: Regional and Sectoral Contributions to the Carbon Leakage,” *The Energy Journal*, Vol. 22, No. 4, pp. 53–79.

Parry, I. W. H. (1995) “Pollution Taxes and Revenue Recycling,” *Journal of Environmental Economics and Management*, Vol. 29, pp. 64–77.

Rutherford, T. F., M. K. Light, and G. Hern´andez (2002) “A Dynamic General Equilibrium Model for Tax Policy Analysis in Colombia.” ARCHIVOS DE ECONOM´IA, Documento 189.

Rutherford, T. F. and S. V. Paltsev (2000) “GTAPinGAMS and GTAP-EG: Global Datasets for Economic Research and Illustrative Models,” September. Working Paper, University of Colorad, Department of Economics.

Takeda, S., T. Arimura, H. Tamechika, C. Fischer, and A. K. Fox (2010) “Output-Based Allocation of Emissions Permits for Mitigating Carbon Leakage for the Japanese Economy.”

Webster, M., S. Paltsev, and J. Reilly (2010) “The hedge value of international emissions trading under uncertainty,” *Energy Policy*, Vol. 38, No. 4, pp. 1787–1796.

Tables

Table 1: Regions and sectors.

Sectors		Regions		
Symbol	Description	Symbol	Description	UR (%)
AGR	Agriculture, forestry and fishery	JPN	Japan	3.9
COL	Coal	USA	USA	4.7
CRU	Crude oil	EUR	EU27	7.2
GAS	Gas	OOE	Other OECD	6.0
OMN	Other mining	RUS	Russia	6.0
PPP	Paper-pulp-print	CHN	China	3.8
OIL	Petroleum and coal products (refined)	IND	India	3.7
CRP	Chemical industry	ROW	Rest of the world	5.4
NMM	Non-metallic minerals			
I_S	Iron and steel industry			
NFM	Non-ferrous metals			
OMF	Other manufacturing			
ELE	Electricity			
TRN	Transport service			
SER	Other services			

UR is the benchmark unemployment rate for each region (%).

Table 2: Reduction scenarios.

	S_ANN	S_RC	S_WORLD
JPN	20	20	20
EUR	20	20	20
USA	20	20	20
OOE	20	20	20
RUS		5	5
CHN		5	5
IND			5
ROW			5

Blank cells indicate no emissions reduction obligation.

Table 3: Effects of IET.

S_ANN

	Net import of permits (MtCO2)				Percentage change of welfare (%)							
	flab	vlab	mwage	wcurve	flab		vlab		mwage		wcurve	
					ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	21	21	26	23	-0.45	-0.41	-0.55	-0.50	-4.88	-4.26	-1.17	-1.04
USA	-127	-128	-148	-124	-0.21	-0.19	-0.32	-0.33	-4.70	-5.42	-0.89	-0.98
EUR	125	125	140	121	-0.40	-0.33	-0.54	-0.43	-4.85	-3.72	-1.64	-1.30
OOE	-19	-18	-18	-20	-0.88	-0.87	-0.93	-0.95	-6.00	-6.53	-2.03	-2.17

S_RC

	Net import of permits (MtCO2)				Percentage change of welfare (%)							
	flab	vlab	mwage	wcurve	flab		vlab		mwage		wcurve	
					ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	157	158	159	158	-0.44	-0.14	-0.55	-0.18	-4.88	-1.56	-1.17	-0.35
USA	568	572	558	572	-0.21	-0.15	-0.32	-0.18	-4.69	-2.13	-0.89	-0.42
EUR	496	497	499	495	-0.40	-0.11	-0.53	-0.15	-4.85	-1.29	-1.64	-0.43
OOE	101	102	101	101	-0.89	-0.47	-0.94	-0.47	-6.01	-2.64	-2.04	-0.92
RUS	-170	-172	-176	-175	-1.65	0.06	-1.39	-0.10	-3.70	-3.68	-2.19	-1.07
CHN	-1,152	-1,157	-1,141	-1,152	-0.29	0.52	-0.28	0.25	-1.42	-4.86	-0.52	-0.67

S_WORLD

	Net import of permits (MtCO2)				Percentage change of welfare (%)							
	flab	vlab	mwage	wcurve	flab		vlab		mwage		wcurve	
					ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	188	188	189	189	-0.40	-0.05	-0.52	-0.08	-4.84	-0.97	-1.13	-0.18
USA	712	714	700	714	-0.20	-0.11	-0.31	-0.13	-4.68	-1.53	-0.89	-0.30
EUR	583	583	583	582	-0.38	-0.04	-0.52	-0.07	-4.86	-0.80	-1.63	-0.24
OOE	127	127	125	127	-0.95	-0.41	-0.99	-0.40	-6.10	-2.00	-2.11	-0.73
RUS	-112	-113	-121	-116	-2.02	-0.49	-1.69	-0.51	-4.20	-3.48	-2.60	-1.36
CHN	-871	-875	-874	-871	-0.29	0.21	-0.27	0.05	-1.41	-3.89	-0.51	-0.67
IND	-299	-298	-282	-295	0.19	0.30	0.16	0.19	0.31	-0.91	0.23	0.01
ROW	-329	-327	-321	-329	-0.64	-0.29	-0.56	-0.28	-1.76	-1.64	-0.92	-0.63

NTR is the scenario without IET and TR is the scenario with IET.
Green cells indicates permit exporters.
Blue color indicates cells with larger values.

Table 4: Impact of IET on OOE (S_ANN), CHN and RUS (S_RC).

