ECONOMYWIDE EFFECTS OF REDUCING CO_2 EMISSIONS: A COMPARISON BETWEEN NET AND GROSS EMISSIONS

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ABSTRACT

In the paper, the economywide effects of setting emission limits on net emissions and on gross emissions from fossil fuels are compared, by using a computable general equilibrium model. Net emissions include carbon accumulating in forests, in addition to emissions from wood and fossil fuels. The forest owners are given an incentive to increase the amount of carbon in the forest, by taxing the emissions from wood. The efficient tax rate on emissions from wood is found to depend on the ability of export sectors to shift costs abroad.

If the reduction of net emissions is small, it is efficient to reduce only the emissions from fossil fuels. On the other hand, when stabilizing the net emissions to the level of year 1990, nearly half of the emission reduction is achieved by increasing the carbon sink. The carbon tax that is needed to achieve the net emission level is clearly lower than the tax needed to stabilize gross emissions. However, there is only a minor difference between the welfare losses associated with stabilizing net emissions and stabilizing gross emissions. In most simulations, the net emission limit is more advantageous than gross emission limit.

Keywords: CO_2 emissions, carbon sink, economywide effects.

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INTRODUCTION

Climate change is considered by many to be the most important environmental problem of the 1990's. Global warming is due to the increasing amount of greenhouse gases in the atmosphere, the most important of which is carbon dioxide. The amount of carbon dioxide can be reduced by decreasing emissions from fossil fuels (gross emissions) and by increasing the amount of carbon in the biomass. To prevent global warming efficiently, all of these options should be brought into use. In the Kyoto protocol, sinks are taken into account. However, there are severe methodological problems related to carbon sinks, and further research is needed before sinks can be included in climate policy in a satisfactory way.

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In Finland, forests have been acting as a carbon sink[1] for some decades. For example, in the year 1990, the gross emissions were 53 million tons (Mt) of CO_2, while the carbon sink was 30 Mt of CO_2. This implies that net emissions were only 20 Mt of CO_2. Therefore, sinks might have a significant role in reducing emissions in Finland. Although net emissions are significantly lower than gross emissions, it cannot be argued *a priori* that the reduction of net emissions would be more advantagenous for Finland than the reduction of gross emissions. For example, if emissions have to be reduced to the level of a given year (*e.g.*, the year 1990), the reduction of net emissions is larger both in million tons of CO_2 and in percentages. This is because net emissions are estimated to be growing faster than gross emissions in Finland. On the other hand, when reducing net emissions, the economy has more measures with which to adjust to the emission constraint. Therefore, it might be possible to decrease the costs of emission reduction when the goal is to reduce net emissions. The international aspects may also affect the comparison, since there might be different effects on world market prices, and thus on international competitiveness. Also, the use of carbon-tax revenue will probably affect the results. The tax revenue can be collected and redistributed nationally or globally.

The economywide effects of emission reduction proposals have been widely studied by using economic models. However, in the economywide model simulations, the emission target has only been defined to include gross emissions. This paper contributes to the earlier literature by taking into account the possibility of decreasing emissions by increasing the carbon sink. Thus, the economic effects of setting the emission limit on gross emissions can be compared with the effects of setting the emission limit on net emissions. The economic effects are estimated by using a computable general equilibrium (CGE) model.

In CGE models, the carbon tax is levied on fossil fuels according to their carbon content[2]. In the case of setting the emission limit on net emissions, the emissions from wood should also be taxed, and the sequestrating of car-

[1] The carbon sink is defined as the amount of carbon sequestrated in the forest in a given period, minus the amount of carbon in timber fellings.

[2] This is equivalent to levying the tax on emissions, since there are no end-pipe technologies.

bon into the forest should be subsidized,[3] since wood emissions cause a negative externality and carbon sequestration causes a positive externality. In our study, it is found that it is not efficient to tax emissions from wood according to carbon content. The analytic models built so far have included only one dirty good/input and one sector, and therefore they have not been able to answer the question of whether various fuels or sectors should be taxed differently. Since determining the efficient tax rate analytically is beyond the scope of this study, the tax rate on emissions from wood that minimizes the welfare loss is evaluated by solving the model with various tax rates.

In the policy simulations, gross or net CO_2 emissions are stabilized to the level of the year 1990 by the year 2010. This is somewhat in line with Finland's commitment under Kyoto protocol. However, in this study, other greenhouse gases are excluded. Also, the treatment and measurement of carbon sink used in this analysis differs from that of the Kyoto protocol. According to present state of the Kyoto protocol, only land-use changes are taken into account when estimating carbon sinks. In this study, on the other hand, the amount of carbon sink depends on the use of the forest, *i.e.*, the amount of timber fellings. Also, the Kyoto protocol suggests that the emissions limit is based on gross emissions, and carbon sinks can be used to meet the emission reduction needed. In this study, however, the emission limit is defined in terms of net emissions, i.e. net emissions have to be reduced to the level of year 1990.

Many important aspects of the problem had to be excluded from this analysis. The dynamics of the model are simple, which means that intertemporally efficient policies cannot necessarily be evaluated with the model. Since a single-country model is used, the emission target is adopted unilaterally[4]. This implies that the effects on the interna-

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[3] Though the forest has been acting as a carbon sink in Finland, this has not happened as a result of a conscious policy decision.

[4] It is possible to analyze the effects of the global emission reduction with a single-country model (see, *e.g.*, Proost and van Regemorter 1990). Typically, it has been assumed that emission reduction does not affect international competitiviness. However, in the case of Finland, this is not a very good approximation. This is because, in Sweden and Canada, which are Finland's main competitors in the paper industry, the share of fossil fuels in the production of electricity is smaller than in Finland.

tional competitiveness of the export-oriented sectors is overestimated. The possible effects on international income transfers are not taken into account.

Section two includes a short description of the model, and a discussion of efficient emission taxation. In section three, the efficient tax rate on emissions from wood is evaluated for the base simulation. The effects of CO_2 emission stabilization in the base case are reported in section four. Section five provides a sensitivity analysis. The conclusions appear in section six.

Model Description

The model is a recursively dynamic computable general equilibrium model for an open economy, developed for the purpose of estimating the economic effects of environmental and energy policy measures. The advantage of an economywide model, compared to a partial-equilibrium model, is that it includes all substitution and income effects and takes into account the interaction among all sectors. The equations of the model are represented in the Appendix.

Forest Sector

The description of the forest sector is simple. The forest is treated as an aggregate, which implies that the age structure of the forest is not included in the model. In addition, the treatment of the forest as an aggregate means that the model abstracts from the fact that the forest has a variety of species. In reality, the amount of carbon sequestrated by forests can be increased by afforestation, by increasing the productivity of land with forest management, and by decreasing the amount of fellings. In the model, however, only the last of these measures is taken into account[5]. Thus, in this study, the use of the existing forest is analyzed. The forest is modelled as an endowment, and forest management is not included.

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[5] In the literature, the most widely studied measure to reduce net emissions has been afforestation (see Apps & Price, 1996). In the case of Finland, afforestation may not be a very important issue. However, some interesting analysis might be done, for example, related to agricultural policy. The increase in productivity of forest land could be taken into account with an exogenously-given productivity parameter. In that case, the amount of carbon tax/subsidy would not have any effect on productivity. Also, the forest management would be costless. However, the same problems appear in the case of modelling energy efficiency.

The timber supply is described by using a simple "*ad hoc*" function.[6] In the model, the supply of timber depends on the price of timber, the carbon-tax rate, the interest rate, and the timber stock. In analytical models of the forest sector, a two-period model is commonly used. However, with static expectations and with the assumptions used in this analysis (perfect capital markets, no non-timber benefits), the price of timber does not affect timber supply. Therefore, this kind of timber-supply function cannot be included in a CGE model[7]. The advantage of the *ad hoc* function is that the elasticities can be given independently, instead of having to depend on values of parameters and data. The timber growth function is concave. The timber stock is updated according to the amounts of fellings and growth.

Timber is used as a raw material in the pulp-and-paper industry and in the wood- products industry, and as a fuel in the production of electricity and heat and in the households. The price of timber equilibrates the supply and demand of timber.

