A Computable General Equilibrium Analysis of Environmental Tax Reform in Japan

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Abstract

The Japanese government plans to reduce greenhouse gas emissions by 80% by 2050. However, it is not yet clear which policy measures the government will adopt to achieve this goal. In this regard, environmental tax reform, which is the combination of carbon regulation and the reduction of existing distortionary taxes, has attracted much attention. This paper examines the effects of environmental tax reform in Japan. Using a dynamic computable general equilibrium (CGE) model, we analyze the quantitative impacts of environmental tax reform and clarify which types of environmental tax reform are the most desirable. In the simulation, we introduce a carbon tax and consider the following five scenarios for the use of carbon tax revenue: 1) a lump-sum rebate to the household, 2) a cut in social security contributions, 3) a cut in income taxes, 4) a cut in corporate taxes and 5) a cut in consumption taxes. The first scenario is a pure carbon tax, and the other four scenarios are types of environmental tax reform. Our CGE simulation shows that environmental tax reform tends to generate more desirable impacts than the pure carbon tax by improving welfare or increasing GDP while reducing emissions (double dividend). In particular, we show that a cut in corporate taxes leads to the most desirable policy in terms of GDP and national income.

1. Introduction

The Paris Agreement gave momentum to many countries' long-term commitments to reduce greenhouse gases (GHGs). The Japanese government plans to reduce GHG emissions by 80% by 2050. However, it is not yet clear which policy measures the government will adopt to meet this target. The choice of policy measures influences the economic burden of emission regulation. Therefore, the government has been careful in designing policy measures.

To reduce the economic burden of GHG regulation, it is desirable and reasonable to use efficient policy measures. From that perspective, it is natural to adopt carbon pricing, i.e., either carbon taxes or emissions trading schemes (ETSs). In Japan, however, ETSs have been introduced only at the local level in Tokyo (Arimura and Abe, 2020) and Saitama (Hamamoto, 2020). Furthermore, the national government introduced a very low carbon tax of 289 yen per ton (MOE, 2012). Carbon pricing has faced opposition from industry stakeholders who prefer a voluntary approach (Arimura et al., 2019).

However, this opposition to the carbon tax could be overcome if revenue from the carbon tax is used wisely. If the government implements environmental tax reform (ETR), which is the combination of a carbon tax and a reduction in existing distortionary taxes, Japan may achieve both economic growth and emission reduction. This is known as the double dividend (DD) of the carbon tax (Bovenberg and Goulder, 2002). Although environmental regulation is often considered to be a burden for economies and thus difficult to introduce in many countries, the revenue recycling (RR) of environmental taxes is expected to mitigate this problem by improving economic efficiency with the reduction of distortionary taxes. For example, if the government uses carbon tax revenue to reduce corporate taxes, investment will increase. If the labor tax is reduced by RR, the labor supply will increase. If the economic improvement due to the RR is strong enough, there are possibilities for economic growth alongside GHG emission reduction.

The RR of the carbon tax, however, may not always lead to economic growth for two reasons. First, if the reduction of economic activities due to carbon pricing is greater than the expansion of economic activities from tax reduction, GDP will decrease. Second, if the tax interaction effect (Bovenberg and Goulder, 2002) of the carbon tax is large enough, economic growth under carbon pricing will be difficult. Even before a carbon tax is introduced, economies face various distortionary taxes, such as corporate taxes or income taxes. When a carbon tax is added to these distortionary taxes, the deadweight loss due to the existing tax may become even larger. Thus, the benefit of RR must be large enough to achieve economic growth under carbon pricing. To examine the validity of this

hypothesis, we must conduct a numerical simulation.

Previous literature has examined the possibility of DD quantitatively. Saveyn et al. (2011) developed a computable general equilibrium (CGE) model for the EU and found a DD when permit revenues are used to reduce employees' social security contribution. Developing a dynamic CGE model for the US economy, Carbone et al. (2013) found a DD with the RR of capital taxes (i.e., corporate taxes or personal income taxes on interest, dividends, or capital gains). Jorgenson et al. (2013) also found a DD when carbon tax revenues were used to reduce capital taxes for the US economy. Constructing a dynamic CGE model for Portugal, Pereira et al. (2016) showed a DD when carbon tax revenues were used for the reduction in personal income taxes and social security contribution. Freire-González (2017) conducted a comprehensive literature review of the DD.

A few studies examined the DD for the Japanese economy. Takeda (2007) assessed the possibility of a DD using RR for corporate taxes with a dynamic CGE model. Using a macroeconometric model, Lee et al. (2016) examined the DD for the Japanese economy. These studies provided useful information about climate change policy in Japan. However, they have shortcomings. First, Takeda (2007) only examined a mild reduction target of 1995 levels that was discussed at that time. Furthermore, he did not consider carbon capture sequestration (CCS) or renewable energies, which are expected to be important options in the future. On the other hand, Lee et al. (2016) examined the ETR of consumption taxes, social security payments and income taxes but not corporate taxes. Thus, no studies have examined the possibility of DD, including the reform of corporate taxes, for the long-term emission reduction goal for 2050. Moreover, the model in this paper is more realistic than Takeda's model because we consider CCS and renewable energies.

In this paper, using a dynamic CGE model, we analyze the quantitative impacts of ETRs and clarify which types of ETRs are the most desirable. Specifically, we simulated four types of ETRs depending on the types of existing taxes as the target of RR: 1) social security contributions, 2) income taxes, 3) corporate taxes and 4) consumption taxes. The model is more innovative than the previous CGE studies of the DD on the Japanese economy because we incorporate CCS and renewable energy.

We show that the RR of the carbon tax can lead to economic growth in 2030 in the case of the Japanese economy. They show that the Japanese economy can achieve economic growth while reducing GHG emissions in 2030.

2. Methods and Data

2.1. Model

We use the simulation based on a CGE model. In this section, we explain the model and data used for the simulation. The structure of the model is basically the same as that of Takeda (2007), although we make some improvements. Our model is relatively simple, but we cannot provide a full description of the model due to space limitations. For details on the model, see the supplementary material[6].
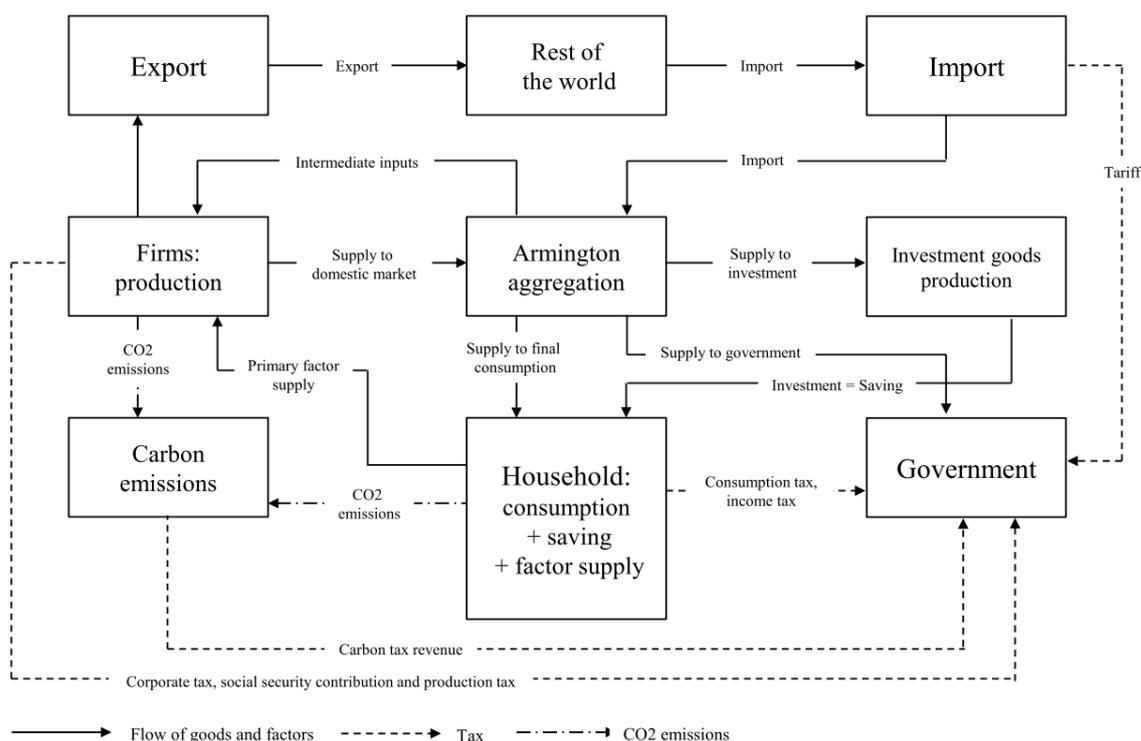
Figure 1: The basic structure of the model.

Our model is a single country model for Japan that divides the economy into 47 goods and 39 sectors, as listed in Table 1. Basically, one sector produces one good, but some sectors produce multiple goods, and some goods are produced by multiple sectors. For example, the "petroleum products (PET)" sector produces eight petroleum goods, and "electricity" is produced by multiple electricity sectors. Thus, the number of goods does not coincide with that of sectors. The model is a dynamic model that covers the years 2011 to 2050. We treat five years as one period and solve the model for every five years

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[6] The full model description is provided in the supplementary material. In addition, the simulation programs are available from the authors upon request. Complete and accurate information about the model structure and the simulation setting can be obtained by reading the program code.

to 2050. The model includes three types of agents: a representative household, firms and the government. We assume that all markets in the model are perfectly competitive and that all agents behave as price takers. The basic structure of the model is depicted in Figure 1.