OOE under S_ANN	flab		vlab		mwage		wcurve	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
Permit price ($/tCO2)	37.3	42.3	36.7	41.6	30.3	33.9	35.7	40.7
%Ch. in CO2 (%)	-20.0	-21.9	-20.0	-21.9	-20.0	-21.8	-20.0	-22.0
net permit imp (MtCO2)	0.0	-18.8	0.0	-18.4	0.0	-17.7	0.0	-19.6
v of net permit imp (bil$)	0.0	-0.8	0.0	-0.8	0.0	-0.6	0.0	-0.8
Welfare (%)	-0.9	-0.9	-0.9	-1.0	-6.0	-6.5	-2.0	-2.2
Real GDP (%)	-0.4	-0.4	-0.6	-0.7	-3.2	-3.6	-1.0	-1.1
Export (%)	-1.0	-1.3	-1.2	-1.5	-3.6	-4.1	-1.6	-1.9
Import (%)	-1.6	-1.6	-1.8	-1.8	-4.2	-4.5	-2.1	-2.2
TOT (%)	-0.5	-0.4	-0.5	-0.4	-0.5	-0.5	-0.5	-0.4
Labor supply (%)	0.0	0.0	-0.4	-0.4	-4.7	-5.2	-1.1	-1.2
Wage rate for HH (%)	-2.0	-2.2	-1.8	-2.0	0.0	0.0	-1.5	-1.7
Labor income (%)	-2.0	-2.2	-2.2	-2.5	-4.7	-5.2	-2.6	-2.9
HH income (%)	-0.9	-0.9	-1.2	-1.2	-6.0	-6.5	-2.0	-2.2
CHN under S_RC	**flab**		**vlab**		**mwage**		**wcurve**	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
Permit price ($/tCO2)	2.3	14.3	2.2	14.0	2.0	12.3	2.2	13.9
%Ch. in CO2 (%)	-5.0	-23.2	-5.0	-23.3	-5.0	-23.1	-5.0	-23.2
net permit imp (MtCO2)	0.0	-1,152.3	0.0	-1,156.7	0.0	-1,140.9	0.0	-1,151.5
v of net permit imp (bil$)	0.0	-16.5	0.0	-16.2	0.0	-14.1	0.0	-16.0
Welfare (%)	-0.3	0.5	-0.3	0.3	-1.4	-4.9	-0.5	-0.7
Real GDP (%)	0.0	-0.3	-0.1	-0.7	-0.4	-2.4	-0.1	-0.8
Export (%)	-0.2	-1.8	-0.2	-2.0	-0.4	-3.1	-0.3	-2.1
Import (%)	-0.5	-0.5	-0.6	-0.8	-0.9	-2.2	-0.6	-0.8
TOT (%)	-0.2	0.3	-0.2	0.4	-0.1	0.6	-0.1	0.4
Labor supply (%)	0.0	0.0	-0.1	-0.8	-0.8	-4.2	-0.2	-1.0
Wage rate for HH (%)	-0.5	-2.8	-0.5	-2.3	0.0	0.0	-0.4	-2.2
Labor income (%)	-0.5	-2.8	-0.5	-3.1	-0.8	-4.2	-0.6	-3.1
HH income (%)	-0.3	0.5	-0.4	-0.1	-1.4	-4.9	-0.5	-0.7
RUS under S_RC	**flab**		**vlab**		**mwage**		**wcurve**	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
Permit price ($/tCO2)	4.8	14.3	4.9	14.0	3.9	12.3	4.6	13.9
%Ch. in CO2 (%)	-5.0	-15.9	-5.0	-16.0	-5.0	-16.3	-5.0	-16.2
net permit imp (MtCO2)	0.0	-170.4	0.0	-172.1	0.0	-176.4	0.0	-174.9
v of net permit imp (bil$)	0.0	-2.4	0.0	-2.4	0.0	-2.2	0.0	-2.4
Welfare (%)	-1.6	0.1	-1.4	-0.1	-3.7	-3.7	-2.2	-1.1
Real GDP (%)	-0.1	-0.3	-0.1	-0.6	-0.9	-2.2	-0.4	-0.9
Export (%)	0.8	-0.8	0.8	-0.9	0.5	-1.7	0.7	-1.1
Import (%)	-2.4	0.6	-2.4	0.4	-4.0	-1.2	-2.8	0.1
TOT (%)	-2.9	0.6	-2.9	0.6	-3.6	0.3	-3.0	0.6
Labor supply (%)	0.0	0.0	0.1	-0.7	-1.9	-4.4	-0.5	-1.4
Wage rate for HH (%)	-1.1	-2.8	-1.2	-2.4	0.0	0.0	-0.8	-2.0
Labor income (%)	-1.1	-2.8	-1.1	-3.1	-1.9	-4.4	-1.4	-3.3
HH income (%)	-1.6	0.1	-1.6	-0.5	-3.7	-3.7	-2.2	-1.1

NB: "net permit imp" is net permit import ($MtCO_2$), "v of net permit imp" is value of net permit import (billions of US$), TOT is % change in the terms of trade (the ratio of the weighted average of export prices and the weighted average of import prices), HH income is % change in the household income.

Table 5: Scenarios of sensitivity analysis.

Scenarios in sensitivity analysis		flab	vlab	mwage	wcurve
Change in reduction rates.	hrd: ×1.5 lrd: ×1/2	○	○	○	○
Change in labor supply elasticity in VLAB	elas_l: ×1/2 elas_h: ×2		○		
Change in the benchmark labor tax rate in VLAB	ltax_l: ×1/2 ltax_h: ×2		○		
Change in the wage curve elasticity in WCURVE.	phi_l: ×1/2 phi_h: ×2				○
Change in the benchmark unemployment rate in WCURVE.	ur_l: ×1/2 ur_h: ×2				○
Labor tax cut by revenue recycling			○	○	○

Table 6: Sensitivity analysis: percentage change in welfare (%) in S_ANN.

The benchmark case

	flab		vlab		mwage		wcurve	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-0.45	-0.41	-0.55	-0.50	-4.88	-4.26	-1.17	-1.04
USA	-0.21	-0.19	-0.32	-0.33	-4.70	-5.42	-0.89	-0.98
EUR	-0.40	-0.33	-0.54	-0.43	-4.85	-3.72	-1.64	-1.30
OOE	-0.88	-0.87	-0.93	-0.95	-6.00	-6.53	-2.03	-2.17
RUS	-1.81	-1.63	-1.48	-1.33	-2.68	-2.42	-1.98	-1.79
CHN	-0.24	-0.24	-0.21	-0.21	-0.44	-0.47	-0.27	-0.27
IND	0.15	0.17	0.14	0.15	0.28	0.31	0.22	0.24
ROW	-0.52	-0.49	-0.43	-0.41	-0.82	-0.79	-0.56	-0.53

Increase in reduction rate (hrd).