Energy Sector

The model includes seven fuels, namely, coal, natural gas, peat, wood, light fuel oil, heavy fuel oil, and traffic fuels. Coal, natural gas, and fuel oils are imported, while peat and wood are domestic fuels. The supplies of imported fuels are perfectly elastic at the exogenously given world market prices. The supply of peat is also assumed to be perfectly elastic at the fixed price. As mentioned above, the price of timber is endogenous, and the supply of timber depends on various factors. Coal, peat, and natural gas are mainly used in the production of electricity and heat. Heavy fuel oil is used in the production of electricity and heat, and in several industries. Light fuel oil is used in various industries. Traffic fuels are used in households and transportation.

The production of electricity and heat is divided into an endogenous component, coming from fossil fuels and tim-

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[6] In other words, the timber-supply function is not explicitly derived from an optimization problem.

[7] Very few CGE models have an explicit forestry sector. In the model of Alavalapati, *et al*. (1997), timber supply is obtained as the output of the forestry sector. The forestry sector is modelled as any other sector, except that it uses land as an input.

ber, and an exogenous component, including nuclear power, hydro power, and imports of electricity. The exogenous supply is kept at the benchmark level. In Finland, a significant amount of electricity and heat is produced in combined production. Therefore, the production of electricity and heat is modelled together, and the total combined production is divided into electricity and heat with fixed shares. The demands of electricity and heat are described below.

Emissions and Emission Tax

Gross emissions are emissions from the use of fossil fuels. Emissions are calculated separately for each fuel, by using the demand for the fuel and fuel-specific emission coefficients. Net emissions are calculated by adding the emissions from timber to gross emissions, and subtracting the carbon sequestrated in forest during the period. It is assumed that all of the carbon in felled timber is released during the same period in which the timber is felled[8].

The emission tax is calculated as the shadow price of the emission constraint, in the case that the emission limit is given exogenously. Another alternative is to specify the carbon-tax rate(s) exogenously, while the model estimates the amount of emissions. The carbon tax is modelled as a unit tax.

In the case of setting the emission limit on net emissions, there has to be an incentive in the economy to take the carbon sink into account. Only a very small number of analytical papers have analyzed the optimal/efficient tax/subsidy policy in the case of reducing net emissions. In the analysis of Tahvonen (1995), both a subsidy and a tax are needed to achieve a socially optimal outcome. On the other hand, in the analysis of Backlund *et al.* (1995), only a tax is needed. In the literature, therefore, one is not able to find a clear answer regarding the way in which to incorporate taxes and/or subsidies.

In this model, both a tax on harvesting and a subsidy on growth are included. However, because the dynamics of

[8] In reality, the time period in which carbon is released will depend on the way in which the timber is used. Since each period in the model lasts five years, the amount of carbon in timber that is used in pulp-and-paper production is also released during the same period also in reality. Instead, the amount of carbon in timber that is used for construction purposes could remain for 100 years, or even longer.

the model are recursive (decision making is static), the subsidy on growth has no effect at the margin, *i.e.*, the subsidy has no effect on the felling decision of the forest owner[9]. Although subsidies can therefore be excluded from the equation describing fellings, they do appear in the household budget constraint (increasing income) and in the government budget constraint (decreasing net emission tax revenue).

In CGE models, carbon-dioxide taxes on various fuels have typically been based on their carbon contents. However, Goulder (1992) points out that in the case of predistortionary taxes, the optimal tax for various fuels is not likely to be based solely on their carbon contents, since their demand elasticities differ. Unfortunately, analytical models have included only one sector and one source of externality, and thus have not been able to analyze whether the carbon tax should vary among fuels or sectors[10].

In this study, it is found that it is not efficient to tax emissions from wood according to their carbon content. Since it is not possible to derive the tax rule from an analytical model, the efficient tax rate is evaluated by solving the numerical model with various tax rates (see below).

The more obvious reason to deviate from a tax based on carbon content is related to the ability of export sectors to shift the tax to foreign consumers. Thus, this reason is related to an terms-of-trade effect and optimal-tariff argument. If the price elasticities of the export sectors vary among sectors, it is efficient to tax relatively more the emission sources that are used in sectors with lower elasticities, since these sectors are able to shift a portion of the tax burden abroad[11]. Another reason to deviate from a tax based

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[9] This is due to the fact that the growth of the forest cannot be affected in the current period.

[10] Hoel (1996) has analyzed whether energy-intensive exporting sectors should be taxed at lower tax rates than other sectors. Hoel's results show that, in the case in which tariffs can be chosen optimally, the CO_2 tax should be the same for all sectors. However, if tariffs cannot be set optimally, the CO_2 tax should differ by sectors. Even in a very simple model, the determination of the optimal set of CO_2 taxes is very complicated.

[11] In principle, the efficiency of a deviation from a tax based on carbon content is not related only to emissions from wood. For example, in simulations in which emissions from coal used in the manufacture of iron and steel were taxed, and in which the iron-and-steel industry was unrealistically assumed to have market power, it was efficient to set the tax rate on coal used in the iron-and-steel industry above the level of the tax determined according to carbon content.

solely on carbon content seems to be related to the fact that timber is modelled as an endowment whose supply is endogenous. Taxation of timber decreases fellings of timber, and therefore the tax on timber leads to a decrease in the amount of primary resources that are utilized. This implies a reduced set of production possibilities for the economy. According to the results, if the emission source is an endowment, it is efficient to set tax below the level determined by carbon content. Neither of the reasons is related to the pre-distortionary taxes[12].

Production

The production technology is modelled with nested Leontief-CES function. The inputs are labour, capital, timber as a raw material, electricity, heat, and various fuels. Fossil fuels and wood (used as fuel) are combined at the bottom nest of the production function, to create a fuel aggregate. This fuel aggregate is combined with electricity and heat at the next level, to create an energy aggregate. The energy aggregate is combined with capital, and the energy-capital aggregate is combined with wood as a raw material. In the top CES nest, labour is combined with the aggregate of all other inputs. Finally, a Leontief function combines the CES aggregate of inputs with intermediate (non-energy) inputs and traffic fuels. Intermediate inputs are CES aggregates of domestic and imported inputs, according to the Armington assumption.

The production sectors of the model includes the pulp- and paper industry, the paper-products industry, the manufacture of industrial chemicals, the manufacture of fertilizers, the manufacture of other chemicals, the manufacture of rubber and plastic, the manufacture of iron and steel, the manufacture of other basic metals, the manufacture of machinery and equipments, wood-products industry, the manufacture of food and textiles, the manufacture of clay, glass and stone, other industries, agriculture, mining, construction, transportation, dwellings and other services.

[12] Related issue is discussed in Goulder (1994). In this paper, Goulder suggests that if the terms of trade gains are large enough, they could produce the strong double dividend from the point of view of the domestic economy. According to Goulder, this is the only circumstance in which strong double dividend could arise without involving an inefficiency in the existing non-environmental tax system.

Consumer Behaviour

The consumer allocates her income among savings, leisure, and consumption goods. Savings is assumed to be a constant fraction of income. Leisure and aggregate consumption are combined in a CES function, which is calibrated to be consistent with an exogenously specified elasticity of labor supply with respect to the real wage. Expenditures on the aggregate consumption bundle are allocated among various non-energy goods, gasoline, electricity, and heating, according to a linear expenditure system. Heating is a CES aggregate of district heating, electric heating, oil heating, and wood heating. Non-energy goods are CES aggregates of domestic and imported components.

Dynamics and Savings-investment Behaviour

The model is recursively dynamic, which implies that the development of the economy is characterised by a sequence of period-related but intertemporally uncoordinated equilibria. The decision-making is static; accumulation equations for capital and the timber stock are the only links between periods. Investment is determined by the savings of private households. The investment good is a composite of goods from machinery, construction, and imports. The value shares of these components of the investment good are given exogenously.

Foreign Sector

The Armington assumption (see Armington, 1969) is adopted on both the import side and the export side. The production sectors have been divided into two groups, according to the degree to which they are dependent on world market prices. The first group has quite high price elasticities of export and import demands, implying that their prices cannot deviate very much from world market prices. Thus, these sectors are very sensitive to changes in production costs. On the other hand, the production sectors of second group are able to shift the increase in costs to their prices to some extent, since they are assumed to have much lower price elasticities. The sectors that are assumed to be close to price-takers from world market are: basic metal industries, chemical industries, and the pulp-and-paper industry.