Table 1: List of goods and sectors.

Goods		Sectors		Goods		Sectors	
1 AGR	Agriculture, forestry and fishery	1 AGR		26 EMA	Electrical machinery	16 EMA	
2 MIN	Mining excl. fossil fuels	2 MIN		27 TEQ	Transportation equipment	17 TEQ	
3 COA	Coal	3 F_F	Fossil fuels	28 OMA	Other manufacturing products	18 OMA	
4 OIL	Crude oil			29 CON	Construction	19 CON	
5 GAS	Natural gas			30 ELY	Electricity	20 E_F	Electricity (fossil fuel)
6 FOO	Bevarages and foods	4 FOO				21 E_N	Electricity (nuclear)
7 TXT	Textile products	5 TXT				22 E_H	Electricity (hydro)
8 PPP	Paper, pulp and wooden products	6 PPP		31 G_H	Gas and heat supply	23 G_H	
9 CHM	Chemical products	7 CHM		32 WWM	Water supply and waste	24 WWM	
10 GSO	Gasoline	8 PET	Petroleum products	33 COM	Commerce	25 COM	
11 JET	Jet fuel oils			34 FIN	Finance and insurance	26 FIN	
12 KER	Kerosene			35 RES	Real estate	27 RES	
13 LOI	Light oils			36 RAI	Railway transport	28 RAI	
14 HOI	Heavy oils			37 R_P	Road transport (passenger)	29 R_P	
15 NAP	Naphtha			38 R_F	Road transport (freight)	30 R_F	
16 LPG	LPG			39 WAT	Water transport	31 WAT	
17 OPP	Other petroleum refinery products			40 AIR	Air transport	32 AIR	
18 COK	Coke	9 COP	Coal products	41 OTR	Other transport service	33 OTR	
19 COP	Other coal products			42 C_B	Communication and broadcasting	34 C_B	
20 CSC	Ceramic, stone and clay products	10 CSC		43 E_R	Education and research	35 E_R	
21 CEM	Cement	11 CEM		44 MHS	Medical, health care and welfare	36 MHS	
22 I_S	Iron and steel	12 I_S		45 BUS	Buisiness services	37 BUS	
23 NFM	Non-ferrous metals	13 NFM		46 PER	Personal services	38 PER	
24 MET	Metal products	14 MET		47 GGO	Government service	39 GGO	
25 GMA	General-purpose machinery	15 GMA					

2.2. Production Side

Firms produce goods with constant-returns-to-scale technology using primary factors and intermediate inputs. The primary factors are labor, capital stock, land and resources. Land is a specific factor used only in the AGR sector. Similarly, resources are specific to the F_F and electricity sectors.

The production technology in each sector is represented by a constant elasticity of substitution (CES) production function. To consider the difference in production technology of goods and services with completely different properties, we divide production sectors into the following five types: 1) general sectors, 2) AGR sector, 3) F_F sector, 4), electricity sector, and 5) PET, COP and G_H sectors. General sectors include all sectors not included in sectors 2-5. We assume different production functions for different types of sectors. Below, we explain the production structure of each sector.
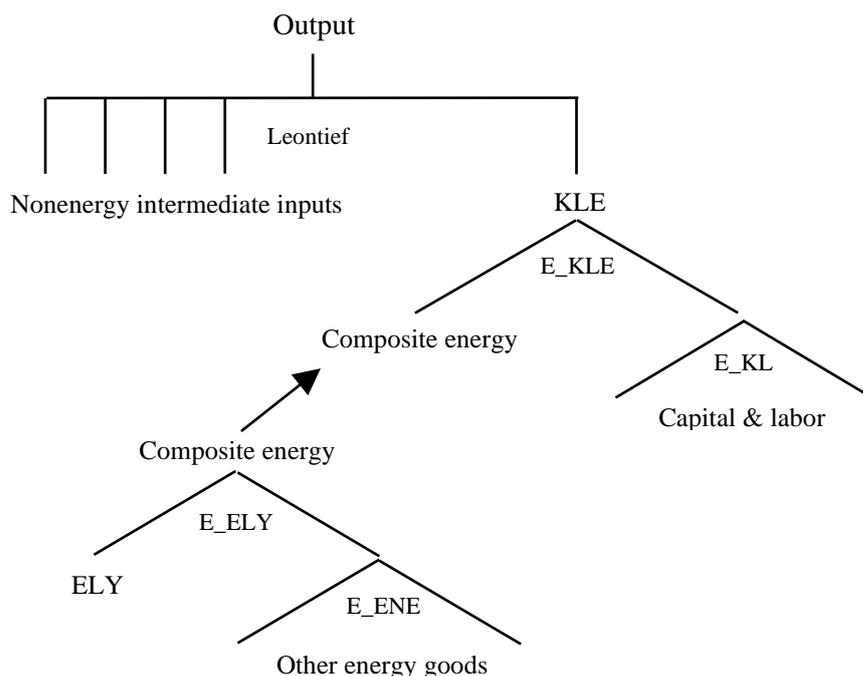
Figure 2: Production function of general sectors.

First, general sectors have the CES production function in Figure 2. The tree diagram in the figure represents the structure of the nested CES function, where symbols such as E_XX indicate values of the elasticity of substitution (EOS) between inputs. In general sectors, output is produced by the Leontief aggregation of nonenergy intermediate inputs and an energy-primary factor composite (KLE). The energy-primary factor composite is a nested CES function of composite energy and primary factors (capital and labor). A composite energy is the CES aggregation of electricity and other energy composites, which is, in turn, the CES aggregation of all other energy goods. We use this type of nested production structure because we would like to consider the differences in values of EOS between various inputs.

Next, the production function of the AGR sector is given by Figure 3. In the AGR sector, the primary factor of land plays an important role in production. Thus, we assume a production function that emphasizes the role of land. In the AGR sector, output is produced by the CES aggregation of land and nonland input, where land is the specific primary factor used only in the AGR sector. The structure of nonland input is the same as the production tree of general sectors. This production function implies that the output of AGR is strongly restricted by the amount of land.

The production function of F_F is basically the same as that of AGR except that resources are used as a specific factor instead of land. The production function of the three electricity sectors has a structure similar to AGR and F_F but slightly different. In the

production function of electricity sectors depicted in Figure 4, the energy composite enters the second level Leontief nest as a nonenergy intermediate input. We assume this shape for electricity sectors so that energy input and the capital-labor composite cannot be substituted in electricity generation by fossil fuels.
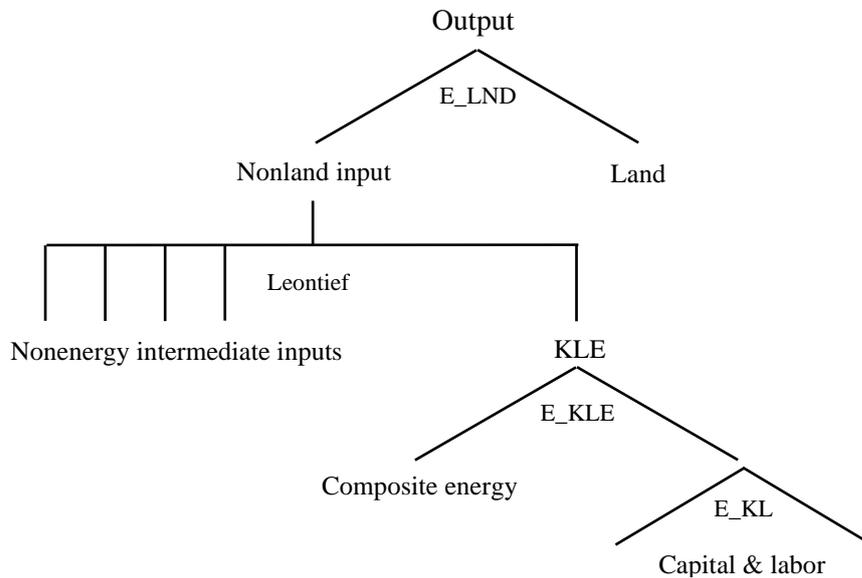
Figure 3: Production function of AGR.
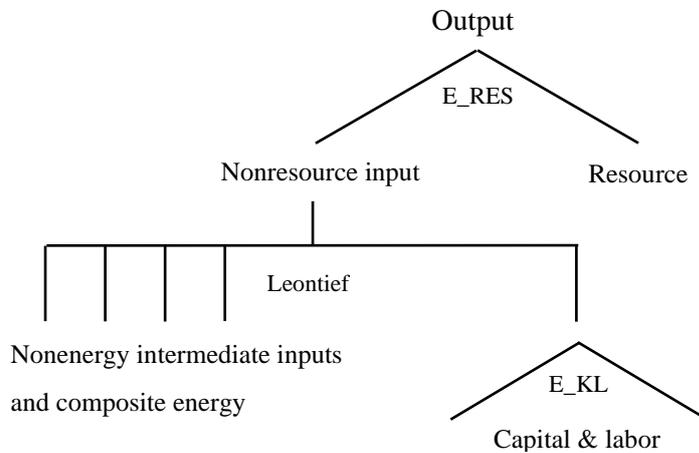
Figure 4: Production function of the electricity sector.