	flab		vlab		mwage		wcurve	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-1.17	-1.08	-1.31	-1.19	-9.15	-7.85	-2.65	-2.31
USA	-0.57	-0.53	-0.74	-0.75	-8.43	-9.65	-1.90	-2.08
EUR	-1.00	-0.85	-1.20	-0.99	-8.76	-6.88	-3.36	-2.74
OOE	-1.70	-1.70	-1.78	-1.82	-10.58	-11.53	-3.90	-4.21
RUS	-2.89	-2.65	-2.35	-2.16	-4.30	-3.96	-3.18	-2.93
CHN	-0.47	-0.47	-0.40	-0.41	-0.81	-0.88	-0.53	-0.54
IND	0.24	0.27	0.21	0.24	0.44	0.51	0.34	0.38
ROW	-0.87	-0.83	-0.72	-0.69	-1.37	-1.33	-0.96	-0.91

Sensitivity of wcurve model.

	phi_l		phi_h		ur_l		ur_h	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-1.76	-1.54	-0.83	-0.75	-0.84	-0.75	-1.47	-1.30
USA	-1.44	-1.62	-0.57	-0.61	-0.57	-0.61	-1.18	-1.31
EUR	-2.39	-1.88	-1.10	-0.87	-1.10	-0.87	-2.07	-1.64
OOE	-2.81	-3.06	-1.51	-1.58	-1.51	-1.59	-2.45	-2.65
RUS	-2.10	-1.90	-1.91	-1.72	-1.91	-1.71	-2.05	-1.85
CHN	-0.29	-0.30	-0.26	-0.26	-0.26	-0.26	-0.28	-0.29
IND	0.26	0.28	0.19	0.21	0.19	0.21	0.24	0.26
ROW	-0.59	-0.56	-0.54	-0.51	-0.54	-0.51	-0.58	-0.54

Decrease in reduction rate (lrd).

	flab		vlab		mwage		wcurve	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-0.10	-0.10	-0.16	-0.15	-1.90	-1.72	-0.37	-0.34
USA	-0.04	-0.04	-0.09	-0.10	-1.95	-2.25	-0.31	-0.34
EUR	-0.10	-0.08	-0.17	-0.13	-2.00	-1.49	-0.60	-0.45
OOE	-0.35	-0.35	-0.37	-0.38	-2.54	-2.77	-0.80	-0.86
RUS	-0.83	-0.74	-0.68	-0.60	-1.23	-1.11	-0.91	-0.81
CHN	-0.09	-0.09	-0.08	-0.08	-0.18	-0.19	-0.10	-0.10
IND	0.08	0.08	0.07	0.07	0.14	0.15	0.10	0.11
ROW	-0.23	-0.22	-0.19	-0.18	-0.36	-0.35	-0.24	-0.23

Sensitivity of VLAB model.

	elas_l		elas_h		ltax_l		ltax_h	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-0.51	-0.47	-0.56	-0.51	-0.46	-0.42	-0.76	-0.69
USA	-0.27	-0.27	-0.35	-0.38	-0.24	-0.24	-0.49	-0.52
EUR	-0.49	-0.39	-0.56	-0.44	-0.45	-0.36	-0.73	-0.58
OOE	-0.92	-0.93	-0.87	-0.90	-0.83	-0.85	-1.15	-1.19
RUS	-1.65	-1.48	-1.14	-1.02	-1.47	-1.32	-1.49	-1.34
CHN	-0.23	-0.23	-0.17	-0.17	-0.21	-0.21	-0.21	-0.21
IND	0.15	0.17	0.11	0.13	0.13	0.15	0.14	0.16
ROW	-0.48	-0.45	-0.33	-0.32	-0.43	-0.41	-0.43	-0.41

Labor tax cut scenarios.

	vlab		mwage		wcurve	
	ntr	tr	ntr	tr	ntr	tr
JPN	-0.23	-0.22	-0.45	-0.41	-0.45	-0.41
USA	-0.09	-0.05	-0.21	-0.19	-0.21	-0.19
EUR	-0.17	-0.14	-0.40	-0.33	-0.40	-0.33
OOE	-0.54	-0.51	-0.88	-0.87	-0.88	-0.87
RUS	-1.40	-1.25	-1.97	-1.76	-1.85	-1.66
CHN	-0.19	-0.18	-0.28	-0.26	-0.25	-0.25
IND	0.12	0.14	0.17	0.19	0.19	0.21
ROW	-0.39	-0.37	-0.52	-0.49	-0.50	-0.47

Table 7: Sensitivity analysis: percentage change in welfare (%) in S_RC.

The benchmark case

	flab		vlab		mwage		wcurve	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-0.44	-0.14	-0.55	-0.18	-4.88	-1.56	-1.17	-0.35
USA	-0.21	-0.15	-0.32	-0.18	-4.69	-2.13	-0.89	-0.42
EUR	-0.40	-0.11	-0.53	-0.15	-4.85	-1.29	-1.64	-0.43
OOE	-0.89	-0.47	-0.94	-0.47	-6.01	-2.64	-2.04	-0.92
RUS	-1.65	0.06	-1.39	-0.10	-3.70	-3.68	-2.19	-1.07
CHN	-0.29	0.52	-0.28	0.25	-1.42	-4.86	-0.52	-0.67
IND	0.16	0.08	0.14	0.07	0.29	0.14	0.23	0.11
ROW	-0.54	-0.25	-0.45	-0.21	-0.84	-0.41	-0.58	-0.26

Increase in reduction rate (hrd).

	flab		vlab		mwage		wcurve	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-1.16	-0.41	-1.30	-0.43	-9.15	-2.88	-2.65	-0.79
USA	-0.57	-0.39	-0.74	-0.42	-8.43	-3.89	-1.90	-0.89
EUR	-1.00	-0.32	-1.19	-0.35	-8.75	-2.40	-3.36	-0.89
OOE	-1.72	-0.96	-1.79	-0.92	-10.60	-4.73	-3.91	-1.77
RUS	-2.68	0.32	-2.26	-0.01	-5.93	-6.07	-3.57	-1.75
CHN	-0.57	1.67	-0.53	1.04	-2.40	-7.43	-0.94	-0.52
IND	0.25	0.12	0.22	0.11	0.46	0.22	0.36	0.17
ROW	-0.90	-0.42	-0.74	-0.35	-1.41	-0.69	-0.98	-0.44