Factor Markets

Labour and capital are primary factors of production, in addition to timber and peat. The labor supply is determined through a labor/leisure choice. Both labor and capital are assumed to be homogenous and perfectly mobile between sectors. Thus, the wage rate and the price of capital are equalized across sectors.

Reduction of Gross and Net Emissions to the Level of Year 1990 by the Year 2010

Reference and Policy Scenarios

The benchmark year of the model is 1990. One model equilibrium is calculated for every five years, until the year 2020. The results are reported for the year 2010. The reference scenario is calibrated so that it is very close to a balanced-growth path. The values of exogenously given growth rates are chosen such that the amount of total emissions is close to the estimates from other sources. This implies that the overall growth rate of the economy is 2%. The current carbon taxes are not included in the reference scenario. However, traffic fuels are taxed since this tax is purely fiscal. The amounts of emissions are represented in Figure 1. Net emissions are growing more rapidly than gross emissions, since the carbon sink is decreasing. This follows from the fact that fellings are increasing faster than the sequestration of carbon.

In the policy scenarios, the emission limit is only adopted domestically. This implies that there is a decrease in the international competitiveness of export-oriented, energy-intensive sectors. The manufacture of iron and steel is exempted from the carbon tax, according to current practice. The emission tax revenue is returned to households in lump-sum fashion. The results are expressed as percentage changes (except the welfare loss and the reductions of emissions that are expressed as absolute changes) compared to reference scenario.

Evaluation of the Efficient Tax Rate for Emissions from Wood

The efficient tax rate on emissions from wood has to be estimated for the simulations in which emission limit is set in terms of net emissions. The tax rate that minimizes the

Table 1. Welfare Loss (Billion FIM), Reduction in GDP (%), and Emission Tax.

Emission tax (FIM/t CO_2) when emissions from wood are taxed at various rates.

	Tax Rate								
	1	0.85	0.7	0.65	0.6	0.55	0.3	0.15	0
EV	-5.650	-5.620	-5.600	**-5.598**	-5.598	-5.602	-5.719	-5.979	-6.794
GDP	-0.925	-0.920	-0.917	-0.917	**-0.917**	-0.917	-0.932	-0.966	-1.074
Tax	103	113	126	131	137	143	187	235	335

welfare loss is evaluated by solving the model with various tax rates. The efficient tax rate depends on the amount of emission reduction. The tax rate is chosen such that the welfare loss is minimized in the year 2010 when the amount of net emission reduction is 33 Mt CO_2.

The results for the simulation in which net emissions are reduced to the level of the year 1990 by the year 2010, with our base set of assumptions, are presented in Table 1. Exogenously given tax rates are presented in the first row of the table. Tax rate 1 indicates that emissions from wood are taxed according to their carbon content while tax rate 0.7 indicates that amount of tax is 70% of the amount of tax determined according to carbon content. When tax rate is zero, the emissions from wood are not taxed at all.

The welfare loss is minimized when the tax of emissions from wood is 65% of the amount of tax determined according to carbon content. In this case, the welfare loss is 5.6 billion FIM. If the emissions from wood were taxed according to carbon content, the welfare loss would be 5.65 billion FIM. The extra loss is thus 52 million FIM. On the other hand, if emissions from wood were not taxed at all, the welfare loss would be 6.8 billion FIM. In this case, the additional loss is 1.2 billion FIM. GDP and welfare provide slightly different estimations of the efficient tax rate. The reduction of GDP is minimized when the tax is 60% of the tax determined according to carbon content. However, the reduction in GDP is basically same with tax rates from 0.55 to 0.85. In the simulations presented below, fossil fuels are taxed according to their carbon content,[13] while the tax on

[13] The one exception is that coal and heavy fuel oil used in the manufacture of iron and steel are not subject to the carbon tax, according to current practice.

emissions from wood is 65% of the amount of tax determined according to carbon content.

In the base simulations, it is assumed that the pulp-and-paper industry does not have market power, and thus its emissions should not be taxed more than according to carbon content. On the other hand, the wood-products industry is assumed to have market power, and thus its emissions should be taxed more. The "endowment" effect implies that emissions from wood should be taxed at a rate that is less than the rate that would apply if they were taxed according to carbon content. Since in the evaluation above it was found that emissions from wood should be taxed less than according to carbon content, the "endowment" effect dominates the "burden-transfer" effect in the base case.

The efficient tax rate depends on the several assumptions of the model. Therefore, when performing sensitivity analysis, the efficient tax rate has to be evaluated for every set of assumptions. For example, as seen below, in the case of assuming that the pulp- and-paper industry has market power, the emissions from wood should be taxed more than according to carbon content, since in that case the "burden-transfer" effect dominates the "endowment" effect.

Effects on Emissions, Consumption of Fuels, and Fellings

In order to stabilize emissions from fossil fuels to the level of the year 1990 by the year 2010, the emissions must be reduced by 27 Mt CO_2. Figure 1 shows emissions from fossil fuels in the reference and policy scenarios. The reduction can be achieved by a tax of 288 FIM/t CO_2. In the year 2010, the consumption and emissions of coal are reduced by 54%, of peat by 61%, of heavy fuel oil by 34%, of light fuel oil by 27%, of natural gas by 23%, and of traffic fuels by 6%. The reduction of traffic fuels is smaller than the reduction of other fuels, since it is assumed that the relative price of traffic fuels does not affect their consumption in the transport sector. Also, the price of traffic fuels increases by relatively less than the prices of other fuels, due to the fact that traffic fuels already have a relatively high before-tax price. One-half of the reduction of 27 Mt is achieved by decreasing emissions from the use of coal. The emissions from peat are reduced by 5 Mt, the emissions from heavy and light fuel oils are both reduced by a little less than 3

Mt, and the emissions from natural gas are reduced by 2 Mt. The emission tax reduces emissions from traffic fuels by only 1 Mt, even though the traffic fuels are a significant source of emissions.

Net emissions must be reduced by 33 Mt, in order to stabilize them to the level of the year 1990. Figure 1 shows net emissions in the reference and policy scenarios. The amount of tax that achieves this result is 131 FIM/t CO_2 in the year 2010. However, since the emissions from wood are taxed by using the tax rate 0.65, the amount of tax for emissions from wood equals 85 FIM/t CO_2. The amount of tax is clearly smaller than the tax needed to stabilize gross emissions. Since timber's share of the total production costs is high, even a relatively small tax increases the total production costs, and thus reduces production and emissions in the wood-intensive sectors. The tax reduces gross emissions by 18 Mt. Thus, the reduction of gross emissions is 9

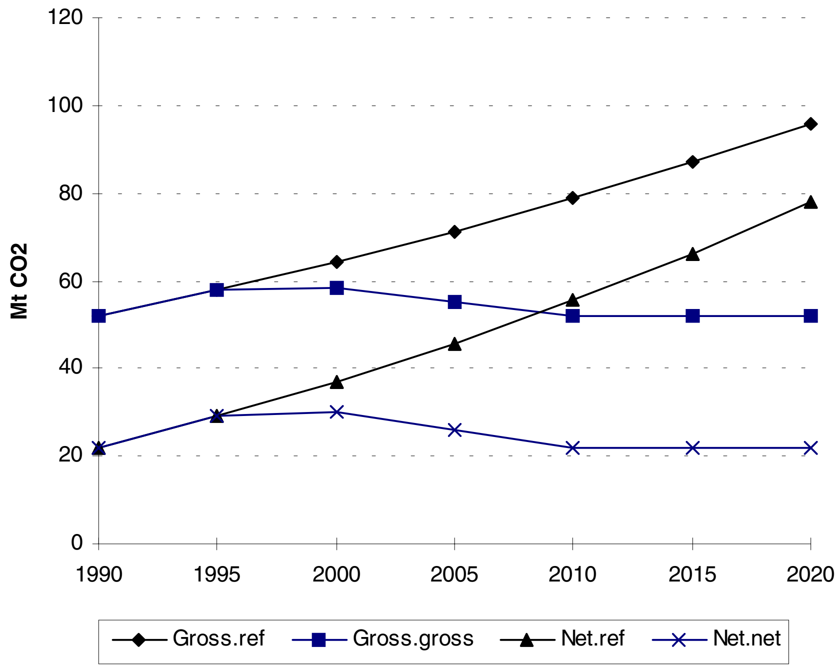

FIGURE 1. GROSS AND NET EMISSIONS IN POLICY AND REFERENCE SCENARIOS.