The PET, COP and G_H sectors have almost the same production function as the general sectors depicted in Figure 2, but the method of treating energy inputs is slightly different. For example, a large amount of "OIL" (crude oil) is used in the PET sector, but almost all of it is used as feedstock, which means that "OIL" is used as a material. Thus, it is desirable to treat oil input in the PET sector as an other non-energy input. For this, "OIL" enters the top Leontief nest in the PET sector. A similar treatment is also applied

to "COA" used in the COP sector and "GAS" and "LPG" used in the G_H sector.

The production functions explained above include many parameters, in particular, many EOS parameters. The values of these parameters are provided in XXX. Each sector determines outputs and inputs to maximize their profits. Produced output is allocated to the domestic market or export market. The allocation is conducted through a constant elasticity of transformation (CET) function as in Lofgren et al. (2002) and Takeda (2007).
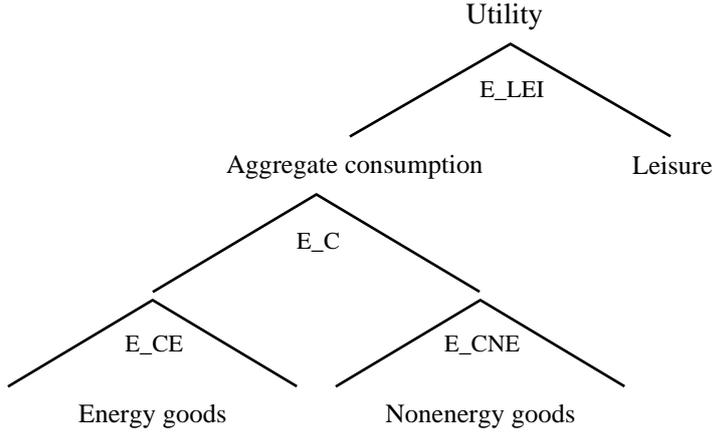
Figure 5: Period utility function.

2.3. Demand Side

To represent the demand side of the economy, we assume a representative household. The representative household's utility depends on consumption and leisure. The utility at a period (hereafter, period utility) for the household is represented by the nested CES function in Figure 5. Aggregate consumption is a CES aggregation of an energy composite and a nonenergy composite with an EOS of E_C. The energy composite is a CES aggregation of energy goods with an EOS of E_CE, and the nonenergy composite is a CES aggregation of nonenergy goods with an EOS of E_CNE. From period utility in all periods, the lifetime utility of the household is derived as

$$u^L = \left[\sum_t \alpha_t^u (u_t)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}$$

where u^L is lifetime utility, u_t is period utility at period t, and σ is the intertemporal elasticity of substitution. This means that lifetime utility is assumed to be a CES aggregation of period utility. The representative household chooses consumption and leisure subject to its lifetime budget constraint to maximize the lifetime utility. Since hours of leisure are equal to the total available time minus hours of work, the leisure decision is similar to the labor supply decision. Similarly, since the total budget is

allocated to consumption and savings, the consumption decision is a savings decision. The representative household provides primary factors to production sectors and obtains factor income.

2.4. The Dynamics of the Model

Our model is a forward-looking dynamic model that assumes a household's dynamic optimizing behavior. Many CGE models used for the analysis of climate change policy, for example, the MIT EPPA model (Chen et al., 2015) and OECD ENV-Linkages model (Chateau et al., 2014), are dynamic models, but they are usually recursive dynamic models[7]. The recursive dynamic model is a kind of dynamic model that depicts the dynamic path of the economy by solving a myopic or static model iteratively. The recursive dynamic model has some merits, but it cannot incorporate investment behavior properly because investment, which is intrinsically forward-looking behavior, is based only on the past and present information in the recursive dynamic model.

In this study, we want to analyze the reduction in corporate taxes, which are modeled as a tax on return from investment. To capture the forward-looking investment behavior, we need to use the forward-looking dynamic model. When we solve the forward-looking model, we need to solve all periods simultaneously, which means that the model, particularly the multigoods, multisector model, includes a large number of variables. To reduce the number of variables included in the model, we set one period to five years and solve the model for every five years until 2050[8].

Investment is determined by the dynamic optimization of the household, and capital stock is accumulated through investment over time. Investment is financed by the household's savings. In addition, the amount of endowments of primary factors such as land and resources change over time. We assume that the total time available for leisure and hours of labor evolves over time according to the change in population. Since our model covers a long time span, the change in technology plays an important role in determining the impacts of climate change policy. For this, we consider growth in total factor productivity (TFP) and autonomous energy efficiency improvement (AEEI).

2.5. Government

The government collects revenue from consumption taxes, income taxes, corporate taxes, production taxes, tariffs, and social security contributions by employers. Then, the government uses this revenue to finance government consumption. We assume that

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[7] The EPPA model has a forward-looking version; see Babiker et al. (2008).

[8] Strictly speaking, we solve for 2011, 2016, 2021,…,2046, 2051. However, for notational simplification, we use the expression 2011, 2015, 2020,…,2045, 2050.

government consumption grows exogenously in line with economic growth.

Since the benchmark year for the data is 2011, we use a 5% consumption tax rate in 2011. After 2020, we assume that the consumption tax is raised to 10%[9]. Income tax is incorporated into the model as a tax on the labor income of the household, and corporate tax is a tax on return from investment (capital stock). Strictly speaking, social security contribution by employers is not a tax. However, it plays a role similar to the labor tax because it increases the costs of employment. In addition, the total value of social security contributions is much larger than that of other taxes. Thus, we consider social security contributions. With respect to income taxes, corporate taxes and social security contributions, we derive the (average) tax rate by dividing tax payments by the tax base in the benchmark year. Social security contributions are collected by sector, and the rates for social security contributions are different across sectors. All tax rates are kept constant except when we consider ETR.

2.6. International Trade

Our model focuses only on Japan, but we need to consider international trade in goods and services. To incorporate international trade, as in Takeda (2007), we assume that Japan is a small country, which means that terms of trade of Japan are constant. We assume that the foreign exchange rate is adjusted so that the trade balance is kept constant at the benchmark level. As with other CGE models, we use the Armington assumption (Armington, 1969), which means that domestic goods and imported goods are imperfect substitutes and are aggregated through a CES function.

2.7. Carbon Tax

In the later simulation, we use a carbon tax to regulate CO_2 emissions. The carbon tax is a tax based on the amount of CO_2 from fossil fuels. Thus, let p_i be the original price of fossil fuel i, t^{CO2} be the carbon tax rate, and δ_i be the carbon coefficient (the amount of CO_2 per unit of fossil fuel i). Then, the user price of fossil fuel is given by

$$p_i^A = p_i + t^{CO2}\delta_i$$

We determine the carbon tax rate so that total carbon emissions are equal to the target value. The introduction of a carbon tax generates additional tax revenue. The use of carbon tax revenue is discussed in the later section.

2.8. Renewable Energy and CCS

New technology and energy play important roles in the long-term analysis of climate

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[9] The tax rate for the consumption tax in Japan was raised from 5% to 8% in 2014 and raised to 10% in 2019.

change policy. Specifically, renewable energy and CCS are considered to be important measures to mitigate climate change. Thus, we incorporate these two factors into our model. First, in addition to electricity generated by conventional energy (fossil fuel, nuclear and hydropower), we add electricity generated by renewable energy. Similar to conventional electricity sectors, renewable electricity sectors generate electricity by using various production inputs but do not use fossil fuels and thus do not emit CO_2. We assume that the cost of electricity generated by renewables is higher than that of conventional electricity sectors. Thus, the supply of electricity generated by renewables is small in the early period and increases gradually as CO_2 regulation is strengthened and the price of electricity rises.

Second, we consider CCS activity. CCS is usually combined with coal-fired electricity generation, but for simplicity, we assume that CCS activity is conducted by an independent sector. Similarly to electricity from renewable energy, we assume that the cost of CCS is high (10,000 yen/per ton); thus, CCS is not supplied in the early periods. However, the supply of CCS increases as the carbon price rises. There is an upper limit on CCS (180 $MtCO_2$). The existence of CCS means that net CO_2 emissions are equal to gross CO_2 emissions minus CCS.

2.9. Data

CGE analysis is based on the benchmark data that represent the economy at a certain period. We use Japanese input-output data from 2011 (MIC, 2016) for the benchmark data and aggregate sectors and goods of the original IO data into the sectors and goods in Table 1. For CO_2 emissions data, we use 3EID data from 2011 (Center for Global Environmental Research, 2018). For the taxation data, we use the data from the Ministry of Finance Statistics Monthly No. 722 (PRI, 2012).

3. Simulation Scenarios

3.1. Scenarios

In the simulation, we consider the six scenarios listed in Table 2. The BAU scenario is a reference scenario in which no explicit CO_2 regulation (carbon tax) is adopted. We determine some of the exogenous parameters in the model so that the equilibrium in BAU replicates the situation under the "current policies scenario" in the World Energy Outlook 2018 (IEA, 2018). Specifically, we determine rates of TFP growth and AEEI so that values of GDP and CO_2 emissins derived from the model replicate those of WEO 2018. In the other five scenarios, we impose a carbon tax to reduce CO_2 emissions by 80% by 2050. We use 2020 as the benchmark year for the reduction rate. Thus, if the amount of CO_2 in

2020 is 800 $MtCO_2$, an 80% reduction means that (net) CO_2 must be reduced to 160 $MtCO_2$ by 2050.

Table 2: List of scenarios.