Sensitivity of wcurve model.

	phi_l		phi_h		ur_l		ur_h	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-1.75	-0.51	-0.82	-0.26	-0.83	-0.26	-1.46	-0.44
USA	-1.44	-0.62	-0.57	-0.29	-0.57	-0.29	-1.18	-0.53
EUR	-2.39	-0.61	-1.10	-0.29	-1.10	-0.29	-2.06	-0.54
OOE	-2.82	-1.22	-1.52	-0.72	-1.52	-0.72	-2.46	-1.09
RUS	-2.52	-1.73	-1.96	-0.58	-1.96	-0.60	-2.38	-1.43
CHN	-0.67	-1.52	-0.42	-0.12	-0.42	-0.15	-0.60	-1.10
IND	0.28	0.14	0.20	0.10	0.20	0.10	0.26	0.13
ROW	-0.61	-0.27	-0.56	-0.25	-0.56	-0.26	-0.59	-0.27

Decrease in reduction rate (lrd).

	flab		vlab		mwage		wcurve	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-0.10	-0.03	-0.16	-0.05	-1.90	-0.63	-0.37	-0.11
USA	-0.04	-0.03	-0.09	-0.05	-1.94	-0.87	-0.31	-0.14
EUR	-0.10	-0.02	-0.17	-0.04	-2.00	-0.52	-0.59	-0.15
OOE	-0.35	-0.17	-0.38	-0.18	-2.55	-1.11	-0.81	-0.36
RUS	-0.74	-0.01	-0.63	-0.07	-1.72	-1.66	-0.99	-0.48
CHN	-0.11	0.05	-0.11	-0.03	-0.63	-2.35	-0.21	-0.45
IND	0.08	0.04	0.07	0.03	0.14	0.07	0.11	0.05
ROW	-0.24	-0.11	-0.20	-0.09	-0.38	-0.18	-0.25	-0.12

Sensitivity of VLAB model.

	elas_l		elas_h		ltax_l		ltax_h	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-0.51	-0.16	-0.56	-0.18	-0.46	-0.15	-0.76	-0.24
USA	-0.27	-0.16	-0.35	-0.18	-0.24	-0.15	-0.49	-0.25
EUR	-0.48	-0.13	-0.55	-0.15	-0.45	-0.12	-0.73	-0.20
OOE	-0.93	-0.48	-0.87	-0.42	-0.84	-0.43	-1.16	-0.55
RUS	-1.52	-0.03	-1.10	-0.16	-1.37	-0.06	-1.44	-0.19
CHN	-0.29	0.37	-0.23	0.10	-0.26	0.33	-0.31	0.10
IND	0.15	0.08	0.12	0.06	0.14	0.07	0.15	0.08
ROW	-0.49	-0.23	-0.35	-0.16	-0.45	-0.21	-0.45	-0.21

Labor tax cut scenarios.

	vlab		mwage		wcurve	
	ntr	tr	ntr	tr	ntr	tr
JPN	-0.23	-0.08	-0.44	-0.14	-0.44	-0.14
USA	-0.08	-0.09	-0.21	-0.15	-0.21	-0.14
EUR	-0.16	-0.05	-0.40	-0.11	-0.40	-0.11
OOE	-0.55	-0.32	-0.89	-0.47	-0.89	-0.47
RUS	-1.25	0.25	-1.65	0.06	-1.65	0.06
CHN	-0.20	0.60	-0.29	0.52	-0.29	0.52
IND	0.13	0.07	0.18	0.10	0.20	0.10
ROW	-0.40	-0.18	-0.54	-0.25	-0.52	-0.23

Table 8: Sensitivity analysis: percentage change in welfare (%) in S_WORLD

The benchmark case

	flab		vlab		mwage		wcurve	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-0.40	-0.05	-0.52	-0.08	-4.84	-0.97	-1.13	-0.18
USA	-0.20	-0.11	-0.31	-0.13	-4.68	-1.53	-0.89	-0.30
EUR	-0.38	-0.04	-0.52	-0.07	-4.86	-0.80	-1.63	-0.24
OOE	-0.95	-0.41	-0.99	-0.40	-6.10	-2.00	-2.11	-0.73
RUS	-2.02	-0.49	-1.69	-0.51	-4.20	-3.48	-2.60	-1.36
CHN	-0.29	0.21	-0.27	0.05	-1.41	-3.89	-0.51	-0.67
IND	0.19	0.30	0.16	0.19	0.31	-0.91	0.23	0.01
ROW	-0.64	-0.29	-0.56	-0.28	-1.76	-1.64	-0.92	-0.63

Increase in reduction rate (hrd).

	flab		vlab		mwage		wcurve	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-1.11	-0.20	-1.27	-0.23	-9.12	-1.80	-2.61	-0.44
USA	-0.56	-0.29	-0.73	-0.31	-8.42	-2.78	-1.90	-0.63
EUR	-0.97	-0.16	-1.18	-0.19	-8.81	-1.49	-3.37	-0.52
OOE	-1.82	-0.81	-1.87	-0.76	-10.75	-3.54	-4.03	-1.38
RUS	-3.27	-0.73	-2.75	-0.79	-6.71	-5.76	-4.22	-2.28
CHN	-0.57	0.73	-0.52	0.38	-2.40	-6.07	-0.94	-0.81
IND	0.29	0.70	0.25	0.48	0.48	-1.31	0.36	0.21
ROW	-1.09	-0.47	-0.95	-0.46	-2.95	-2.77	-1.56	-1.07

Sensitivity of wcurve model.