Gross.ref: emissions from fossil fuels in reference scenario. Gross.gross:gross emissions when emission target is set to gross emissions. Net.ref: net emissions in reference scenario. Net.net: net emissions when emission target is set to net emissions.

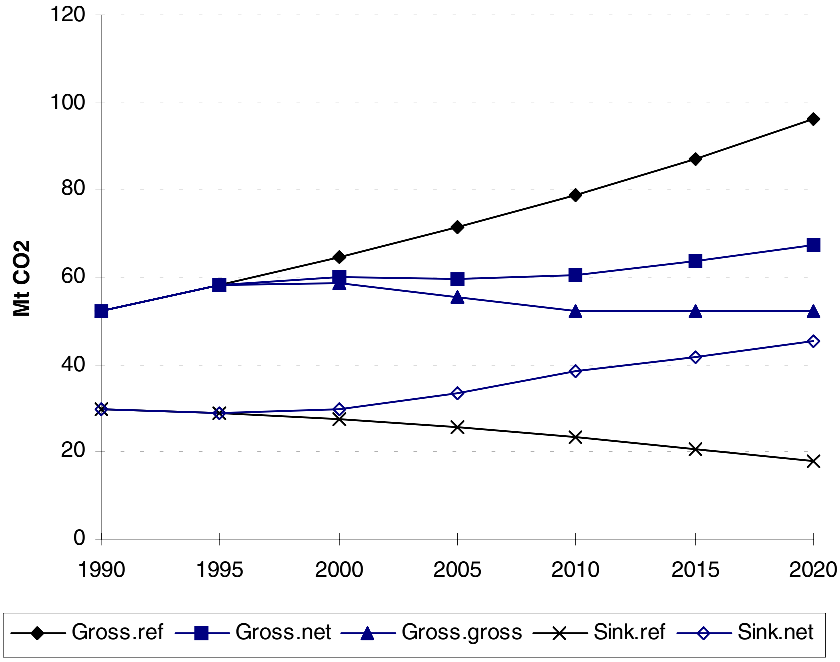

FIGURE 2. GROSS EMISSIONS AND CARBON SINK
IN THE REFERENCE AND POLICY SCENARIOS.

Gross.gross: gross emissions when emission limit is set to gross emissions.Gross.net: gross emissions when emission limit is set to net emissions. Sink.ref: carbon sink in reference scenario. Sink.net: Sink when emission limit is set to net emissions.

Mt smaller when the emission limit is set on net emissions than in the case of setting the limit on gross emissions. Emissions from timber are reduced by 14 Mt of CO_2, and sequestration is increased by 1 Mt of CO_2. This means that the sink is increased by 15 Mt. The reduction of gross emissions is a little larger than the increase of the carbon sink. Figure 2 shows gross emissions and carbon sink in the reference and policy scenarios.

We can use marginal-cost curves for reducing emissions from fossil fuels and wood, to illustrate the way in which a given amount of reduction in net emissions can be achieved. Marginal-cost (MC) curves are represented in Figure 3. They

[14] The marginal cost associated with an emission reduction of R is the change in the equivalent variation associated with the incremental change in emission reduction from R to R+e, divided by e, where e is arbitrarily small. Here, e has been given the value of 0.001 Mt. The emissions are reduced at intervals of 5 Mt of CO_2.

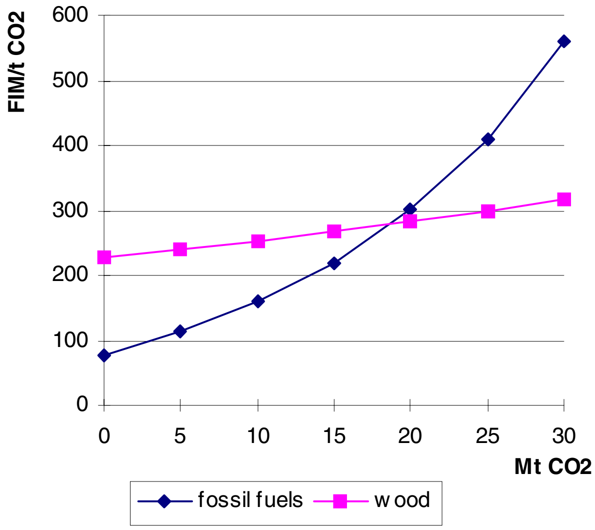

FIGURE 3. MARGINAL COST CURVES.
The figure shows the marginal cost curves for reducing gross emissions and emissions from wood.

have been calculated by using the equivalent variation (see Goulder *et al.* 1996, p. 16)[14]. The costs are therefore defined as the welfare losses of the entire economy. The MC curves are estimated for the year 2010.

The MC curve for reducing emissions from wood differs significantly from the curve for reducing emissions from fossil fuels. The marginal cost of reducing emissions from fossil fuels increases quite rapidly, while the marginal cost of reducing emissions from wood is almost constant. For small reductions in emissions, the marginal cost of reducing emissions of wood is significantly higher than marginal cost of reducing emissions from fossil fuels.

The MC curves show that, when reducing net emissions by 33 Mt, the first 16 Mt should be reduced by decreasing emissions from fossil fuels[15]. After that, it is beneficial to decrease mainly emissions from wood, since the marginal cost of additional reductions of emissions from fossil fuels

[15] This implies that, if the necessary emission reduction is less than 16 Mt, the possibility of increasing the carbon sink would be of no help.

rises considerably faster than the marginal cost associated with emissions from wood. The amounts of reductions are in line with the result obtained above, that net emission reduction is achieved efficiently by reducing emissions from fossil fuels by 18 Mt and emissions from wood by 14 Mt.

Reduction of emissions from timber by 14 Mt implies that timber fellings are reduced by 14%. Since fellings decrease, the timber stock grows faster, and thus timber growth is higher than in the reference scenario. However, the effects of the decrease in fellings are only realized slowly over time. The timber stock is 2% above its reference level in the year 2010, and 7% above its reference level in the year 2020. The growth of the forest exceeds its reference level by 1% in the year 2010 and by 5% in the year 2020. Also, in the case of setting the emissions limit to emissions from fossil fuels, timber fellings are reduced by 4%, even though emissions from wood are not taxed. This is due to the reduction of timber demand because of the significantly reduced production in the paper-and-pulp industry.

The Effects on Welfare and GDP

The welfare loss is 5.9 billion FIM when the emission target is defined in terms of gross emissions, and 5.6 billion FIM when the emission target is defined in terms of net emissions. Therefore, according to the model simulations, it would be slightly better for Finland if the emission reduction target were set for net emissions instead of gross emissions. Though the reduction of emissions is 6 Mt larger in the case of setting the emission limit to net emissions, the possibility of using the forest as a carbon sink is so beneficial, that it compensates for the additional costs that follow from the larger reduction in emissions. Also, GDP is reduced by slightly less when the target is defined in terms of net emissions. However, the difference is small: The reduction of GDP is approximately 0.9 % in both cases.

If emissions from wood were taxed according to their carbon content, the welfare loss would be 5.65 billion FIM. Also in this case, the reduction of net emissions would be more advantageous than the reduction of gross emissions. On the other hand, if emissions from timber were not taxed, even though the emission limit is set for net emissions, the welfare loss would be 6.8 billion FIM. In that case, the economic costs of reducing net emissions would be considerably higher than the costs of reducing gross emissions.

The reduction of GDP can be explained in terms of the efficiency loss due to the reallocation and reduction of amounts of inputs. In the case of reducing gross emissions, labor supply is reduced by 0.4% in the year 2010, while in case of reducing net emissions, labor supply is reduced by 0.2%. Capital stock is affected by even smaller amount. In the case of reducing gross emissions, investments are decreased by 0.3% in the year 2010. In the case of reducing net emissions, investment is reduced by 0.6% in the year 2010. When reducing gross emissions, the capital stock is 0.3% below reference its level in the year 2020. In the case of a net-emissions target, the capital stock is reduced by 0.1% in the year 2010, and by 0.5% in the year 2020.