Scenario	Explanation
BAU	Business As Usual (BAU) scenarios
LMP	Carbon tax + lump-sum rebate
SSC	Carbon tax + cut in social security contributions
INC	Carbon tax + cut in income tax
COR	Carbon tax + cut in corporate tax
CON	Carbon tax + cut in cunsomption tax

LMP is the scenario in which carbon tax revenue is rebated to the household in a lump-sum way. This scenario does not change existing tax rates and thus represents the scenario of a pure carbon tax. The other four scenarios are ETR scenarios in which the carbon tax replaces the existing taxes. First, SSC is a scenario with a cut to social security contributions. The cut to social security contributions lowers the labor cost for employers and thus is likely to increase employment.

Second, INC is a scenario in which income tax is reduced. The income tax in this model is a tax on the labor income of the household and lowers the incentive to work. The cut in income taxes has the effect of stimulating incentives to work and increasing the labor supply. It leads to an increase in production and generates positive impacts on the economy. COR is a scenario featuring a cut in corporate taxes. Corporate tax in our model is a tax on returns from capital stock and thus suppresses incentives to invest. The cut in corporate taxes increases investment and accelerates the accumulation of capital, leading to an increase in output. Finally, CON is the scenario of cuts in consumption taxes. In the second half of the 2010s, the consumption tax became the major tax in Japan, and its share of the total tax was the largest. The cut in consumption tax is expected to stimulate consumption demand and thereby production. In the simulation, we compare the results from BAU with those from other scenarios. Specifically, we check how equilibrium, particularly macroeconomic variables, changes from the BAU equilibrium when CO_2 regulations are imposed.

3.2. Criteria for the Double Dividend

Many studies have investigated ETR and the possibility of the DD. Some studies report the existence of the DD, and others do not, and there are wide varieties in conclusions (see Freire-González, 2017). One reason for these diverse conclusions is that different

studies use different criteria for judging the existence of the DD. Theoretical studies often use "utility" as a criterion for the DD (Bovenberg and Goulder, 2002), but some use the volume of employment instead (e.g., Bovenberg and van der Ploeg, 1998). On the other hand, CGE studies often use GDP and income for the criteria. In addition, when utilizing a dynamic model, there are two types of utility that can be used as criteria: period utility and lifetime utility[10]. Since these variables move differently, the existence of the DD depends on which variable is used as criteria.

From a theoretical point of view, utility may be the most important variable, but it cannot be directly observable and is thus difficult to use as a policy criterion. Actually, utility is rarely used as a policy evaluation criterion in policy making. Since each criterion has some advantages and disadvantages, we decide to use multiple criteria for the DD. Specifically, we use the following four criteria (variables): GDP, (national) income, period utility and lifetime utility.

In addition, there are two types of DD, that is, a "strong DD" and a "weak DD" (Goulder, 1995). The former indicates the situation where ETR generates a positive impact on the criterion variable, for example, the increase in GDP when GDP is used as a criterion. The latter DD indicates the situation in which ETR generates better results than the lump-sum rebate of carbon tax revenue. A strong DD is the most desirable result, but even a weak DD shows ETR's superiority to the pure carbon tax.

4. Results

4.1. BAU Equilibrium

Table 3 reports GDP and CO_2 emissions in the BAU scenario. In BAU, GDP increases at an annual rate of 0.6% to 0.8% and reaches approximately 700 trillion yen in 2050. The growth of GDP is due mainly to capital accumulation and TFP growth. On the other hand, CO_2 emissions decrease gradually and decrease to 830 $MtCO_2$ in 2050. Although GDP increases and there is no explicit CO_2 regulation (carbon tax) in BAU, CO_2 emissions decrease over time because we have AEEI and an increase in renewable energy.

Figure 6 shows the path of electricity generation in BAU (TWh). Electricity generation decreases in the long run in BAU. In addition, electricity generation by fossil fuels decreases significantly, while electricity generation by renewable energy increases, leading to a decrease in CO_2 emissions, as described in the previous paragraph. The levels of electricity from nuclear power and hydropower are kept constant in the assumption.

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[10] For example, Takeda (2007) uses lifetime utility for the criterion of the DD.

Table 3: GDP and CO$_2$ emissions in BAU.

	Level		Annual growth rate (%)	
	GDP	CO2	GDP	CO2
2020	561.4	997.1	0.6	-1.7
2025	581.9	961.0	0.7	-0.7
2030	599.7	925.2	0.6	-0.8
2035	622.0	894.3	0.7	-0.7
2040	646.1	869.0	0.8	-0.6
2045	671.7	848.8	0.8	-0.5
2050	698.2	833.6	0.8	-0.4

GDP is trillion yen, and CO$_2$ is MtCO$_2$.
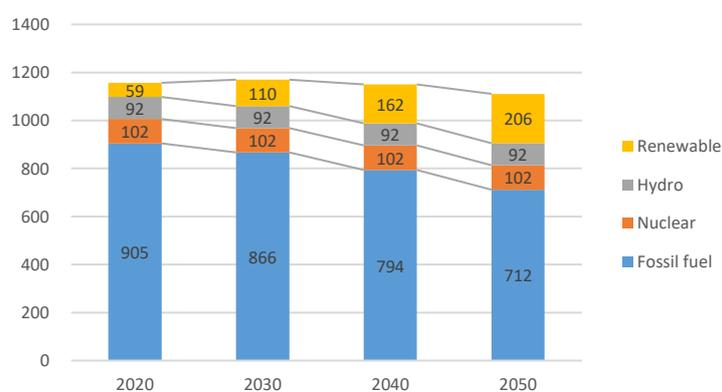
Figure 6: Electricity generation in BAU (TWh)

Table 4 reports BAU values of revenues from taxes that are reduced in the ETR scenarios. The rates of all taxes are kept constant, but economic growth in BAU increases revenues from all taxes over time.

Table 4: Tax revenue in BAU (trillion yen).

	SSC	INC	COR	CON
2020	26.5	13.8	10.0	19.2
2025	27.5	14.4	10.6	20.0
2030	28.3	14.8	11.0	20.8
2035	29.3	15.4	11.5	21.7
2040	30.4	16.0	12.0	22.7
2045	31.6	16.7	12.6	23.7
2050	32.8	17.3	13.1	24.9

4.2. Impacts of the Carbon Tax

Now, let us examine the impacts of the carbon tax. Table 5 reports CO$_2$ emissions (gross

and net), the volume of CCS and the carbon tax rate in 2030 and 2050. In BAU, CO_2 emissions in 2030 and 2050 are 925 $MtCO_2$ and 834 $MtCO_2$, respectively. Under CO_2 regulation, these values decrease to 652 $MtCO_2$ and 217 $MtCO_2$, respectively. The 80% reduction target means an 80% reduction from the 2020 CO_2 level, and the reduction rate from the 2050 level is slightly smaller (approximately 74%). Nevertheless, it shows that Japan has to reduce a significant amount of CO_2 emissions.

Table 5: CO_2 emissions under the carbon tax.

		BAU	LMP	SSC	INC	COR	CON
2030	CO2 (gross)	925.2	652.1	652.4	652.5	657.8	652.9
	CO2 (net)	925.2	652.1	652.1	652.1	652.1	652.1
	CCS	0.0	0.0	0.3	0.4	5.7	0.8
	Carbon tax rate (yen/ton)	0	15,054	15,489	15,463	15,230	15,698
2050	CO2 (gross)	833.6	397.4	397.4	397.4	397.4	397.4
	CO2 (net)	833.6	217.4	217.4	217.4	217.4	217.4
	CCS	0.0	180.0	180.0	180.0	180.0	180.0
	Carbon tax rate (yen/ton)	0	60,140	61,411	61,385	62,307	61,210

The unit of CO_2 and CCS is $MtCO_2$.

Table 6: Macroeconomic impacts (% change from BAU value).

		LMP	SSC	INC	COR	CON
2030	GDP	-0.59	-0.10	-0.10	0.38	-0.14
	Income	-0.83	-0.34	-0.33	0.44	0.37
	Period util.	-0.91	-1.05	-1.05	-0.89	-0.58
2050	GDP	-2.06	-1.44	-1.45	-0.95	-1.95
	Income	-2.93	-2.25	-2.25	-1.51	-2.41
	Period util.	-2.69	-2.64	-2.64	-2.47	-2.51
	Lifetime util.	-0.98	-0.98	-0.98	-1.10	-0.93

The blue cells indicate a strong DD, and the orange cells indicate a weak DD.

CO_2 emissions here indicate net CO_2 emissions. Because of the existence of CCS activity, gross CO_2 emissions do not decrease as much as net CO_2 emissions. The amount of CCS in 2050 reaches 180 $MtCO_2$, which is the upper limit, and thus, gross CO_2 emissions are greater than net emissions by 180 $MtCO_2$.

The significant decrease in CO_2 emissions is realized by the carbon tax. The required carbon tax rate in LMP is approximately 15,000 yen in 2030 and 60,000 yen in

2050. These tax rates are not very different in ETR scenarios, which shows that a significantly high carbon tax rate is needed to reduce CO_2 emissions by 80%.

Next, let us observe the impacts on macroeconomic variables. Table 6 reports the percentage change in GDP, income, period utility and lifetime utility from BAU values. GDP, income and period utility are reported for two periods: 2030 and 2050. From these values, we can see whether ETR generates the DD or not.