	phi_l		phi_h		ur_l		ur_h	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-1.72	-0.28	-0.79	-0.12	-0.80	-0.12	-1.43	-0.24
USA	-1.43	-0.44	-0.56	-0.21	-0.57	-0.21	-1.17	-0.38
EUR	-2.39	-0.36	-1.08	-0.15	-1.09	-0.15	-2.06	-0.32
OOE	-2.90	-0.95	-1.58	-0.59	-1.59	-0.59	-2.54	-0.86
RUS	-2.95	-1.87	-2.35	-0.99	-2.35	-0.99	-2.80	-1.65
CHN	-0.67	-1.29	-0.41	-0.27	-0.41	-0.28	-0.60	-0.99
IND	0.26	-0.18	0.21	0.14	0.21	0.14	0.25	-0.09
ROW	-1.09	-0.84	-0.80	-0.48	-0.80	-0.48	-1.01	-0.75

Decrease in reduction rate (lrd).

	flab		vlab		mwage		wcurve	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-0.08	0.01	-0.14	-0.01	-1.87	-0.39	-0.35	-0.05
USA	-0.04	-0.02	-0.09	-0.03	-1.93	-0.63	-0.30	-0.10
EUR	-0.09	0.01	-0.16	-0.01	-1.99	-0.32	-0.59	-0.08
OOE	-0.38	-0.16	-0.40	-0.15	-2.59	-0.85	-0.85	-0.29
RUS	-0.91	-0.24	-0.77	-0.24	-1.96	-1.58	-1.19	-0.61
CHN	-0.11	0.00	-0.11	-0.05	-0.63	-1.86	-0.21	-0.38
IND	0.09	0.07	0.08	0.04	0.15	-0.48	0.11	-0.05
ROW	-0.28	-0.13	-0.25	-0.13	-0.79	-0.73	-0.40	-0.28

Sensitivity of VLAB model.

	elas_l		elas_h		ltax_l		ltax_h	
	ntr	tr	ntr	tr	ntr	tr	ntr	tr
JPN	-0.48	-0.07	-0.54	-0.09	-0.43	-0.06	-0.73	-0.12
USA	-0.27	-0.12	-0.35	-0.13	-0.24	-0.11	-0.48	-0.18
EUR	-0.46	-0.06	-0.55	-0.08	-0.43	-0.05	-0.72	-0.10
OOE	-0.98	-0.41	-0.91	-0.35	-0.89	-0.37	-1.21	-0.46
RUS	-1.86	-0.51	-1.33	-0.46	-1.67	-0.48	-1.74	-0.58
CHN	-0.29	0.12	-0.23	-0.04	-0.26	0.10	-0.30	-0.07
IND	0.18	0.24	0.13	0.12	0.16	0.21	0.17	0.15
ROW	-0.61	-0.29	-0.45	-0.24	-0.55	-0.26	-0.58	-0.31

Labor tax cut scenarios.

	vlab		mwage		wcurve	
	ntr	tr	ntr	tr	ntr	tr
JPN	-0.19	-0.01	-0.40	-0.05	-0.40	-0.05
USA	-0.08	-0.06	-0.20	-0.11	-0.20	-0.11
EUR	-0.13	0.01	-0.38	-0.04	-0.38	-0.04
OOE	-0.59	-0.28	-0.95	-0.41	-0.95	-0.41
RUS	-1.54	-0.23	-2.02	-0.49	-2.02	-0.49
CHN	-0.20	0.30	-0.29	0.21	-0.29	0.21
IND	0.16	0.32	0.19	0.30	0.19	0.30
ROW	-0.45	-0.16	-0.64	-0.29	-0.64	-0.29

Figures

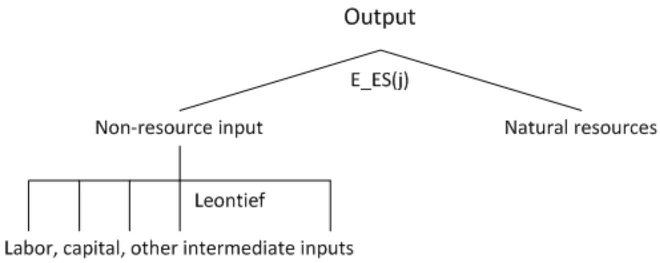

Figure 1: Production function of fossil fuel sectors.

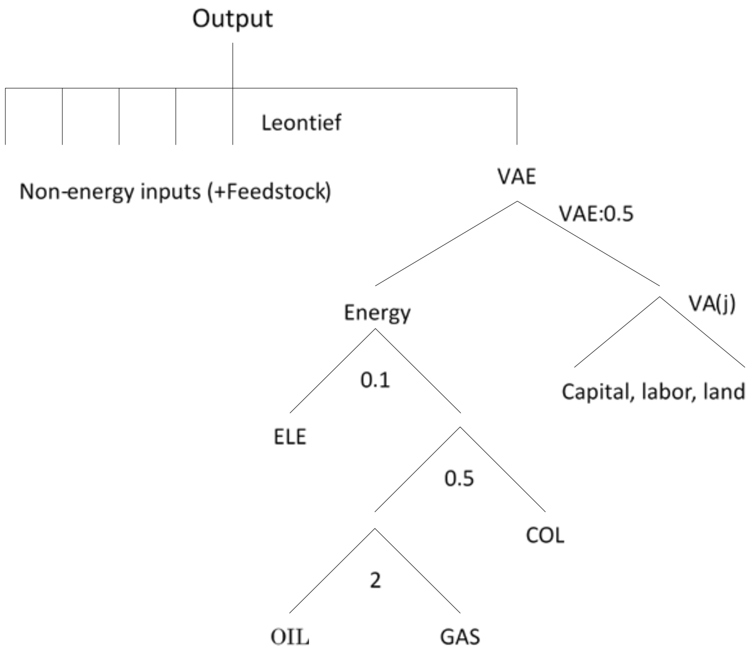

Figure 2: Production function of nonfossil fuel sectors.

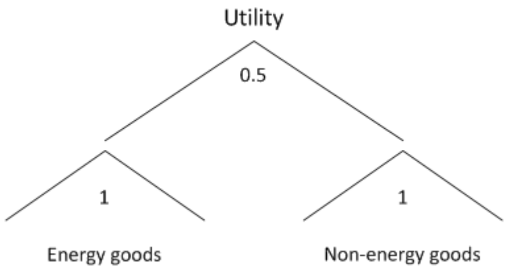

Figure 3: Utility function.