Sectoral Effects

The percentage changes in production levels are represented in Figure 4. The pulp-and-paper industry suffers the most in both cases. The production level is reduced from its reference level by more than 20% in the year 2010. When the emission limit is set in terms of gross emissions, the reduction in production of pulp and paper is mainly explained by the increase in the price of electricity. On the other hand, in the case of reducing net emissions, the reduced production is mainly explained by the increase in timber costs.

The changes in production level are largest in those sectors that produce mainly for the export market, and whose price elasticity of export demand is assumed to be high. In the case of reducing gross emissions, the production of industrial chemicals is significantly reduced, since electricity accounts for a large share of the total production costs in this industry. Also, the iron-and-steel industry and the other-basic-metal industry suffer from gross emission reduction. On the other hand, some sectors that have a high price elasticity benefit from the emission limit. The decrease in labor and capital costs leads to a substantial percentage increase in exports of fertilizers, other chemicals, and rubber and plastics, since these goods are assumed to have a high elasticity of export demand. However, this does not lead to a significant increase in the production level, because exports have a relatively small share of output in these sectors.

In those sectors whose price elasticity of export demand is assumed to be small or who produce mainly for home-market, the changes in production levels are modest. The sectors that suffer from emission limit includes mining, manufacture of clay, glass, and stone, transports, services, and construction. On the other hand, capital and labor-intensive sectors benefit from emission reduction. Machinery and equipment benefits most for those sectors that have a low elasticity of export demand, since the share of exports is high in that sector. Also, the wood-products industry benefits from the increase in exports. However, the production of wood products is only increased by a relatively small amount, since a substantial portion of its output is used in the pulp-and-paper industry, which suffers a lot from the policy change. The food-and-textile industry, dwellings, and other services produce mainly for home markets. Thus, they suffer from the decrease in real income. To a significant degree, this income effect offsets the substitution effect due to the decrease in production costs in these labor and/or capital-intensive sectors.

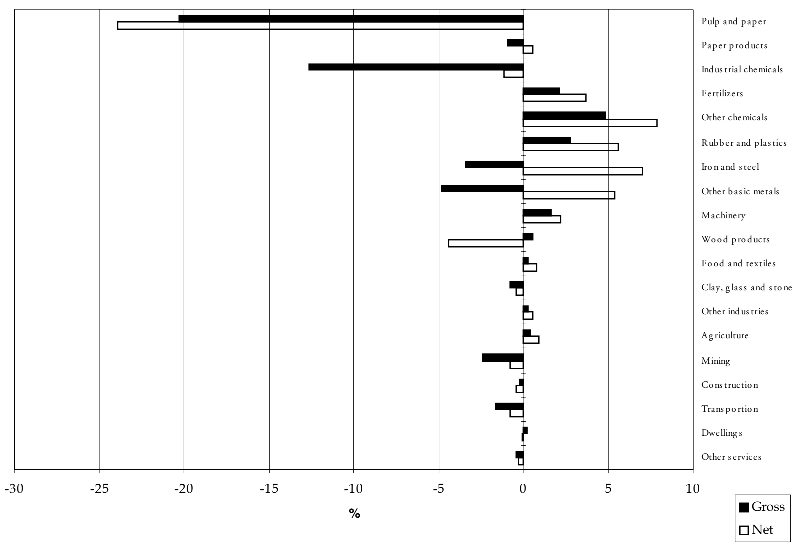

FIGURE 4. PERCENTAGE CHANGES IN PRODUCTION LEVELS.
Changes in production levels in year 2010 when reducing gross and net emissions.

When setting the emission limit on net emissions, the forest owners have incentive to decrease the supply of timber. This implies that the price of timber, and thus the production costs of the wood-products industry, will increase. This implies that gross emissions reduction and net emissions reduction have opposite effects on the production level of the wood-products industry. An opposite effects are observed also for the manufacture of iron and steel and the manufacture of other basic metals. This follows from the fact that the reduction of net emissions leads to a smaller increase in the price of electricity than that which occurs as a result of the reduction of gross emissions. Except for the paper-products industry, the qualitative changes in the other sectors are similar for gross emissions reduction and net emissions reduction.

The energy-intensive sectors are not significant employers. Although there is a 15% decrease of labor in the pulp-and-paper industry, this has very small effect on total labor demand. Those sectors that benefit most from the policy change are not significant users of labor, either. Thus, the labor that is displaced from the pulp-and- paper industry and from the production of electricity and heat moves mainly to the manufacture of machinery and equipment, other services, and the manufacture of food and textiles.

Sensitivity Analysis

The sensitivity of the results was analyzed with respect to several assumptions of the model. These assumptions include the values of the elasticity of substitution between energy inputs, the values of the price elasticities of export demand, the use of the emission-tax revenue, and tax exemptions.[16] The sensitivity of the welfare losses is repre-

[16] For energy substitution, we decrease the value of the elasticities of substitution between fuels from 1.2 to 0.7, and we decrease the elasticities between the fuel aggregate, electricity, and heat from 0.8 to 0.5. For market power, the price elasticity of export demand for the pulp-and-paper industry is decreased from -10 to -2. For the higher price elasticities of export and import demands, we increase the values of elasticities of export and import in the "price-taking" sectors from -10 to -20 (for exports) and from 5 to 10 (for imports). We also analyze the sensitivity of the results with respect to the possibility that no exemptions will be given. In this simulation, coal and HFO used in the manufacture of iron and steel are taxed. Finally, we perform a sensitivity analysis with respect to the distribution of the carbon-tax revenue, by using the revenue to reduce the payroll tax, instead of making a lump-sum redistribution.

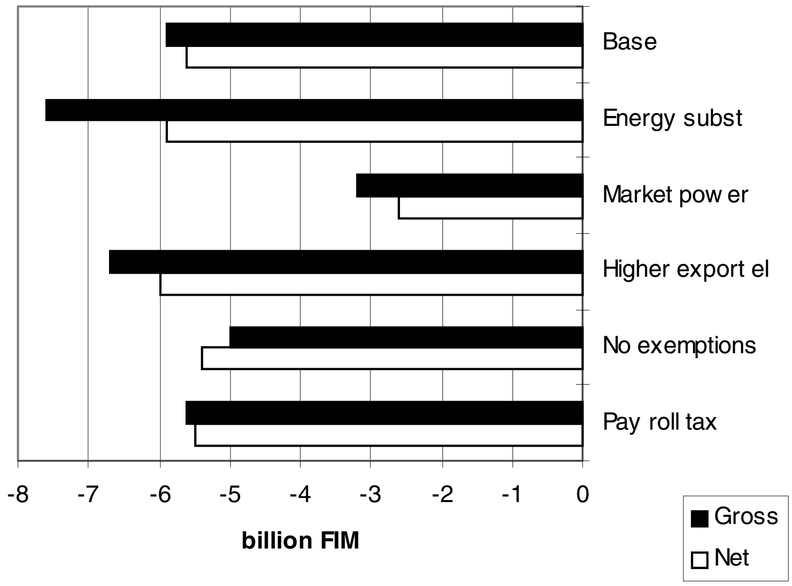

FIGURE 5. THE SENSITIVITY OF THE WELFARE LOSSES.
Sensitivity of welfare loss in case of setting emission limit to emissions from fossil fuels and net emissions.

sented in Figure 5, both for reducing gross emissions and for reducing net emissions.

For the Finnish economy as a whole, setting the emission limit to net emissions is more advantageous than setting the emission limit to gross emissions in all cases examined, expect in the case of no tax exemptions. Gross emission reduction is more advantageous than net emission reduction for the paper-and-pulp industry and the wood-products industry in all cases. For every other sector, net emission reduction is more beneficial.

In the base simulations, it was assumed that the paper-and-pulp industry would be close to a price taker in the world market. However, this assumption is questionable. In sensivity analysis, the value of the price elasticity of export demand was changed from -10 to -2. In the case of the low price elasticity, the paper-and-pulp industry is able to shift the cost increase (to a limited extent) to the export price. Therefore, the production level of the paper-and-pulp industry is only 10% below its reference level in the year 2010 in the case of setting the emission limit to gross emissions. As mentioned above, the efficient tax on emissions from wood is sensitive to some of the assumptions used in the model. In the case in which the paper-and-pulp industry is able to shift part of the tax burden abroad, it is beneficial to tax emissions from wood relatively more than emissions from fossil fuels. The efficient carbon-tax coefficient is 1.6, while in the base simulation, it was 0.65. With tax rate 1.6, production in the paper-and-pulp industry is reduced 15% compared to the reference scenario. In the wood-products industry, the production loss is 11%.