First, we examine the impacts in 2030. In LMP, all three variables (GDP, income and period utility) decrease with the carbon tax. This is the expected result because LMP represents the scenario of the pure carbon tax. On the other hand, GDP and income increase from BAU in some ETR scenarios. Specifically, GDP increases in COR and income increases in both COR and CON, which means that if we use GDP as the criterion, we find a strong DD in COR. Similarly, if income is used as the criterion, we find a strong DD in both COR and CON. Although we find no strong DD in SSC and INC, we still find a weak DD in terms of GDP and income. These results mean that ETR generally has more desirable impacts than the pure carbon tax.

Next, let us observe the impacts in 2050. In 2050, we find no strong DD for any scenario or criterion. However, there are still many cases with a weak DD, which means that ETR is desirable. Finally, in terms of lifetime utility, we find no strong DD in any case and do not find even a weak DD in INC and COR, which suggests that ETR may not necessarily be a desirable policy when lifetime utility is used as the criterion.

In terms of types of ETR, COR seems to be the most desirable policy scenario because it generates a strong DD of GDP and income in 2030, and the sizes of the decreases in GDP and income in 2050 is smaller than those in other policy scenarios. The reason why COR increases GDP and income (or reduces the sizes of the decreases in GDP and income) is that COR stimulates investment and thereby increases the capital stock, leading to an increase in production in the long run. Other policy scenarios generate desirable impacts in terms of some criteria and in some periods, but their impacts are generally ambiguous.

Our simulation implies that ETR generally has more desirable impacts than the pure carbon tax. Specifically, the cut in corporate taxes is desirable because it is likely to generate the DD. However, note that the result that ETR is superior to the pure carbon tax does not always hold and the existence of the DD depends on the criteria and policy scenarios.

4.3. Sensitivity Analyses

In the previous section, we obtained several insights from the simulation. The simulation is based on specific assumptions and scenarios that are not necessarily realistic. To see

how our insights depend on the assumptions of the simulation and how changing the assumptions can change the results, we conduct sensitivity analyses of the following aspects below: 1) CCS, 2) renewable energy, and 3) nuclear power. The list of sensitivity analyses is presented in Table 7. The simulation conducted so far is referred to as the benchmark case.

Table 7: List of scenarios in the sensitivity analyses.

Scenario	Explanation
CCS_MORE	Scenario with more CCS
CCS_LESS	Scenario with less CCS
RENE_MORE	Scenario with more renewable energy
RENE_LESS	Scenario with less renewable energy
NUKE_MORE	Scenario with more nuclear energy
NUKE_LESS	Scenario with less nuclear energy

First, we change the amount of CCS because the amount of CCS available is highly uncertain. In the benchmark case, the upper limit of CCS is set to 180 $MtCO_2$. We change the limit on CCS to 200 $MtCO_2$ in CCS_MORE and to 160 $MtCO_2$ in CCS_LESS. Next, we change the amount of electricity generated by renewable energy because there is huge uncertainty in the cost and limit of renewable energy, as there is in CCS. In the benchmark case, electricity generated by renewable energy reaches approximately 206 TWh in 2050 under the BAU scenario. We change the amount of resources used for electricity generation by renewables and thereby the amount of supply of electricity. Specifically, we increase electricity generated by renewables by 25% in RENE_MORE and decrease it by 20% in RENE_LESS.

Finally, we change the amount of electricity generated by nuclear power. After the Great East Japan Earthquake in 2011, many nuclear power plants have closed, and the supply of electricity from nuclear power remains low. Since the government has not provided a clear plan for future nuclear use, there is huge uncertainty in nuclear use in the future. Thus, we checked the sensitivity of nuclear use. In the benchmark setting, electricity generated by nuclear power is set to approximately 100 TWh, which is basically constant over time. We increase electricity generated by nuclear by 100% in NUKE_MORE and decrease it by 90% in NUKE_LESS. Below, we check how the change in assumptions alters the results. Note that RENE_MORE/LESS and NUKE_MORE/LESS alter the BAU equilibrium itself; thus, we cannot directly compare the results for these scenarios with those for the benchmark case.

Table 8 reports the simulation results of the sensitivity analyses. They show that we find at least a weak DD in many cases and a strong DD of GDP and income under

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COR and CON. By changing assumptions, the quantitative impacts of the carbon tax often change to a large extent, but almost all qualitative insights derived from the benchmark case remain unchanged. It follows that the analyses in the previous sections have a certain level of robustness.

Table 8: Results of the sensitivity analyses.

		CCS_MORE					CCS_LESS				
		LMP	SSC	INC	COR	CON	LMP	SSC	INC	COR	CON
2030	GDP	-0.61	-0.12	-0.12	0.32	-0.17	-0.57	-0.08	-0.08	0.46	-0.11
	Income	-0.85	-0.36	-0.35	0.37	0.34	-0.80	-0.31	-0.30	0.54	0.42
	Period util.	-0.90	-1.04	-1.04	-0.85	-0.57	-0.92	-1.07	-1.07	-0.94	-0.60
2050	GDP	-1.89	-1.35	-1.35	-0.87	-1.74	-2.26	-1.57	-1.58	-1.06	-2.21
	Income	-2.67	-2.06	-2.06	-1.36	-2.14	-3.25	-2.49	-2.49	-1.73	-2.77
	Period util.	-2.47	-2.39	-2.39	-2.24	-2.33	-2.98	-2.94	-2.94	-2.74	-2.74
	Lifetime util.	-0.94	-0.93	-0.94	-1.04	-0.90	-1.04	-1.04	-1.05	-1.17	-0.97

		RENE_MORE					RENE_LESS				
		LMP	SSC	INC	COR	CON	LMP	SSC	INC	COR	CON
2030	GDP	-0.53	-0.12	-0.12	0.25	-0.17	-0.64	-0.07	-0.07	0.53	-0.10
	Income	-0.74	-0.34	-0.33	0.27	0.23	-0.89	-0.31	-0.30	0.64	0.49
	Period util.	-0.95	-1.08	-1.08	-0.95	-0.66	-0.86	-0.99	-0.99	-0.84	-0.53
2050	GDP	-1.94	-1.41	-1.42	-1.18	-2.07	-2.18	-1.48	-1.48	-0.70	-1.81
	Income	-2.78	-2.17	-2.18	-1.80	-2.69	-3.09	-2.33	-2.33	-1.22	-2.11
	Period util.	-2.72	-2.68	-2.68	-2.48	-2.51	-2.67	-2.60	-2.60	-2.46	-2.51
	Lifetime util.	-1.04	-1.04	-1.05	-1.11	-0.97	-0.93	-0.91	-0.92	-1.08	-0.89

		NUKE_MORE					NUKE_LESS				
		LMP	SSC	INC	COR	CON	LMP	SSC	INC	COR	CON
2030	GDP	-0.55	-0.17	-0.17	0.18	-0.21	-0.58	0.02	0.02	0.62	-0.06
	Income	-0.76	-0.39	-0.38	0.18	0.14	-0.82	-0.20	-0.19	0.76	0.53
	Period util.	-0.84	-0.96	-0.96	-0.83	-0.58	-1.01	-1.11	-1.10	-0.96	-0.70
2050	GDP	-1.96	-1.49	-1.50	-1.24	-2.02	-2.17	-1.45	-1.46	-0.74	-1.90
	Income	-2.75	-2.21	-2.22	-1.82	-2.60	-3.14	-2.35	-2.35	-1.32	-2.28
	Period util.	-2.46	-2.40	-2.40	-2.23	-2.30	-2.97	-2.91	-2.92	-2.76	-2.79
	Lifetime util.	-0.94	-0.94	-0.94	-1.00	-0.88	-1.06	-1.05	-1.06	-1.22	-1.01

5. Conclusions

Using a dynamic computable general equilibrium model, we analyze the quantitative impacts of ETR and examine the validity of the DD of the carbon tax by RR in the Japanese economy. As the emission reduction target, we chose the goal set by the Japanese government, i.e., the 80% reduction in GHG emission by 2050. As ETRs, we

examined the four types of RR of the carbon tax. The four scenarios we examined were the reduction in 1) social security contributions, 2) income taxes, 3) corporate income taxes and 4) consumption taxes and compared these scenarios with the pure carbon tax (the carbon tax with a lump-sum rebate to households).

Our CGE simulations show that ETR tends to generate more desirable impacts than the pure carbon tax. ETR generates a strong DD in 2030 under some policy scenarios and at least a weak DD in 2050 in many scenarios, which implies that the government should use ETR instead of the pure carbon tax. In particular, we found that the corporate tax cut is likely to generate the DD in terms of GDP and income. The corporate tax cut generates a strong DD of GDP and income in 2030 and tends to generate more desirable impacts than other ETR policy scenarios in 2050. Following our simulation results, the carbon tax with RR into corporate taxes may attract support from some stakeholders. The government may be able to obtain more public support for the carbon tax if they adopt the scenario of corporate tax reduction with RR.

However, our simulation results also have ambiguities. They show that ETR does not always generate better impacts, and the existence of the DD can depend on the criteria and policy scenarios. This ambiguous result implies that we need to continue a more elaborate analysis of ETR in the future.

In addition, in understating the implications of our simulation, some caution must be adopted because there are some limitations to our modeling. First, our model does not incorporate certain new technologies. For example, we do not model hydrogen fuel, which is an important energy source to realize decarbonization. The diffusion of hydrogen fuel may not be relevant in 2030 but is expected to be crucial in 2050. Furthermore, we do not model the transportation sector in a sophisticated manner. Thus, electric vehicles or fuel cell vehicles that make use of hydrogen fuel are not captured in detail. These aspects of the modeling are areas for future research. With these revisions in the modeling, we will be able to understand the possibilities of the DD in 2050 more accurately.