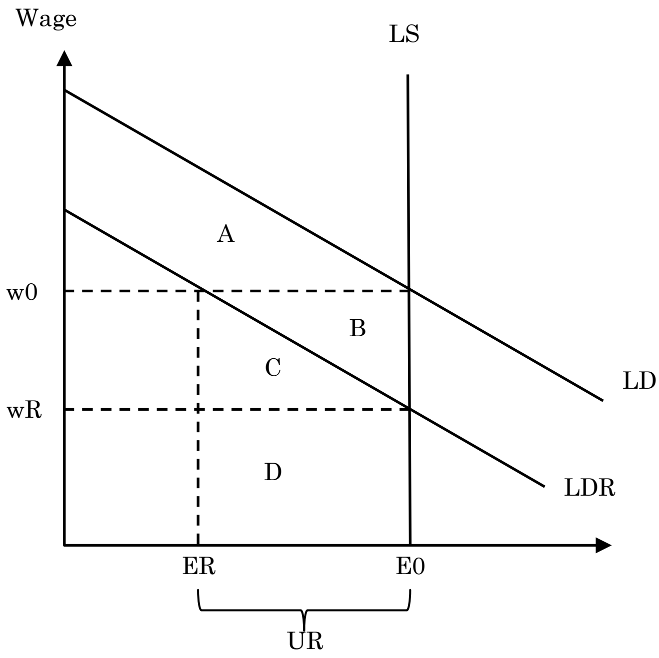

Figure 4: Labor market in FLAB and MWAGE.

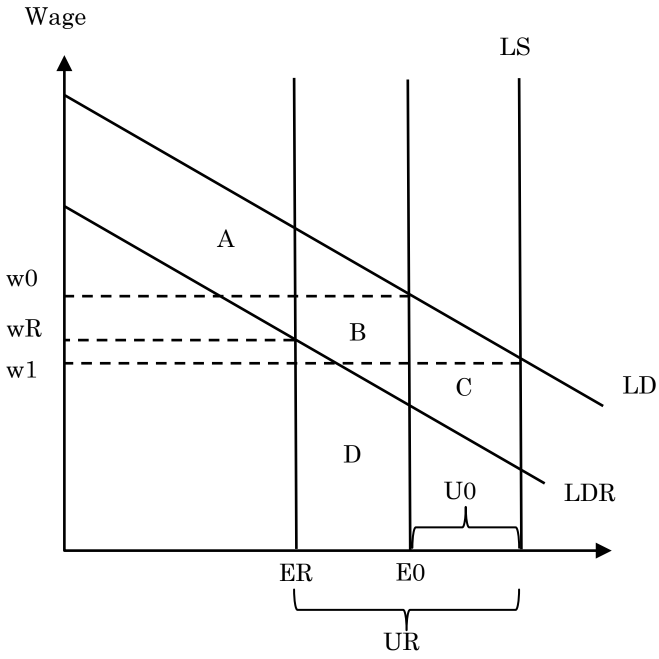

Figure 5: Labor market in wage curve model (WCURVE).

Appendix.

A-1: Results of sensitivity analysis.

In the following, volume of permits traded in the sensitivity analysis.

Volume of permits traded in S_ANN

The benchmark case

	flab	vlab	mwage	wcurve
JPN	21	21	26	23
USA	-127	-128	-148	-124
EUR	125	125	140	121
OOE	-19	-18	-18	-20
RUS	0	0	0	0
CHN	0	0	0	0
IND	0	0	0	0
ROW	0	0	0	0

Increase in reduction rates (hrd).

	flab	vlab	mwage	wcurve
JPN	34	34	41	36
USA	-159	-161	-196	-154
EUR	151	153	180	146
OOE	-27	-26	-24	-28
RUS	0	0	0	0
CHN	0	0	0	0
IND	0	0	0	0
ROW	0	0	0	0

Sensitivity of wcurve model.

	phi_l	phi_hm	ur_l	ur_h
JPN	24	22	22	23
USA	-124	-125	-125	-123
EUR	120	122	122	120
OOE	-20	-19	-19	-20
RUS	0	0	0	0
CHN	0	0	0	0
IND	0	0	0	0
ROW	0	0	0	0

Decrease in reduction rates (lrd).

	flab	vlab	mwage	wcurve
JPN	8	8	10	9
USA	-75	-75	-82	-73
EUR	77	77	82	75
OOE	-10	-10	-10	-11
RUS	0	0	0	0
CHN	0	0	0	0
IND	0	0	0	0
ROW	0	0	0	0

Sensitivity of VLAB model.

	elas_l	elas_h	ltax_l	ltax_h
JPN	21	21	21	21
USA	-127	-127	-129	-129
EUR	125	125	126	126
OOE	-19	-19	-18	-18
RUS	0	0	0	0
CHN	0	0	0	0
IND	0	0	0	0
ROW	0	0	0	0

Labor tax cut scenarios.

	vlab	mwage	wcurve	
JPN	21	21	21	
USA	-75	-75	-82	
EUR	77	77	82	
OOE	-10	-10	-10	
RUS	0	0	0	
CHN	0	0	0	
IND	0	0	0	
ROW	0	0	0	

Unit: $MtCO_2$

Green cells indicate permit exporters.

Volume of permits traded in S_RC

The benchmark case

	flab	vlab	mwage	wcurve
JPN	157	158	159	158
USA	568	572	558	572
EUR	496	497	499	495
OOE	101	102	101	101
RUS	-170	-172	-176	-175
CHN	-1,152	-1,157	-1,141	-1,152
IND	0	0	0	0
ROW	0	0	0	0

Increase in reduction rates (hrd).

	flab	vlab	mwage	wcurve
JPN	227	228	230	229
USA	800	807	784	807
EUR	703	706	712	702
OOE	143	144	142	143
RUS	-271	-273	-276	-277
CHN	-1,601	-1,612	-1,593	-1,603
IND	0	0	0	0
ROW	0	0	0	0

Sensitivity of wcurve model.

	phi_l	phi_hm	ur_l	ur_h
JPN	159	158	158	159
USA	573	570	571	573
EUR	495	495	495	495
OOE	101	101	101	101
RUS	-177	-173	-173	-176
CHN	-1,152	-1,152	-1,152	-1,151
IND	0	0	0	0
ROW	0	0	0	0