In the case of net-emissions reduction, the emission-tax revenue[17] is significantly smaller than in case of gross-emissions reduction, since the emission level and also the amount of carbon tax are lower. Therefore, if it is possible to reduce the level of tax distortions in the economy by using the tax revenue to reduce other taxes, our relative evaluation of the gross-emissions limit and the net-emission limit might change. Carbon-tax revenue is 13 billion FIM in the case of setting the emission limit to gross emissions, while in case of net emissions, revenue is only 5 billion FIM. According to our simulations, using the emission tax revenue to reduce the payroll tax instead of making a lump-sum distribution does not reduce the welfare loss almost at all. Therefore, setting the emission limit to net emissions remains more beneficial, when measured by the welfare loss. However, if the comparison were made according to the loss of GDP, setting the emission limit to gross emissions would be much more beneficial. GDP is reduced only 0.5 % when tax revenue is used to reduce the payroll tax rate, compared with a reduction of 0.9% when the carbon-tax revenue is redistributed in a lump sum.

CONCLUSIONS

The economywide effects of reducing CO_2 emissions have so far been estimated only by setting the emission limit in terms of the amount of emissions from fossil fuels. It is true that global warming can be slowed down by reducing emissions from fossil fuels, but global warming can also be delayed by increasing carbon sinks. The contribution of this paper is to integrate carbon sinks into an economywide CGE model. Thus, the economic effects of reducing gross and net emissions can be compared.

[17] Tax revenue also includes subsidies to forest owners.

The effects of reducing gross and net emissions were examined in a detailed way in the case of reducing emissions to the level of the year 1990 by the year 2010. The amount of emission reduction was larger in the case of setting emission limit in terms of net emissions than in terms of gross emissions, since net emissions grow faster in the reference scenario. Net emissions had to be reduced by 33 Mt of CO_2, while the reduction of gross emissions needed to stabilize them to the level of the year 1990 was 27 Mt. On the other hand, when reducing net emissions, the economy has more measures with which to adjust to the emission limit. Thus, it cannot be said *a priori* whether it would be more advantageous to Finland to set the emission limit in terms of gross emissions or net emissions.

The emission tax needed to reduce net emissions to the level of the 1990 was significantly lower than the emission tax needed to reduce gross emissions. However, the economywide effects are not directly related to the amount of emission tax. The welfare loss, measured in the year 2010, was 5.9 billion FIM in the case of reducing gross emissions, and 5.6 billion FIM in the case of reducing net emissions. Thus, according to these simulations, it would be more advantageous to Finland if the emission limit were set in terms of net emissions. However, the difference in the welfare losses is clearly fairly small. In the case of setting emission limit in terms of net emissions with our most-preferred set of values of parameters, the welfare loss was minimized by taxing emissions from wood at a tax that is 65 % of the tax determined according to carbon content. If emissions from wood were taxed according to carbon content, the welfare loss would be 5.7 billion FIM. On the other hand, if emissions from wood were not taxed at all, and if the emission limit were set in terms of net emissions, the welfare loss would be as high as 6.8 billion FIM. Setting the emission limit in terms of net emissions was more advantagenous in all cases examined, except in the case in which no tax exemptions are allowed. When the emissions limit is set in terms of reducing net emissions, the gross emissions were reduced by 18 Mt of CO_2, and the carbon sink was increased by 15 Mt of CO_2 in the simulation with our most-preferred set of values of parameters.

Regardless of whether the emissions limit is set in terms of net emissions or gross emissions, the sector that suffers the most is the manufacture of pulp and paper. Pulp and paper production was reduced by more than 20% below its reference level in the year 2010. When reducing gross emissions, the explanation is the increase in the price of electricity, while when reducing net emissions, the losses in the pulp-and-paper industry are explained mainly by the increase in timber costs. The manufacture of wood products also suffers from reduced timber supply, in the case of reducing net emissions. Several sectors benefitted from emission reduction, since their production costs were lower than in the reference scenario. The increases in production were highest in those sectors that make intensive use of labor and capital (rather than fuels) and produce mainly for export markets. On the other hand, home-market sectors suffered from the decrease in real income in the domestic economy.

The main deficiency of the model is its static character. Thus, when forest owners make decisions about the amount of timber fellings in the model, they do not take into account the effects of those decisions on the future economy, and they do not take into account the effects of future prices on current decisions. This implies that intertemporally efficient strategies cannot be evaluated with the current version of the model. However, to truly dynamize the model is a very demanding task, since natural resources have typically not been included in intertemporally dynamic CGE models. Also, the description of the forest could be improved, by including the age structure and different species of trees in the model. However, there is a potential trade-off between dynamization and modelling the forest in a more detailed way.

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APPENDIX

THE MODEL

A. EQUATIONS

Forest Sector

Timber supply

$$NR^S = NR_O^S \cdot \left(\frac{PK}{PCT / PCT_O} \right)^{\alpha} \cdot \left(\frac{PNRT}{PNRT_O \cdot (PCT / PCT_O)} \right)^{\beta} \cdot \left(\frac{NRST}{NRST_O} \right)^{\chi} \quad (1)$$

$$\begin{aligned} &\textit{for net emission}\ \text{limit: } PNRT = PNR - t_{EM} \cdot nrem \cdot effc \\ &\textit{for gross emission}\ \text{limit: } PNRT = PNR \end{aligned} \quad (2)$$

Growth of forest

$$NRG = NRST^a \quad (3)$$

Timber stock

$$NRST_{t+1} = NRST_t + NRG_t - NR_t^S \quad (4)$$

Energy Sector, Emissions and Carbon Tax

Cost function for production of electricity and heat

Electricity and heat are produced by using intermediate inputs, labor, capital and various fuels (natural gas, coal, LFO, HFO, peat, wood).

$$MC_{EH} = a_{Y,EH} \cdot PY_{EH} + \sum_j a_{j,EH} \cdot P_j \quad (5)$$

$$PY_{EH} = \frac{1}{\phi_Y} \cdot \left[(\delta_L)^{\sigma_Y} \cdot (PLT_{EH})^{1-\sigma_Y} + (\delta_K)^{\sigma_Y} \cdot PK^{1-\sigma_Y} + (\delta_F)^{\sigma_Y} \cdot (PFA_{EH})^{1-\sigma_Y} \right]^{\frac{1}{1-\sigma_Y}} \quad (6)$$

$$PFA_{EH} = \frac{1}{\phi_f} \left[\sum_f \delta_f^{\ \sigma_f} \cdot PFT_{f,EH}^{\ 1-\sigma_f} + \delta_{NR}^{\ \sigma_f} \cdot PNR^{1-\sigma_f} \right]^{\frac{1}{1-\sigma_f}} \quad (7)$$

$$f = NG,\ COAL,\ HFO,\ LFO,\ PEAT$$

Emissions from fossil fuels

$$EMF = \sum_f emco_f \cdot F_f^S \quad (8)$$

Emissions from wood

$$EMNR = nrem \cdot NR^S \quad (9)$$

Carbon sequestrated in the forest in a given period

$$ACC = nrem \cdot NRG \quad (10)$$

Carbon sink

$$SINK = ACC - EMNR \quad (12)$$

Net emissions

$$EMNET = EMF - SINK \quad (13)$$

Carbon tax

$$\begin{aligned} &EM - \overline{EM} \le 0 \\ &t_{EM} \cdot \left(EM - \overline{EM} \right) = 0 \\ &t_{EM} \ge 0 \end{aligned} \quad (14)$$

In case of setting emission limit on gross emissions, $EM = EMF$, and in case of setting emission limit on net emissions, $EM = EMNET$.