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Supplementary material

In this supplementary material, we provide the complete algebraic representation of the model and parameter values.

1. Notes
- All functions are written in calibrated share form.
- All reference prices are omitted for notational simplicity.

2. Notations.
Sets:

Symbol	Description
i	Index of goods
j	Index of sectors
S_ELY	All conventional electricity sectors: E_F, E_N, E_H
S_PCG	Set of PET, COP and G_H.
S_TRN	Set of transport sectors: RAI, R_P, R_F, WAT, AIR.
G_F_F	All primary energy goods: OIL, COA, GAS.
G_PET	All petroleum products: GSO, JET, KER, LOI, HOI, NAP, LPG, OPP.
G_COP	All coal products: COK, COP.
G_ENE	All energy goods: ELY ∪ G_H ∪ G_F_F ∪ G_PET ∪ G_COP – NAP – OPP – COP
G_NELY	Non-electricity energy: G_ENE−ELY.

Activity variables:

Symbol	Description
Q_{jt}	Production in sector j
Q_{it}^{DX}	Allocation of goods i to domestic and export markets
A_{ijt}^{F}	Armington aggregate of good i used for sector j.
A_{it}^{C}	Armington aggregate of good i used for private consumption.
A_{it}^{G}	Armington aggregate of good i used for government consumption.
A_{it}^{I}	Armington aggregate of good i used for investment.
A_{jt}^{E}	Energy aggregation for sector j.
C_t	Aggregate consumption.
G_t	Government consumption.
I_t	Investment.
EX_t	Export of goods i.
IM_t	Import of goods i.

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U_t^P	Period utility at period t.
U^L	Lifetime utility
L_t^S	Labor supply
Q_t^{RENE}	Electricity generation by renewable energy
CCS_t	CCS activity
K_t	Capital stock at period t.

Price variables:

Symbol	Description
p_{it}	Output price of goods i.
p_{it}^D	Price of domestic goods i.
p_{it}^X	Price of export goods i.
p_{ijt}^{AF}	Price of Armington good i used for sector j.
p_{it}^{AC}	Price of Armington good i used for private consumption.
p_{it}^{AG}	Price of Armington good i used for government consumption.
p_{it}^{AI}	Price of Armington good i used for investment.
p_{it}^M	Price of import goods i.
w_t	Wage rate.
$\tilde{w}_{jt}$	Wage rate including social security contribution payment.
p_t^{LEI}	Price of leisure.
p_t^{FX}	Foreign exchange rate (price of foreign exchange).
p_t^{GOV}	Price of government consumption.
p_t^C	Price of aggregate consumption.
p_t^U	Price of period utility.
p^{LU}	Price of lifetime utility.
p_t^{LND}	Rental price of land.
p_{jt}^{RES}	Price of resources used in sector j.
$p_{RENE,t}^{RES}$	Price of resources used in electricity generation by renewable energy .
$p_{CCS,t}^{RES}$	Price of resources used in CCS.
p_t^K	Price of capital stock.
p_t^{INV}	Price of investment goods.
r_t^K	Rental price of capital.
$\tilde{r}_t^K$	Rental price of capital after corporate tax.
r_{jt}^Q	Unit revenue of sector j.
p_{jt}^{KLE}	Price of capital-labor composite for sector j.
p_{jt}^{NLND}	Price of nonland inputs for sector j.
p_{jt}^{NRES}	Price of nonresource inputs for sector j.
$\tilde{p}_{it}^{AC}$	Consumer price of goods i.

p_t^{RENE}	Price of nonresource inputs for electricity generation by renewable energy.	

Income and policy variables:

Symbol	Description
m^H	Household lifetime income.
m_t^G	Government income at period t.
m_t^{CCS}	Factor income from CCS.
m_t^{RENE}	Factor income from renewable energy electricity.
m^H	Household lifetime income.
τ_{jt}^{SSC}	Social security contribution payment rate.
τ_t^{INC}	Income tax rate.
τ_t^{COR}	Corporate tax rate.
τ_t^C	Consumption tax rate.
τ_{it}^M	Tariff rates for goods i.
T_t^{LUMP}	Lump-sum tax on the household.
τ_t^{CO2}	Carbon tax rate.
$CO2_t$	Net CO2 emissions.
VT_t^{CO2}	Carbon tax revenue.
$\overline{CO2}_t$	Exogenous target of net CO2 emissions.
$\bar{G}_t$	Exogenous level of government consumption.

Endowments and emissions coefficients

Symbol	Description
$\overline{L}_t$	Total time available for leisure and labor hour.
E_t^{LND}	Endowment of land.
E_{jt}^{RES}	Endowment of resources used for sector j.
E_t^{RENE}	Endowment of resources used for renewable energy electricity.
E_t^{CCS}	Endowment of resources used for CCS.
E_{it}^H	Household endowment of domestic goods i.
E_{it}^{INV}	Household endowment of investment goods.
TB_t	Exogenous value of trade balance.
K_0	Exogenous initial capital stock.
ξ_{ij}^F	Carbon emissions coefficient for energy goods i used for sector j.
ξ_i^C	Carbon emissions coefficient for energy goods i used for consumption.
δ	Depreciation rate.

Elasticity of substitution (EOS) parameters.

Symbol	Description	Value
η_{DX}	Elasticity of transformation for domestic and export allocation.	2.0

σ_{KLE}	EOS between energy composite and capital-labor composite.	0.5
σ_j^{KL}	EOS between capital and labor in sector j.	
σ_j^{ELY}	EOS between electricity and non-electricity energy input in sector j.	
σ_j^{ENE}	EOS between non-electricity energy inputs in sector j.	
σ_{LND}	EOS between land and non-land input in AGR.	0.1
σ_{RES}	EOS between resource and non-resource inputs.	0.1
σ^{IT}	Intertemporal EOS.	0.5
σ_{LEI}	EOS between consumption and leisure in period utility function.	0.73
σ_C	EOS between energy consumption and non-energy consumption in period utility.	0.5
σ_{CE}	EOS between goods in energy consumption.	1.0
σ_{CNE}	EOS between goods in non-energy consumption.	1.0
σ_{RENE}	EOS between resource and non-resource inputs in renewable energy electricity generation.	0.2
σ_{DM}	EOS between domestic and imported goods in Armington aggregation.	4.0

- Values of σ_j^{KL}
  - 0.1 for $j \in S\_ELY$
  - 0.7 for all other sectors.
- Values of σ_j^{ELY}
  - 0.1 for $j \in S\_ELY$
  - 0.5 for all other sectors.
- Values of σ_j^{ENE}
  - 0.3 for $j \in S\_ELY$
  - 0.5 for $j \in S\_TRN$
  - 1.0 for all other sectors.

Cost share parameters:

Symbol	Description
θ_{ij}^Q	Share of good i in production of sector j.
θ_j^K	Share of capital in capital-labor composite in sector j.
θ_j^{ELY}	Share of electricity in energy inputs for sector j.
θ_{ij}^{ENE}	Share of energy goods i in non-electricity energy for sector j.
θ_{ij}	Share of intermediate good i for sector j.
θ_j^{KLE}	Share of KLE composite for sector j.
θ_j^{AE}	Share of energy composite for sector j.
θ_j^{KL}	Share of capital-labor composite for sector j.

θ_j^{LND}	Share of land for sector j.
θ_j^{RES}	Share of resources for sector j.
θ_i^{DX}	Share of supply of goods i to the domestic market in total supply
θ_{ij}^{AF}	Share of domestic goods i in Armington composite for sector j.
θ_i^{AC}	Share of domestic goods i in Armington composite for consumption
θ_i^{AG}	Share of domestic goods i in Armington composite for government consumption.
θ_i^{AI}	Share of domestic goods i in Armington composite for investment.
θ_{ij}^{AF}	Share of domestic goods i in Armington composite for sector j.
θ^{EC}	Share of energy goods in consumption.
θ_i^{CE}	Share of energy goods i in total energy consumption.
θ_i^{CNE}	Share of non-energy goods i in total non-energy consumption.
θ^{C}	Share of consumption.
θ_t^{U}	Share of period utility of period t.
θ_i^{G}	Share of Armington good i in government consumption.
θ_i^{INV}	Share of Armington good i in investment.
θ_i^{RENE}	Share of intermediate input i in renewable energy electricity.
θ_K^{RENE}	Share of capital in renewable energy electricity.
θ_L^{RENE}	Share of labor in renewable energy electricity.
θ_{RENE}^{RES}	Share of resources in renewable energy electricity.
θ_i^{CCS}	Share of intermediate input i in CCS.
θ_K^{CCS}	Share of capital in CCS.
θ_L^{CCS}	Share of labor in CCS.
θ_{CCS}^{RES}	Share of resources in CCS.