Decrease in reduction rates (lrd).

	flab	vlab	mwage	wcurve
JPN	81	82	82	82
USA	303	304	297	304
EUR	261	261	261	260
OOE	54	54	53	54
RUS	-81	-82	-85	-83
CHN	-618	-619	-609	-617
IND	0	0	0	0
ROW	0	0	0	0

Sensitivity of VLAB model.

	elas_l	elas_h	ltax_l	ltax_h
JPN	158	158	158	158
USA	570	574	572	572
EUR	497	498	497	497
OOE	102	103	102	102
RUS	-171	-173	-172	-172
CHN	-1,155	-1,160	-1,157	-1,157
IND	0	0	0	0
ROW	0	0	0	0

Labor tax cut scenarios.

	vlab	mwage	wcurve	
JPN	157	157	157	
USA	303	304	297	
EUR	261	261	261	
OOE	54	54	53	
RUS	-81	-82	-85	
CHN	-618	-619	-609	
IND	0	0	0	
ROW	0	0	0	

Unit: MtCO2

Green cells indicate permit exporters.

Volume of permits traded in S_WORLD

The benchmark case

	flab	vlab	mwage	wcurve
JPN	188	188	189	189
USA	712	714	700	714
EUR	583	583	583	582
OOE	127	127	125	127
RUS	-112	-113	-121	-116
CHN	-871	-875	-874	-871
IND	-299	-298	-282	-295
ROW	-329	-327	-321	-329

Increase in reduction rates (hrd).

	flab	vlab	mwage	wcurve
JPN	275	276	277	277
USA	1,026	1,030	1,007	1,030
EUR	846	847	849	845
OOE	183	184	181	183
RUS	-182	-183	-193	-188
CHN	-1,237	-1,246	-1,243	-1,239
IND	-388	-387	-370	-384
ROW	-524	-520	-508	-525

Sensitivity of wcurve model.

	phi_l	phi_hm	ur_l	ur_h
JPN	189	189	189	189
USA	715	713	714	714
EUR	582	582	582	582
OOE	127	127	127	127
RUS	-118	-114	-114	-117
CHN	-872	-871	-871	-871
IND	-293	-297	-297	-294
ROW	-329	-329	-329	-330

Decrease in reduction rates (lrd).

	flab	vlab	mwage	wcurve
JPN	96	96	96	96
USA	370	370	363	370
EUR	300	300	300	299
OOE	66	66	65	66
RUS	-52	-53	-57	-54
CHN	-458	-459	-459	-458
IND	-166	-165	-156	-164
ROW	-155	-154	-152	-156

Sensitivity of VLAB model.

	elas_l	elas_h	ltax_l	ltax_h
JPN	188	189	188	188
USA	713	714	714	714
EUR	583	583	583	583
OOE	127	128	127	127
RUS	-112	-113	-113	-113
CHN	-873	-879	-875	-875
IND	-298	-297	-298	-298
ROW	-328	-325	-327	-327

Labor tax cut scenarios.

	vlab	mwage	wcurve	
JPN	188	188	188	
USA	370	370	363	
EUR	300	300	300	
OOE	66	66	65	
RUS	-52	-53	-57	
CHN	-458	-459	-459	
IND	-166	-165	-156	
ROW	-155	-154	-152	

Unit: $MtCO_2$

Green cells indicate permit exporters.

A-2: Model description.

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.

2. Notations.

Energy goods:

Symbol	Description
CRU	Crude oil
GAS	Gas
COL	Coal
OIL	Petroleum and coal products
ELE	Electricity

Sets:

Symbol	Description
i, j	Sectors and goods
r, s	Regions
EG	All energy goods: CRU, GAS, COL, OIL and ELE
FF	Primary fossil fuels: CRU, GAS, COL.
EN	Emissions source: CRU, GAS, COL and OIL.
LQ	Liquid fuels: GAS and OIL.
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.
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
A_{ir}^{I}	Armington aggregate for good j used for investment 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 (only appeared in VLAB).
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.
INV_r	Investment in region 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_{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_{ir}^{AI}	Price of Armington good i used for investment in region r.
p_{r}^{C}	Price of aggregate household consumption in region r (only appeared in VLAB)
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}	After-tax wage rate (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.
p^{CO2W}	Price of emissions permit in international permit market.

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 the 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}^{COL}	Share of coal in fossil fuel demand by sector i in region r $(i \notin FF)$
θ_{ir}^{ELE}	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_{ir}^{AI}	Share of domestic variety in Armington good i for investment 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 (only appeared in VLAB).
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}^{I}	Share of Armington good i in investment in region r
θ_{ir}^{EC}	Share of energy good i in energy household consumption demand 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.
$\overline{INV}_r$	Exogenous of investment in region r.

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}^{AFD}	Carbon emissions coefficient for domestic fossil fuel i used for sector j in region $(i \in EN)$. This parameter has 0 for $i \notin EN$.
a_{ijr}^{AFM}	Carbon emissions coefficient for imported fossil fuel i used for sector j in region $(i \in EN)$. This parameter has 0 for $i \notin EN$.
a_{ir}^{APD}	Carbon emissions coefficient for domestic fossil fuel i used for private consumption in region $(i \in EN)$. This parameter has 0 for $i \notin EN$.
a_{ir}^{APM}	Carbon emissions coefficient for imported fossil fuel i used for private consumption in region $(i \in EN)$. This parameter has 0 for $i \notin EN$.
a_{ir}^{AGD}	Carbon emissions coefficient for domestic fossil fuel i used for government expenditure in region $(i \in EN)$. This parameter has 0 for $i \notin EN$.
a_{ir}^{AGM}	Carbon emissions coefficient for imported fossil fuel i used for government expenditure in region $(i \in EN)$. This parameter has 0 for $i \notin EN$.
τ_{jirs}	Amount of global transport service j required for the 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}.	$\mu_{COL} = 2$ $\mu_{CRU} = 2$ $\mu_{GAS} = 2$
σ_{ELE}	Substitution between electricity and the fossil fuel aggregate in production	0.1
σ_{COL}	Substitution between coal and the liquid fossil fuel composite in production	0.5
σ_{LQD}	Substitution between gas and oil in the liquid fossil fuel composite in production	2
σ_i^A	Substitution between the import aggregate and the 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 (only appeared in VLAB).	
σ_i^C	Substitution between the fossil fuel composite and the non-fossil fuel	0.5

	consumption aggregate in household consumption

Variables for MWAGE and WCURVE

Symbol	Description
ue_r	Unemployment in region r
ur_r	Unemployment rate in region r