After-tax prices of fossil fuels

$$PFT_{f,s} = pfw_{f,s} \cdot EXCR + t_{EM} \cdot coef_f \tag{15}$$

f = LFO, HFO, BD, COAL, NG

$$PFT_{f,s} = pf_{f,s} + t_{EM} \cdot coef_f \tag{16}$$

f = PEAT; s = EH

Production

Cost functions for production sector j

Intermediate inputs from tradable and non-tradable sectors, traffic fuels, labor, wood as raw material, capital, electricity, heat and various fuels (natural gas, coal, LFO, HFO, peat, wood) are used as inputs in production sector j.

$$MC_j = PY_j \cdot A_j + \sum_t PCOM_{t,j} \cdot a_{tj} + \sum_{nt} P_{nt} \cdot a_{ntj} + PFT_{BD,j} \cdot bdsh_j + taxs_j \tag{17}$$

$$PY_j = \frac{1}{\phi_{Yj}} \left[\delta_{Yj}^{\ \sigma_{Yj}} \cdot PLT_j^{1-\sigma_{Yj}} + \left(1-\delta_{Yj}\right)^{\sigma_{Yj}} \cdot PR_j^{1-\sigma_{Yj}} \right]^{\frac{1}{1-\sigma_{Yj}}} \tag{18}$$

$$PR_j = \frac{1}{\phi_{Rj}} \left[\delta_{Rj}^{\ \sigma_{Rj}} \cdot PNR^{1-\sigma_{Rj}} + \left(1-\delta_{Rj}\right)^{\sigma_{Rj}} \cdot PU_j^{1-\sigma_{Rj}} \right]^{\frac{1}{1-\sigma_{Rj}}} \tag{19}$$

$$PU_j = \frac{1}{\phi_{Uj}} \left[\delta_{Uj}^{\ \sigma_{Uj}} \cdot PK^{1-\sigma_{Uj}} + \left(1-\delta_{Uj}\right)^{\sigma_{Uj}} \cdot PQ_j^{1-\sigma_{Uj}} \right]^{\frac{1}{1-\sigma_{Uj}}} \tag{20}$$

$$PQ_j = \frac{1}{\phi_{Qj}} \left[\delta_{Ej}^{\ \sigma_{Qj}} \cdot PE^{1-\sigma_{Qj}} + \delta_{Hj}^{\ \sigma_{Qj}} \cdot PH^{1-\sigma_{Qj}} + \left(1-\delta_{Ej}-\delta_{Hj}\right)^{\sigma_{Qj}} \cdot PFA_j^{1-\sigma_{Qj}} \right]^{\frac{1}{1-\sigma_{Qj}}} \tag{21}$$

$$PFA_j = \frac{1}{\phi_{Fj}} \left[\sum_f \delta_{Fj}^{\ \sigma_{Fj}} \cdot PFT_{f,j}^{\ 1-\sigma_{Fj}} + \delta_{NRj}^{\ \sigma_{Fj}} \cdot PNR^{1-\sigma_{Fj}} \right]^{\frac{1}{1-\sigma_{Fj}}} \tag{22}$$

f = LFO, HFO, NG, COAL

Household Consumption of Goods and Leisure

Consumer choice between leisure and consumption goods

$$\max U = \left[\alpha_l^{1/\sigma_l} \cdot LEI^{(\sigma_l-1)/\sigma_l} + \left(1-\alpha_l\right)^{1/\sigma_l} \cdot CT^{(\sigma_l-1)/\sigma_l} \right]^{\frac{\sigma_l}{\sigma_l-1}} \tag{23}$$

$$\begin{aligned} PCT \cdot CT = &-SAVH + PK \cdot conv \cdot KST - DEPR + PL \cdot L^S + PNRT \cdot NR^S + PE \cdot E \\ &+ pf_{PEAT} \cdot F_{PEAT}^S - \sum P_j \cdot SD_j + TRV + k \cdot effc \cdot t_{EM} \cdot nrem \cdot NRG \end{aligned}$$

gross emissions: k=0, net emissions: k=1

Household income consist of capital income, labour income, timber income, income from exogenous capasity of electricity, peat income and transfers from public sector. The value of statistical discrepence has to be subtracted from household income. In case of setting emission limit on net emissions, the value of carbon subsidies $k \cdot effc \cdot t_{EM} \cdot nrem \cdot NRG$ has to be added.

Consumer choice between various consumption goods

Consumer allocates her income between composite good, non-tradable good, gasoline, electricity and heating.

$$\begin{aligned} &\max U = \prod \left(C_C - \lambda_C\right)^{\beta_C} \qquad c\varepsilon\ i, \mathrm{B}, \mathrm{E}, \mathrm{HTING} \\ &s.t. \sum_{kt} PCOM_{kt} \cdot C_{kt} + \sum PC_{knt} \cdot C_{knt} + PFT_{BD,H} \cdot C_B + PE \cdot C_{EOTH} + PHTING \cdot C_{HTING} \\ &= -SAVH + PK \cdot conv \cdot KST - DEPR + PL \cdot L^S + PNRT \cdot NR^S + PE \cdot E \end{aligned} \tag{24}$$

[redacted] $_j \cdot SD_j + TRV + k \cdot t_{EM} \cdot nrem \cdot NRG$

Public Sector

Government allocates its income between composite good, non-tradable good, electricity, heat, gasoline, LFO, HFO, labor and capital.

Goverment consumption

$$\begin{aligned}&\max GU = (\sum_t \beta_t^{1/\sigma}\cdot G_t^{(\sigma-1)/\sigma} + \sum_{nt}\beta_{nt}^{1/\sigma}\cdot G_{nt}^{(\sigma-1)/\sigma} + \beta_E^{1/\sigma}\cdot G_E^{(\sigma-1)/\sigma} + \beta_H^{1/\sigma}\cdot G_H^{(\sigma-1)/\sigma}\\ &+\sum_f \beta_f^{1/\sigma}\cdot G_f^{(\sigma-1)/\sigma} + \beta_L^{1/\sigma}\cdot G_L^{(\sigma-1)/\sigma} + \beta_K^{1/\sigma}\cdot G_K^{(\sigma-1)/\sigma})^{\frac{\sigma}{\sigma-1}}\\ &s.t. \sum_t PCOM_{t,G}\cdot G_t + \sum_{nt} P_{nt}\cdot G_{nt} + PE\cdot G_E + PH\cdot G_H + \sum_f PFT_{f,G}\cdot G_f\\ &+PK\cdot G_K + PLT_G\cdot G_L = RTEM + RTFU + RTL + RTS - TRV\end{aligned} \tag{25}$$

$$f = LFO,\ HFO,\ BD$$

Emission tax revenue

$$\begin{aligned}&RTEM = \sum_f t_{EM}\cdot emco_f\cdot F_f^S + k\cdot t_{EM}\cdot effc\cdot nrem\cdot\left(NR^S - NRG\right)\\ &gross\,emissions: k=0,\ net\,emissions: k=1\end{aligned} \tag{26}$$

Revenue from traffic fuel tax

$$RTFU = taxb\cdot C_B + \sum_j taxd_j\cdot bdsh_j\cdot X_j + taxd_G\cdot G_D \tag{27}$$

Revenue from labor tax

$$RTL = \sum_j taxl_j\cdot PL\cdot\frac{\partial MC_j}{\partial PLT_j}\cdot X_j + taxl_{EH}\cdot PL\cdot\frac{\partial MCEH}{\partial PLT_{EH}}XEH + taxl_G\cdot PL\cdot G_L \tag{28}$$

Revenue from indirect taxes

$$RTS = \sum_j taxs_j\cdot X_j \tag{29}$$

Imports and Exports

Armington imports of intermediate inputs

$$\begin{aligned}&\min\quad PM_t\cdot INTM_{t,j} + P_t\cdot INTD_{t,j}\\ &\text{s.t.}\quad INT_{t,j} = \frac{1}{\phi}\cdot\left[\delta\cdot INTM_{t,j}{}^{\rho} + (1-\delta)\cdot INTD_{t,j}{}^{\rho}\right]^{\frac{1}{\rho}}\end{aligned} \tag{30}$$

Armington imports of goods

$$\begin{aligned}&\max U = C_{kt} = \phi\left[\delta\cdot CM_{kt}{}^{\rho} + (1-\delta)\cdot CD_{kt}{}^{\rho}\right]^{\frac{1}{\rho}}\\ &s.t.\ PCM_{kt}\cdot CM_{kt} + PC_{kt}\cdot CD_{kt} = IN_{kt}\end{aligned} \tag{31}$$

Armington exports

$$Z_t = Z_t{}^0\left(\frac{PW_t}{pw_t}\right)^{\varepsilon}\cdot e^{\gamma t} \tag{32}$$