3. Model

Zero profit conditions and price index

Unit revenue:

$$r_{jt}^{Q} = \sum_i \theta_{ij}^{Q} p_{it} \qquad \{r_{jt}^{Q}\}$$

Price capital-labor composite for sector j:

$$p_{jt}^{KL} = \left[\theta_j^K r_t^{K\,1-\sigma_j^{KL}} + (1-\theta_j^K)\widetilde{w}_{jt}^{\,1-\sigma_j^{KL}}\right]^{\frac{1}{1-\sigma_j^{KL}}} \qquad \{p_{jt}^{KLE}\}$$

User price of labor (= wage rate + social security contribution):

$$\widetilde{w}_{jt} = \left(1 + \tau_{jt}^{SSC}\right)w_t \qquad \{\widetilde{w}_{jt}\}$$

Zero profit condition for sector-specific energy aggregation:

$$\Pi_{jt}^{AE} = p_{jt}^{AE} - \left\{ \theta_j^{ELY}(p_{ELY,jt}^{AF})^{1-\sigma_j^{ELY}} \right.$$

$$\left. + (1-\theta_j^{ELY}) \left[\sum_{i \in G\_NELY} \theta_{ij}^{ENE}(p_{ijt}^{AF})^{1-\sigma_j^{ENE}} \right]^{\frac{1-\sigma_j^{ELY}}{1-\sigma_j^{ENE}}} \right\}^{\frac{1}{1-\sigma_j^{ELY}}} \qquad \{A_{jt}^E\}$$

$$= 0$$

Zero profit condition for general sectors.

$$\Pi_{jt}^Q = r_{jt}^Q - \sum_{i \notin G\_ENE} \theta_{ij} p_{ijt}^{AF} - \theta_j^{KLE} \left[\theta_j^{AE} p_{jt}^{AE^{1-\sigma_{KLE}}} \right.$$

$$\left. + (1-\theta_j^{AE}) p_{jt}^{KL^{1-\sigma_{KLE}}} \right]^{\frac{1}{1-\sigma_{KLE}}} = 0 \qquad \{Q_{jt}\}$$

Price index of nonland inputs in AGR ($j = AGR$) :

$$p_{jt}^{NLND} = \sum_{i \notin G\_ENE} \theta_{ij} p_{ijt}^{AF}$$

$$+ \theta_j^{KLE} \left[\theta_j^{AE} p_{jt}^{AE^{1-\sigma_{KLE}}} + (1-\theta_j^{AE}) p_{jt}^{KL^{1-\sigma_{KLE}}} \right]^{\frac{1}{1-\sigma_{KLE}}} \qquad \{p_{jt}^{NLND}\}$$

Zero profit condition for AGR sector ($j = AGR$) :

$$\Pi_{jt}^Q = r_{jt}^Q - \left[\theta_j^{LND}(p_t^{LND})^{1-\sigma_{LND}} + (1-\theta_j^{LND})(p_{jt}^{NLND})^{1-\sigma_{LND}} \right]^{\frac{1}{1-\sigma_{LND}}} \quad \{Q_{jt}\}_{j=AGR}$$

$$= 0$$

Price index of nonresource inputs in F_F ($j = F\_F$) :

$$p_{jt}^{NRES} = \sum_{i \notin G\_ENE} \theta_{ij} p_{ijt}^{AF}$$

$$+ \theta_j^{KLE} \left[\theta_j^{AE} p_{jt}^{AE^{1-\sigma_{KLE}}} + (1-\theta_j^{AE}) p_{jt}^{KL^{1-\sigma_{KLE}}} \right]^{\frac{1}{1-\sigma_{KLE}}} \qquad \{p_{jt}^{NRES}\}$$

Zero profit condition for F_F sector ($j = F\_F$) :

$$\Pi_{jt}^Q = r_{jt}^Q - \left[\theta_j^{RES}(p_{jt}^{RES})^{1-\sigma_{RES}} + (1-\theta_j^{RES})(p_{jt}^{NRES})^{1-\sigma_{RES}} \right]^{\frac{1}{1-\sigma_{RES}}} \quad \{Q_{jt}\}_{j=F\_F}$$

$$= 0$$

Price index of nonresource inputs in conventional electricity sectors ($j \in S\_ELY$) :

$$p_{jt}^{NRES} = \sum_{i \notin G\_ENE} \theta_{ij} p_{ijt}^{AF} + \theta_j^{AE} p_{jt}^{AE} + \theta_j^{KL} p_{jt}^{KL} \qquad \{p_{jt}^{NRES}\}$$

Zero profit condition for conventional electricity sectors ($j \in S\_ELY$) :

$$\Pi_{jt}^Q = r_{jt}^Q - \left[\theta_j^{RES}\left(p_{jt}^{RES}\right)^{1-\sigma_{RES}} + \left(1 - \theta_j^{RES}\right)\left(p_{jt}^{NRES}\right)^{1-\sigma_{RES}}\right]^{\frac{1}{1-\sigma_{RES}}} \qquad \{Q_{jt}\}_{j \in S_{ELY}}$$
$$= 0$$

Zero profit for allocation of goods to domestic and export markets:

$$\Pi_{it}^{DX} = \left[\theta_i^{DX}\left(p_{it}^D\right)^{\eta_{XD}+1} + \left(1-\theta_i^{DX}\right)\left(p_{it}^X\right)^{\eta_{XD}+1}\right]^{\frac{1}{\eta_{XD}+1}} - p_{it} = 0 \qquad \{Q_{it}^{DX}\}$$

Zero profit for Armington aggregation for intermediate inputs ($i \notin G\_NELY$):

$$\Pi_{ijt}^{AF} = p_{ijt}^{AF} - \left(\theta_{ij}^{AF} p_{it}^{D\,1-\sigma_{DM}} + \left(1-\theta_{ij}^{AF}\right)p_{it}^{M\,1-\sigma_{DM}}\right)^{\frac{1}{1-\sigma_{DM}}} = 0 \qquad \{A_{ijt}^F\}$$

Zero profit for Armington aggregation for intermediate inputs ($i \in G\_NELY$):

$$\Pi_{ijt}^{AF} = p_{ijt}^{AF} - \left(\theta_{ij}^{AF} p_{it}^{D\,1-\sigma_{DM}} + \left(1-\theta_{ij}^{AF}\right)p_{it}^{M\,1-\sigma_{DM}}\right)^{\frac{1}{1-\sigma_{DM}}} - \xi_{ij}^F \tau_t^{CO2} = 0 \qquad \{A_{ijt}^F\}$$

Zero profit for Armington aggregation for private consumption ($i \notin G\_NELY$):

$$\Pi_{it}^{AC} = p_{it}^{AC} - \left(\theta_i^{AC} p_{it}^{D\,1-\sigma_{DM}} + \left(1-\theta_i^{AC}\right)p_{it}^{M\,1-\sigma_{DM}}\right)^{\frac{1}{1-\sigma_{DM}}} = 0 \qquad \{A_{it}^C\}$$

Zero profit for Armington aggregation for private consumption ($i \in G\_NELY$):

$$\Pi_{it}^{AC} = p_{it}^{AC} - \left(\theta_i^{AC} p_{it}^{D\,1-\sigma_{DM}} + \left(1-\theta_i^{AC}\right)p_{it}^{M\,1-\sigma_{DM}}\right)^{\frac{1}{1-\sigma_{DM}}} - \xi_i^C \tau_t^{CO2} = 0 \qquad \{A_{it}^C\}$$

Zero profit for Armington aggregation for government expenditure:

$$\Pi_{it}^{AG} = p_{it}^{AG} - \left(\theta_i^{AG} p_{it}^{D\,1-\sigma_{DM}} + \left(1-\theta_i^{AG}\right)p_{it}^{M\,1-\sigma_{DM}}\right)^{\frac{1}{1-\sigma_{DM}}} = 0 \qquad \{A_{it}^G\}$$

Zero profit for Armington aggregation for investment:

$$\Pi_{it}^{AI} = p_{it}^{AI} - \left(\theta_i^{AI} p_{it}^{D\,1-\sigma_{DM}} + \left(1-\theta_i^{AI}\right)p_{it}^{M\,1-\sigma_{DM}}\right)^{\frac{1}{1-\sigma_{DM}}} = 0 \qquad \{A_{it}^I\}$$

Zero profit for import activity:

$$p_{it}^M = (1 + \tau_i^M)p_t^{FX} \qquad \{IM_{it}\}$$

Zero profit for export activity:

$$p_t^{FX} = p_{it}^X \qquad \{EX_{it}\}$$

Consumer price:

$$\tilde{p}_{it}^{AC} = (1 + \tau_t^C)p_{it}^{AC} \qquad \{\tilde{p}_{it}^{AC}\}$$

Zero profit for consumption aggregation:

$$\Pi_t^C = p_t^C - \left[\theta^{EC}\left(\sum_{i \in G_{ENE}} \theta_i^{CE}\left(\tilde{p}_{it}^{AC}\right)^{1-\sigma_{CE}}\right)^{\frac{1-\sigma_C}{1-\sigma_{CE}}}\right.$$

$$\left. + (1 - \theta^{EC})\left(\sum_{i \notin G_{ENE}} \theta_i^{CNE}\left(\tilde{p}_{it}^{AC}\right)^{1-\sigma_{CNE}}\right)^{\frac{1-\sigma_C}{1-\sigma_{CNE}}} + \right]^{\frac{1}{1-\sigma_C}} = 0 \qquad \{C_t\}$$

Wage rate for the household (= price of leisure):

$$p_t^{LEI} = (1 - \tau_t^{INC})w_t \qquad \{p_t^{LEI}\}$$

Household period utility:

$$\Pi_t^U = p_t^U - [\theta^C(p_t^C)^{1-\sigma_{LEI}} + (1 - \theta^C)(p_t^{LEI})^{1-\sigma_{LEI}}]^{\frac{1}{1-\sigma_{LEI}}} = 0 \qquad \{U_t^P\}$$