3. FLAB

3.1. Zero profit conditions and price index

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

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

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 ($i \in FF$):

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

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

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

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:

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

Armington aggregate for private consumption:

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

Armington aggregate for government expenditure:

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

Armington aggregate for investment:

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

Price of domestic goods for intermediate inputs:

$$p_{ijr}^{AFD} = p_{ir}^{Y} + p_r^{CO2} a_{ijr}^{AFD} \qquad \{p_{ijr}^{AFD}\}$$

Price of import goods for intermediate inputs:

$$p_{ijr}^{AFM} = p_{ir}^{M} + p_r^{CO2} a_{ijr}^{AFM} \qquad \{p_{ijr}^{AFM}\}$$

Price of domestic goods for private consumption:

$$p_{ir}^{APD} = p_{ir}^{Y} + p_r^{CO2} a_{ir}^{APD} \qquad \{p_{ir}^{APD}\}$$

Price of import goods for private consumption:

$$p_{ir}^{APM} = p_{ir}^{M} + p_r^{CO2} a_{ir}^{APM} \qquad \{p_{ir}^{APM}\}$$

Price of domestic goods for government expenditure:

$$p_{ir}^{AGD} = p_{ir}^{Y} + p_r^{CO2} a_{ir}^{AGD} \qquad \{p_{ir}^{AGD}\}$$

Price of import goods for government expenditure:

$$p_{ir}^{AGM} = p_{ir}^{M} + p_r^{CO2} a_{ir}^{AGM} \qquad \{p_{ir}^{AGM}\}$$

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:

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

Household non-energy demand:

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

Household energy demand:

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

Global transport sector:

$$\Pi_i^{T} = p_i^{T} - \prod_{r} \left(p_{ir}^{Y}\right)^{\theta_{ir}^{T}} = 0 \qquad \{Y_i^{T}\}$$

Government expenditure:

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

Investment:

$$\Pi_r^{INV} = p_r^{INV} - \sum_{i} \theta_{ir}^{I} p_{ir}^{AI} = 0 \qquad \{INV_r\}$$

3.2. 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:

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

After-tax wage rate:

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

Output:

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

Sector specific energy aggregate:

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

Import aggregate:

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

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:

$$A_{ir}^{P} = -CC_r \frac{\partial \Pi_r^{CC}}{\partial p_{ir}^{AP}} \qquad \{p_{ir}^{AP}\}_{i \notin EG}$$

$$A_{ir}^{P} = -EC_r \frac{\partial \Pi_r^{EC}}{\partial p_{ir}^{AP}} \qquad \{p_{ir}^{AP}\}_{i \in EG}$$

Armington aggregate for investment:

$$A_{ir}^{I} = -INV_r \frac{\partial \Pi_r^{INV}}{\partial p_{ir}^{AI}} \qquad \{p_{ir}^{AI}\}$$

Household utility:

$$U_r = p_r^{U} H_r \qquad \{p_r^{U}\}$$

Aggregate household energy consumption:

$$EC_r = -U_r \frac{\partial \Pi_r^{U}}{\partial p_r^{EC}} \qquad \{p_r^{EC}\}$$

Aggregate household non-energy consumption:

$$CC_r = -U_r \frac{\partial \Pi_r^{U}}{\partial p_r^{CC}} \qquad \{p_r^{CC}\}$$

Government expenditure:

$$G_r = p_r^{G} H_r^{G} \qquad \{p_r^{G}\}$$

Investment:

$$INV_r = \overline{INV_r} \qquad \{p_r^{INV}\}$$

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 $(r \notin ET)$:

$$\overline{CO2}_r = -\sum_{i \in EN} \left[\sum_j A_{ijr}^F \frac{\partial \Pi_{ijr}^{AF}}{\partial p_r^{CO2}} + A_{ir}^P \frac{\partial \Pi_{ir}^{AP}}{\partial p_r^{CO2}} + A_{ir}^G \frac{\partial \Pi_{ir}^{AG}}{\partial p_r^{CO2}} \right] \qquad \{p_r^{CO2}\}$$

Price of emissions permit with international permit trade:

$$\sum_{r \in ET} \overline{CO2}_r = \sum_{r \in ET, i \in EN} \left[\sum_j A_{ijr}^F \frac{\partial \Pi_{ijr}^{AF}}{\partial p^{CO2W}} + A_{ir}^P \frac{\partial \Pi_{ir}^{AP}}{\partial p^{CO2W}} + A_{ir}^G \frac{\partial \Pi_{ir}^{AG}}{\partial p^{CO2W}} \right] \qquad \{p^{CO2W}\}$$

Regional permit price with international permit trade $(r \in ET)$:

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

3.3. Income.

Household income:

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

Government income:

$$H_r^G = p_r^C T_r^L + V_r^R \qquad \{H_r^G\}$$

Lump-sum transfer (tax) to household:

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

Permit revenue:

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

4. MWAGE.

Unemployment (ue_r):

$$\frac{p_{Lr}^F}{p_r^U} - \bar{v}_r \geq 0 \perp ue_r \geq 0 \qquad \{ue_r\}$$

where $\bar{v}_r$ is the exogenous minimum real wage.

Labor market:

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

5. WCURVE.

Unemployment rate (wage curve):

$$\frac{p_{Lr}^F}{p_r^U} = \alpha_r (ur_r)^{-\phi_r} \qquad \{ur_r\}$$

Unemployment (ue_r):

$$ue_r = ur_r \bar{E}_{Lr} \qquad \{ue_r\}$$

Labor market:

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

6. VLAB.

Household utility:

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

Consumption price index:

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

Labor market:

$$\bar{E}_{Lr} = -\sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{Lr}^F} - U_r \frac{\partial \Pi_r^U}{\partial p_r^{LE}} \qquad \{p_{Lr}^F\}$$