Savings, Investment and Capital Stock

Total savings

$$SAVT = SAVH + DEPR - EXCR\cdot CA \tag{33}$$

Household savings

$$SAVH = s\cdot(IN - \sum P_C\cdot\lambda_C) \tag{34}$$

Depreciation

$$DEPR = depro\cdot PS\cdot KST \tag{35}$$

Price of investment good

$$PS = \sum_j shinv_j\cdot P_j + shinv_{IMP}\cdot PM_{INV} \tag{36}$$

Investment good from sector *j*

$$I_j = \frac{shinv_j \cdot SAVT}{PS} \tag{37}$$

Imported investment good

$$I_M = \frac{shinv_{IMP} \cdot SAVT}{PS} \tag{38}$$

Total amount of investments

$$IT = \sum_j I_j + I_M \tag{39}$$

Capital stock

$$KST_{t+1} = KST_t + IT_t - depro \cdot KST_t \tag{40}$$

Equilibrium Conditions

Capital

$$conv \cdot KST = \sum_j \frac{\partial MC_j}{\partial PK} X_j + \frac{\partial MCEH}{\partial PK} XEH + G_K \tag{41}$$

Labour

$$L^S = \sum_j \frac{\partial MC_j}{\partial PLT_j} X_j + \frac{\partial MCEH}{\partial PLT_{EH}} XEH + G_L \tag{42}$$

Electricity

$$E + XE = \sum_j \frac{\partial MC_j}{\partial PE} X_j + C_{EOTH} + C_{EHEAT} + G_E \tag{43}$$

Heat

$$XH = \sum_j \frac{\partial \mathrm{MC_j}}{\partial \mathrm{PH}} X_j + C_{HEAT} + G_H \tag{44}$$

Timber

$$NR^S = \sum_j \frac{\partial MC_j}{\partial PNR} X_j + \frac{\partial \mathrm{MCEH}}{\partial PNR} \mathrm{XEH} + \mathrm{C_{WOOD}} \tag{45}$$

Peat

$$F^S_{PEAT} = \frac{\partial \mathrm{MCEH}}{\partial PPEATT} \mathrm{XEH} \tag{46}$$

Traffic fuels

$$F^S_{BD} = \sum_j \frac{\partial MC_j}{\partial PFT_{BD,j}} X_j + C_B + G_D \tag{47}$$

LFO

$$F^S_{LFO} = \sum_j \frac{\partial MC_j}{\partial PFT_{LFO,j}} X_j + \frac{\partial MCEH}{\partial PFT_{LFO,EH}} XEH + C_{LFO} + G_{LFO} \tag{48}$$

HFO

$$F^S_{HFO} = \sum_j \frac{\partial MC_j}{\partial PFT_{HFO,j}} X_j + \frac{\partial MCEH}{\partial PFT_{HFO,EH}} XEH + G_{LFO} \tag{49}$$

Natural gas

$$F^S_{NG} = \sum_j \frac{\partial MC_j}{\partial PFT_{NG,j}} X_j + \frac{\partial MCEH}{\partial PFT_{NG,EH}} XEH \tag{50}$$

Coal

$$F^S_{COAL} = \sum_j \frac{\partial MC_j}{\partial PFT_{COAL,j}} X_j + \frac{\partial MCEH}{\partial PFT_{COAL,EH}} XEH \tag{51}$$

Equilibrium condition for tradable sector *t*

$$X_t = \sum_j INTD_{t,j} + a_{t,EH} \cdot XEH + C_t + GD_t + Z_t + I_t + SD_t \tag{52}$$

Equilibrium condition for non-tradable sector *nt*

$$X_{nt} = \sum_j a_{nt,j} \cdot X_j + a_{nt,EH} \cdot XEH + C_{nt} + G_{nt} + I_{nt} + SD_{nt} \tag{53}$$

Current account constraint

$$\sum_t PW_t \cdot Z_t - \sum_t (pmw_t \cdot \sum_j INTM_{t,j}) - \sum_t pmw_t \cdot GM_t - \sum_{kt} pcmw_{kt} \cdot CM_{kt} - pinvmw \cdot I_M - \sum_f pfw_f F_f^S = CA$$

$$f = LFO,\ HFO,\ BD,\ NGAS,\ COAL \tag{54}$$

B. ENDOGENOUS VARIABLES

ACC	sequestration of carbon in forest
C_C	consumption of good *C* (composite good *kt*, non-tradable good *knt*, gasoline *BD*, electricity *EOTH* or heating *HTING*)
C_{EHEAT}	electricity heating in households
CD_{kt}	consumption of domestic good *kt*
CM_{kt}	consumption of imported good *kt*
CT	total consumption of goods excluding necessity consumption
$DEPR$	depreciation
EMF	emissions from fossil fuels
$EMNET$	net emissions
$EMNR$	emissions from wood
$EXCR$	exchange rate
F_f^S	total use of fuel *f*
G_G	consumption of good *G* in public sector (traffic fuels *D*, composite good *t*, non-tradable good *nt*, electricity *E*, heat *H*, fuel *f*, capital *K*, labor *L*)
$GEXP$	expenditures of public sector
GM_t	consumption of imported good *t* in public sector
$GREV$	net income of public sector
GU	utility of public sector
I_j	investment goods produced in sector *j*
I_M	imported investment goods
IN	disposible income
$INT_{t,j}$	use of composite good as intermediate input in sector *j*
$INTD_{t,j}$	use of domestic good *t* as intermediate input in sector *j*
$INTM_{t,j}$	use of imported good *t* as intermediate input in sector *j*
IT	total investment
KST	capital stock
L^S	supply of labor
LEI	leisure
MC_{EH}	marginal cost of production of electricity and heat
MC_j	marginal cost of sector *j*
NR^S	timber supply
NRG	growth of forest
$NRST$	timber stock
P_j	domestic price of intermediate input *j*
Pc_{kt}	domestic price of good *kt* in households
PCM_{kt}	import price of good *kt* in households
$PCOM_{kt}$	composite price of good *kt* in households
$PCOM_{t,G}$	price of composite good *t* in public sector
$PCOM_{t,j}$	price of composite intermediate input *t* in sector *j*
PCT	consumer price index
PE	price of electricity
PFA_j	price of fuel aggregate in sector *j*

[redacted] sector *s* (*j, EH,H,G*)

[redacted] r *s* (*j, EH, G*)

PM_t	import price of good t
PM_{INV}	price of imported investment goods
PNR	price of timber
$PNRT$	after-tax price of timber
PS	price of investment goods
PY_s	implicit price of primary inputs in sector s (j, EH)
PW_t	price of good t in foreign currency
$RTEM$	carbon tax revenue
$RTFU$	traffic fuel tax revenue
RTL	pay roll tax revenue
RTS	indirect tax revenue
$SAVH$	household savings
$SAVT$	total savings
$SINK$	carbon sink
t_{EM}	carbon tax
TRV	transfers
X_j	production in sector j
XE	endogenous production of electricity
XH	production of heat

C. PARAMETERS

$bdsh_j$	Leontief coefficient for traffic fuels in sector j
CA	current account
$coef_f$	unit change coefficient
$conv$	converts capital stock to capital services
$depro$	depreciation rate
E	exogenously given capasity for production of electricity
$e^{\gamma t}$	growth of export demand
$effc$	carbon tax rate for emissions from wood
$\overline{EM}$	exogenously given emission constraint
$emco_f$	emission coefficient for fuel f
$nrem$	emission coefficient for wood
$pcmw_{kt}$	import price of good kt in foreign currency
$pf_{PEAT,EH}$	price of peat
$pfw_{f,s}$	world market price of fuel f in sector s
$pinvmw$	price of imported investment goods in foreign currency
pmw_t	world market price of imported good t in foreign currency
pw_t	world market price of good t in foreign currency
s	savings rate
SD_t	statistical discrepancy
$taxb$	tax on gasoline in households
$taxd_j$	tax on gasoline in sector j
$taxd_G$	tax on traffic fuels in public sector
$taxl_s$	pay roll tax in sector s
$taxs_j$	indirect taxes per unit of production
Z_t^0	exports in benchmark year
α	interest rate elasticity of timber supply
β	price elasticity of timber supply
ε	price elasticity of export demand
λ_C	necessity consumption
χ	timber stock elasticity of timber supply