Household lifetime utility:

$$\Pi^{LU} = p^{LU} - \left[\sum_{t=0}^{T} \theta_t^U(p_t^U)^{1-\sigma_{IT}}\right]^{\frac{1}{1-\sigma_{IT}}} = 0 \qquad \{U^L\}$$

Aggregation of government consumption:

$$\Pi_t^{GOV} = p_t^{GOV} - \sum_i \theta_i^G p_{it}^{AG} = 0 \qquad \{G_t\}$$

Aggregation of investment goods:

$$\Pi_t^{INV} = p_t^{INV} - \sum_i \theta_i^{INV} p_{it}^{AI} = 0 \qquad \{I_t\}$$

Price index of nonresource inputs in electricity generation by renewable energy:

$$p_t^{RENE} = \sum_i \theta_i^{RENE} p_{i,E\_H,t}^{AF} + \theta_K^{RENE} r_t^K + \theta_L^{RENE} w_t \qquad \{p_t^{RENE}\}$$

Zero profit condition for electricity generation by renewable energy:

$$\Pi_t^{RENE} = p_{ELY,t}$$

$$- \left[\theta_{RENE}^{RES}\left(p_{RENE,t}^{RES}\right)^{1-\sigma_{RENE}}\right.$$

$$\left. + (1 - \theta_{RENE}^{RES})(p_t^{RENE})^{1-\sigma_{RENE}}\right]^{\frac{1}{1-\sigma_{RENE}}} = 0 \qquad \{Q_t^{RENE}\}$$

Zero profit condition for CCS:

$$\Pi_t^{CCS} = \tau_t^{CO2} - \left[\theta_{CCS}^{RES}\left(p_{CCS,t}^{RES}\right) + \sum_i \theta_i^{CCS} p_{i,E_H,t}^{AF} + \theta_K^{CCS} r_t^K + \theta_L^{CCS} w_t\right] \qquad \{CCS_t\}$$

After corporate tax rental price of capital:

$$\tilde{r}_t^K = (1 - \tau_t^K)r_t^K \qquad \{\tilde{r}_t^K\}$$

Capital accumulation

$$(1 - \delta)p_{t+1}^K + \tilde{r}_t^K = p_t^K \qquad \{K_t\}$$

Price of investment goods

$$p_t^{INV} = p_{t+1}^K \qquad \{p_t^{INV}\}$$

Market Clearance Conditions

Market for goods i:

$$\sum_j Q_{jt} \frac{\partial \Pi_{jt}^Q}{\partial p_{it}} = Q_{it}^{DX} \qquad\qquad \{p_{it}\}$$

Market for domestic goods i:

$$Q_{it}^{DX} \frac{\partial \Pi_{it}^{DX}}{\partial p_{it}^D} + E_{it}^H = -\sum_j A_{ijt}^F \frac{\partial \Pi_{ijt}^{AF}}{\partial p_{it}^D} - A_{it}^C \frac{\partial \Pi_{it}^{AC}}{\partial p_{it}^D} - A_{it}^G \frac{\partial \Pi_{it}^{AG}}{\partial p_{it}^D} - A_{it}^I \frac{\partial \Pi_{it}^{AI}}{\partial p_{it}^D} \qquad \{p_{it}^D\}$$

Market for export goods i:

$$Q_{it}^{DX} \frac{\partial \Pi_{it}^{DX}}{\partial p_{it}^X} = EX_{it} \qquad\qquad \{p_{it}^X\}$$

Market for Armington goods i for firm j:

$$A_{ijt}^F = -Q_{jt} \frac{\partial \Pi_{jt}^Q}{\partial p_{ijt}^{AF}} \qquad\qquad \{p_{ijt}^{AF}\}$$

Market for Armington goods i for consumption:

$$A_{it}^C = -U_t \frac{\partial \Pi_t^U}{\partial \tilde{p}_{it}^{AC}} \qquad\qquad \{p_{it}^{AC}\}$$

Market for Armington goods i for government consumption:

$$A_{it}^G = -G_t \frac{\partial \Pi_t^{GOV}}{\partial p_{it}^{AG}} \qquad\qquad \{p_{it}^{AG}\}$$

Market for Armington goods i for investment:

$$A_{it}^I + E_{it}^{INV} = -I_t \frac{\partial \Pi_t^{INV}}{\partial p_{it}^{AI}} \qquad\qquad \{p_{it}^{AI}\}$$

Market for import goods:

$$IM_{it} = -\sum_j A_{ijt}^F \frac{\partial \Pi_{ijt}^{AF}}{\partial p_{it}^M} - A_{it}^C \frac{\partial \Pi_{it}^{AC}}{\partial p_{it}^M} - A_{it}^G \frac{\partial \Pi_{it}^{AG}}{\partial p_{it}^M} - A_{it}^I \frac{\partial \Pi_{it}^{AI}}{\partial p_{it}^M} \qquad \{p_{it}^M\}$$

Labor supply

$$L_t^S = \bar{L}_t + U_t^P \frac{\partial \Pi_t^U}{\partial p_t^{LEI}} \qquad\qquad \{L_t^S\}$$

Market for labor:

$$L_t^S = -\sum_j Q_{jt} \frac{\partial \Pi_{jt}^Q}{\partial \tilde{w}_{jt}} \qquad\qquad \{w_t\}$$

Market for foreign exchange:

$$\sum_i EX_{it} = \sum_i IM_{it} + TB_t \qquad\qquad \{p_t^{FX}\}$$

Market for government consumption:

$$G_t = \frac{m_t^{GOV}}{p_t^{GOV}} \qquad\qquad \{p_t^{GOV}\}$$

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Market for private consumption:

$$C_t = -U_t^P \frac{\partial \Pi_t^U}{\partial p_t^C} \hspace{4cm} \{p_t^C\}$$

Market for period utility:

$$U_t^P = -U^L \frac{\partial \Pi^{LU}}{\partial p_t^U} \hspace{4cm} \{p_t^U\}$$

Market for land:

$$E_t^{LND} = -Q_{AGR,t} \frac{\partial \Pi_{AGR,t}^Q}{\partial p_t^{LND}} \hspace{4cm} \{p_t^{LND}\}$$

Market for resources for sector j:

$$E_{jt}^{RES} = -Q_{jt} \frac{\partial \Pi_{jt}^Q}{\partial p_{jt}^{RES}} \hspace{4cm} \{p_{jt}^{RES}\}$$

Market for resources for electricity generation by renewable energy:

$$E_t^{RENE} = -Q_t^{RENE} \frac{\partial \Pi_t^{RENE}}{\partial p_{RENE,t}^{RES}} \hspace{4cm} \{p_{RENE,t}^{RES}\}$$

Market for resources for CCS:

$$E_t^{CCS} = -Q_t^{CCS} \frac{\partial \Pi_t^{CCS}}{\partial p_{CCS,t}^{RES}} \hspace{4cm} \{p_{CCS,t}^{RES}\}$$

Market for capital stock:

$$(1-\delta)K_t + I_t = K_{t+1} + \frac{m_t^{CCS}}{p_{t+1}^K} + \frac{m_t^{RENE}}{p_{t+1}^K} \hspace{4cm} \{p_{t+1}^K\}$$

Market for rental capital:

$$K_t = -\sum_j Q_{jt} \frac{\partial \Pi_{jt}^Q}{\partial r_t^K} \hspace{4cm} \{r_t^K\}$$

Market for lifetime utility:

$$U^L = \frac{m^H}{p^{LU}} \hspace{4cm} \{p^{LU}\}$$

Income.

Household lifetime income:

$$m^H = \sum_t \left[p_t^{LEI} \bar{L}_t + p_t^{LND} E_t^{LND} + \sum_j p_{jt}^{RES} E_{jt}^{RES} + \sum_i p_{it}^D E_{it}^H - p_t^{FX} TB_t \right.$$

$$\left. - p_t^{GOV} T_t^{LUMP} + \sum_i p_{it}^{AI} E_{it}^{INV} \right] + p_0^K K_0 - p_{T+1}^K K_{T+1} \qquad \{m^H\}$$

Net CO2 emissions

$$CO2_t = \sum_{i \in G\_NELY} \left[\sum_j \xi_{ij}^F A_{ijt}^F + \xi_i^C A_{it}^C \right] - CCS_t \qquad \{CO2_t\}$$

Carbon tax revenue:

$$VT_t^{CO2} = \tau_t^{CO2} CO2_t \qquad \{VT_t^{CO2}\}$$

Government income.

$$m_t^{GOV} = p_t^{GOV} T_t^{LUMP} + VT_t^{CO2} \qquad \{m_t^{GOV}\}$$

Lump-sum tax from the household:

$$G_r = \bar{G}_r \qquad \{T_t^{LUMP}\}$$

Income from CCS:

$$m_t^{CCS} = p_{CCS,t}^{RES} E_t^{CCS} \qquad \{m_t^{CCS}\}$$

Income from electricity generation by renewable resources:

$$m_t^{RENE} = p_{RENE,t}^{RES} E_t^{RENE} \qquad \{m_t^{RENE}\}$$

Carbon tax rate:

$$CO2_t = \overline{CO2}_t \qquad \{\tau_t^{CO2}\}$$

Other equations

Capital stock at period $T+1$:

$$\frac{INV_t}{INV_{t-1}} = \frac{C_t}{C_{t-1}} \qquad \{K_{T+1}\}$$